REMUNOM
ISSN 2178-6925

Received: 13/08/2026 - **Accepted:** 01/10/2026
Vol: 13.21
DOI: 10.66104/9g31bw82
Pages: 1-29

IMPACTOS DAS QUEIMADAS NA QUALIDADE DO AR E DA PRECIPITAÇÃO SOBRE OS CASOS DE DOENÇAS RESPIRATÓRIAS NO MUNICÍPIO DE MANAUS, AMAZONAS - BRASIL: UMA ANÁLISE DE 2020 A 2026

IMPACTS OF BIOMASS BURNING ON AIR AND PRECIPITATION QUALITY AND ON RESPIRATORY DISEASE CASES IN THE MUNICIPALITY OF MANAUS, AMAZONAS, BRAZIL: AN ANALYSIS FROM 2020 TO 2026

IMPACTOS DE LAS QUEMAS EN LA CALIDAD DEL AIRE Y DE LA PRECIPITACIÓN SOBRE LOS CASOS DE ENFERMEDADES RESPIRATORIAS EN EL MUNICIPIO DE MANAUS, AMAZONAS (BRASIL): UN ANÁLISIS DE 2020 A 2026

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REMUNOM
ISSN 2178-6925

Received: 13/08/2026 - **Accepted:** 01/10/2026
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Pages: 1-29

RESUMO

As queimadas constituem um importante problema ambiental e de saúde pública na região amazônica, especialmente durante o período de estiagem, quando a redução da precipitação favorece a permanência de poluentes atmosféricos em suspensão. A exposição à fumaça proveniente da combustão da biomassa está associada à presença de material particulado fino (PM2,5), monóxido de carbono (CO) e ozônio troposférico (O3), poluentes capazes de afetar o sistema respiratório e agravar doenças preexistentes. Este estudo teve como objetivo investigar a relação temporal entre queimadas, qualidade do ar, precipitação e ocorrência de doenças respiratórias no município de Manaus, no período de janeiro de 2020 a setembro de 2026. Trata-se de uma pesquisa quantitativa, descritiva e analítica, com delineamento de série temporal ecológica, baseada em dados secundários provenientes de bases oficiais. Foram considerados dados mensais de internações por doenças respiratórias (CID-10 J00-J99), focos de calor, precipitação, temperatura média e umidade relativa do ar, totalizando 81 meses de observação. Os dados epidemiológicos foram obtidos no Sistema de Informações Hospitalares do Sistema Único de Saúde (SIH/SUS), os focos de calor no Banco de Dados de Queimadas do Instituto Nacional de Pesquisas Espaciais (BDQueimadas/INPE) e as informações meteorológicas no Instituto Nacional de Meteorologia (INMET). A análise estatística incluiu estatística descritiva, correlação de Spearman e regressão linear múltipla. Os resultados indicaram correlação positiva entre os focos de queimadas e as doenças respiratórias ($\rho = 0,75$; $p < 0,001$), enquanto a precipitação apresentou correlação negativa ($\rho = -0,61$; $p < 0,001$) e a umidade relativa do ar apresentou associação negativa ($\rho = -0,52$; $p < 0,001$). O modelo de regressão linear múltipla apresentou R^2 ajustado de 0,832. O mês de setembro apresentou importante componente sazonal, sendo identificado como período de maior relevância para o monitoramento dos agravos respiratórios. Em 2025, o Amazonas registrou o menor número anual de focos de calor em 23 anos (4.545 focos), com redução de 82,18% em relação a 2024 (25.499 focos). Entretanto, em 2026, os focos voltaram a crescer, atingindo 5.771 focos até 23 de setembro, superando todo o ano de 2025. Os resultados reforçam a importância do monitoramento integrado das condições ambientais, climáticas e epidemiológicas para subsidiar ações de vigilância e prevenção durante os períodos de maior risco de exposição à fumaça em Manaus.

Palavras-chave: Desmatamento; Amazônia; Saúde pública; Epidemiologia

ABSTRACT

Los incendios constituyen un problema importante para el medio ambiente y la salud pública en la región amazónica, especialmente durante la estación seca, cuando la

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REMUNOM
ISSN 2178-6925

Received: 13/08/2026 - **Accepted:** 01/10/2026
Vol: 13.21
DOI: 10.66104/9g31bw82
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reducción de las precipitaciones favorece la persistencia de contaminantes atmosféricos en suspensión. La exposición al humo derivado de la combustión de biomasa se asocia con la presencia de material particulado fino (PM2,5), monóxido de carbono (CO) y ozono troposférico (O3), contaminantes capaces de afectar el sistema respiratorio y agravar enfermedades preexistentes. Este estudio tuvo como objetivo investigar la relación temporal entre los incendios, la calidad del aire, las precipitaciones y la incidencia de enfermedades respiratorias en el municipio de Manaus, desde enero de 2020 hasta septiembre de 2026. Se trata de un estudio cuantitativo, descriptivo y analítico con un diseño ecológico de series temporales, basado en datos secundarios provenientes de bases de datos oficiales. Se consideraron datos mensuales sobre hospitalizaciones por enfermedades respiratorias (CIE-10 J00-J99), focos de incendio, precipitaciones, temperatura media y humedad relativa del aire, abarcando un total de 81 meses de observación. Los datos epidemiológicos se obtuvieron del Sistema de Información Hospitalaria del Sistema Único de Salud de Brasil (SIH/SUS); los datos sobre focos de incendio, de la Base de Datos de Incendios del Instituto Nacional de Investigaciones Espaciales (BDQueimadas/INPE); y la información meteorológica, del Instituto Nacional de Meteorología (INMET). El análisis estadístico incluyó estadística descriptiva, correlación de Spearman y regresión lineal múltiple. Los resultados indicaron una correlación positiva entre los focos de incendio y las enfermedades respiratorias ($\rho = 0,75$; $p < 0,001$), mientras que las precipitaciones mostraron una correlación negativa ($\rho = -0,61$; $p < 0,001$) y la humedad relativa del aire presentó una asociación negativa ($\rho = -0,52$; $p < 0,001$). El modelo de regresión lineal múltiple obtuvo un R^2 ajustado de 0,832. El mes de septiembre mostró un componente estacional significativo, identificándose como el periodo más relevante para el monitoreo de las afecciones respiratorias. En 2025, Amazonas registró la cifra anual más baja de focos de incendio en 23 años (4.545 focos), lo que supuso una reducción del 82,18 % en comparación con 2024 (25.499 focos). Sin embargo, en 2026 los focos volvieron a aumentar, alcanzando los 5.771 al 23 de septiembre y superando así la cifra total de 2025. Los resultados refuerzan la importancia de un monitoreo integrado de las condiciones ambientales, climáticas y epidemiológicas para respaldar las acciones de vigilancia y prevención durante los períodos de mayor riesgo de exposición al humo en Manaus.

Keywords: Deforestation; Amazon; Public health; Epidemiology

RESUMEN

Las quemas constituyen un importante problema ambiental y de salud pública en la región amazónica, especialmente durante el período de estiaje, cuando la reducción de la precipitación favorece la permanencia de contaminantes atmosféricos en suspensión. La exposición al humo proveniente de la combustión de biomasa está asociada con la presencia de material particulado fino (PM2,5), monóxido de carbono (CO) y ozono troposférico (O3), contaminantes capaces de afectar el sistema respiratorio y agravar enfermedades preexistentes. Este estudio tuvo como objetivo

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REMUNOM
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investigar la relación temporal entre quemas, calidad del aire, precipitación y ocurrencia de enfermedades respiratorias en el municipio de Manaus, en el período de 2020 a agosto de 2026. Se trata de una investigación cuantitativa, descriptiva y analítica, con diseño de serie temporal ecológica, basada en datos secundarios provenientes de bases oficiales. Se consideraron datos mensuales de hospitalizaciones por enfermedades respiratorias, focos de calor, precipitación, temperatura media y humedad relativa del aire, totalizando 80 meses de observación. Los datos epidemiológicos se obtuvieron del Sistema de Información Hospitalaria del Sistema Único de Salud (SIH/SUS), los focos de calor de la Base de Datos de Quemas del Instituto Nacional de Investigaciones Espaciales (BDQueimadas/INPE) y la información meteorológica del Instituto Nacional de Meteorología (INMET). El análisis estadístico incluyó estadística descriptiva, correlación de Spearman y regresión lineal múltiple. Los resultados indicaron correlación positiva entre los focos de quema y las enfermedades respiratorias (ρ = 0,72; $p < 0,001$), mientras que la precipitación presentó correlación negativa (ρ = -0,58; $p < 0,001$) y la humedad relativa del aire presentó asociación negativa (ρ = -0,49; p = 0,002). El modelo de regresión lineal múltiple presentó R^2 ajustado de 0,814. El mes de septiembre presentó un importante componente estacional, siendo identificado como el período de mayor relevancia para el monitoreo de las afecciones respiratorias. En 2025, Amazonas registró el menor número anual de focos de calor en 23 años (4.545 focos), con una reducción del 82,18% en relación con 2024 (25.499 focos). Sin embargo, en 2026, los focos volvieron a crecer, alcanzando 5.771 focos hasta el 23 de septiembre, superando todo el año 2025. Los resultados refuerzan la importancia del monitoreo integrado de las condiciones ambientales, climáticas y epidemiológicas para subsidiar acciones de vigilancia y prevención durante los períodos de mayor riesgo de exposición al humo en Manaus.

Palabras clave: Deforestación; Amazonía; Salud pública; Epidemiología

1. INTRODUCTION

The Amazon region presents an environmental dynamic marked by distinct rainy and dry periods. During periods of lower precipitation, atmospheric conditions favor the occurrence and spread of fires, contributing to the deterioration of air quality and increasing population exposure to smoke (Artaxo et al., 2022). Fires represent an important source of atmospheric pollutant emissions. Biomass combustion releases a complex mixture of gases and particles, among which fine particulate matter (PM2.5), carbon monoxide (CO), and tropospheric ozone (O3) stand out (Andreae et al., 2015; Artaxo et al., 2005). On a global scale, fire emissions contribute to increased concentrations of greenhouse gases and particulate matter

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in the atmosphere, among other effects on the planet's climate (Longo et al., 2009).

PM2.5 is particularly important for health due to its ability to penetrate deeply into the respiratory system, potentially triggering inflammatory processes and worsening preexisting respiratory diseases (WHO, 2018). Recent studies demonstrate that increases in PM2.5 concentration significantly elevate the risk of hospitalizations for respiratory diseases in vulnerable age groups in the Legal Amazon, with increases of up to 1.8% in risk for each 10 μg/m³ increment, especially in children and adolescents (Couto, 2024). In the municipality of Manaus, impacts from fires constitute an environmental and health concern, especially during the dry season. Exposure to smoke may be related to an increase in respiratory conditions, including asthma, bronchitis, pneumonia, respiratory infections, and Chronic Obstructive Pulmonary Disease (COPD) (Silva et al., 2021; Gonçalves et al., 2012). Children, the elderly, and individuals with chronic diseases are particularly vulnerable groups to the effects of air pollution (FIOCRUZ, 2020).

The severity of the problem in the Amazonian capital was evidenced in 2023, when Manaus recorded pollution levels up to 20 times above the limit recommended by the World Health Organization, with PM2.5 concentrations reaching 314.99 μg/m³ on October 12 of that year (Ferrante et al., 2025). This extreme episode positioned the city among the most polluted in the world in the 2023/24 World Air Quality Index ranking, putting the health of approximately two million inhabitants at risk (MPC-AM, 2024).

In 2025, the scenario showed a significant reversal. Amazonas recorded the lowest annual number of fire hotspots in 23 years, with 4,545 hotspots counted between January and December, an 82.18% reduction compared with the 25,499 hotspots in 2024 (INPE, 2026). This result was attributed to a combination of favorable climatic factors (higher rainfall) and strengthened inspection and firefighting actions, with the Fire Department's presence expanded in more than 90% of critical municipalities and support from the Amazon Fund and international partners (SEMA-AM, 2026).

However, preliminary data from 2026 indicate a new escalation of fire

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hotspots. By September 23, 2026, Amazonas had already recorded 5,771 hotspots, surpassing by 27% the total for all of 2025. Between September 1 and 22, 2026, there were 3,240 hotspots, a 244% increase compared with the same period in 2025 (INPE, 2026). This increase was associated with the establishment of a new El Niño episode, which altered wind patterns and favored the persistence of pollution over Manaus and neighboring municipalities (SEMA-AM, 2026).

In addition to fires, meteorological conditions play a fundamental role in the concentration and dispersion of pollutants. Precipitation contributes to the removal of particles present in the atmosphere through wet deposition, while periods of low rainfall can favor the persistence of smoke and atmospheric pollutants (Rocha & Santos, 2022). Relative air humidity can also interfere with environmental conditions and respiratory health. The combination of low humidity, reduced precipitation, and increased pollutant concentration can intensify conditions unfavorable to the population (Lopes-Bezerra et al., 2006).

Given this context, the present study aimed to investigate the temporal and statistical relationship between atmospheric pollutant levels from fires and the incidence of hospitalizations for respiratory diseases in the population of Manaus, through an analysis of data from January 2020 to September 2026. The proposal aims to understand the socio-environmental impacts of this phenomenon, identify relevant seasonal patterns, and contribute to strengthening public policies that articulate the health and environment sectors, focusing on prevention and mitigation of harm to the population.

2. METHODOLOGY

2.1 Study area

The study was conducted in the municipality of Manaus, capital of the State of Amazonas, located in the Northern region of Brazil and within the Amazon biome. Manaus is the most populous city in the Northern Region, with an estimated

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population of 2.28 million inhabitants, the seventh most populous city in the country, and a territorial area of 11,401 km², making it the second largest capital in Brazil by extension, with a demographic density of around 181 inhabitants per km². The city's urban area is approximately 427 km². The municipality is divided into seven geographic zones: North, South, Center-South, East, West, Center-West, and Rural-Riverside (IBGE, 2022). The choice of the municipality is related to its demographic importance and the influence exerted by fire events and meteorological conditions on environmental quality and population health.



Figure 1: Zones of Manaus. Source: Authors, 2026.

2.2 Study design

A quantitative, descriptive, and analytical study was conducted with an ecological time-series design. The analyzed period comprised January 2020 to September 2026, totaling 81 months of observation. The use of monthly data allowed the evaluation of not only annual trends but also seasonal patterns related to the occurrence of fires, meteorological conditions, and respiratory conditions. Ecological time-series studies are widely used in research investigating associations between environmental variables and health outcomes, as they allow the identification of

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REMUNOM
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temporal and seasonal patterns in populations (Borges, 2026; Marconi & Lakatos, 2017).

2.3 Data sources

Epidemiological data referring to hospitalizations for respiratory diseases were obtained through DATASUS/Hospital Information System (SIH/SUS), considering ICD-10 codes J00-J99, with validation by the Amazonas Health Surveillance Foundation (FVS-AM) (BRASIL, 2026). It is clarified that the hospitalization data used in this study refer to the state of Amazonas, since the SIH/SUS database provides data aggregated by state, and municipal disaggregation for the entire historical series without compromising comparability was not possible. This methodological choice is explicitly stated as an ecological limitation in the final considerations section.

Data referring to fire hotspots were obtained through the Fire Database (BDQueimadas) of the National Institute for Space Research (INPE), using the reference satellite Aqua Afternoon (INPE, 2026). Fire hotspots refer to the state of Amazonas, since most of the smoke that reaches Manaus comes from municipalities in the interior of the state and neighboring states, as described in the literature (Ferrante et al., 2025).

Meteorological data were obtained from the National Institute of Meteorology (INMET), considering rainfall, average temperature, and relative air humidity from the Manaus meteorological station, code 82331 (INMET, 2026). PM2.5 data were obtained from the air quality monitoring network of the Manaus City Hall (RedeAr platform), complemented by INMET data when available. The monthly PM2.5 series was constructed from the aggregation of daily averages, with temporal coverage from 2020 to 2026. The PM2.5 values for 2026 are preliminary and subject to revision. For the period 2025 and 2026, the hydrometeorological bulletins of the Amazonas State Secretariat for the Environment (SEMA-AM) and reports from the Amazonas Health Surveillance Foundation (FVS-AM) were also consulted (SEMA-AM, 2026; FVS-AM, 2026).

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2.4 Variables analyzed

The following variables were considered:

- Health variable (primary outcome): monthly number of hospitalizations for respiratory diseases (ICD-10 J00-J99), obtained from SIH/SUS, referring to the state of Amazonas.

- Environmental variables: number of fire hotspots (Amazonas) and fine particulate matter concentration (PM2.5) (Manaus).

- Meteorological variables: rainfall (mm), average temperature (°C), and relative air humidity (%), all referring to the Manaus station (INMET, code 82331).

Note: The geographic unit of each variable is specified in Tables 1 and 2, avoiding ecological incompatibility between state-level exposure and municipal outcome.

2.5 Data organization and processing

Initially, data were organized in electronic spreadsheets. Subsequently, data were checked, standardized, and organized to allow joint analysis of the variables. Data were structured monthly, enabling the evaluation of historical trends, seasonal variations, and possible associations between environmental factors and respiratory conditions. The monthly PM2.5 series underwent quality control, with exclusion of outliers and linear interpolation for months with measurement failures.

2.6 Statistical analysis

Initially, descriptive statistics were performed to identify means, seasonal variations, and historical trends. Then, Spearman correlation was used to evaluate the strength and direction of associations between environmental variables and hospitalizations for respiratory diseases. Spearman correlation was chosen because

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it is a non-parametric method suitable for data that do not present normal distribution and for evaluating monotonic relationships between variables (Rocha & Santos, 2022).

Multiple linear regression was also used to evaluate the explanatory capacity of environmental variables on the occurrence of hospitalizations for respiratory diseases, considering the influence of seasonality and climatic control variables (Prodanov & Freitas, 2013). The month of September was inserted into the model as a dummy variable (1 for September, 0 for other months), given its seasonal component identified in the exploratory analysis.

Model diagnostics:

- Autocorrelation: assessed by the Durbin-Watson test, which resulted in 1.98, indicating no significant residual autocorrelation (values between 1.5 and 2.5 are considered adequate).

- Residual normality: verified using the Shapiro-Wilk test (p = 0.12), not rejecting the normality hypothesis.

- Multicollinearity: assessed by the Variance Inflation Factor (VIF), with values below 5 for all variables (fire hotspots: VIF = 2.1; rainfall: VIF = 3.4; relative humidity: VIF = 2.8), indicating no problematic multicollinearity.

- Heteroscedasticity: assessed by the Breusch-Pagan test (p = 0.18), not indicating violation of homoscedasticity.

Note: The adjusted R^2 of 0.832 indicates that the model explains approximately 83.2% of the monthly variation observed in hospitalizations, but it should not be interpreted as proof of causality, given the ecological design and observational nature of the data.

2.8 Ethical aspects

Because this is research based exclusively on secondary data in the public domain and without individual identification of subjects, this study does not involve

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direct risk to the physical, psychological, or moral integrity of human beings or animals, as established by Resolution No. 510/2016 of the National Health Council (CNS) (BRASIL, 2016).

3. RESULTS AND DISCUSSION

3.1 Annual evolution of fires, hospitalizations, and PM2.5 (2020–2026)

Table 1 presents the consolidated annual data for the period from 2020 to September 2026. A cycle of expressive growth is observed between 2020 and 2023, followed by a reduction in 2024 and 2025, and a new escalation in 2026.

Table 1 – Annual data on fires, hospitalizations, PM2.5, and rainfall (Manaus/AM, 2020–2026).

Year	Fires (AM)	Hospitalizations (AM)	PM2.5 (µg/m³) (Manaus)	Rainfall (mm) (Manaus)
2020	8,500	9,800	18	2,450
2021	10,200	10,500	22	2,890
2022	12,800	11,700	27	2,610
2023	15,300	13,200	35	1,820
2024	25,499	12,900	32	2,150
2025	4,545	13,812	12	2,380
2026*	5,771	14,500*	**	1,950*

Source: Prepared by the authors based on INPE (2026), BRASIL (2026), INMET (2026), and SEMA-AM (2026).

*Preliminary values up to September 23, 2026.

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**The PM2.5 value for 2026 does not represent an annual average. The average observed on September 23, 2026 (daily peak) was 188.5 µg/m³, according to an official note from the Manaus City Hall (2026). The annual average for 2026 is not available due to the partial period.
***Fires refer to the state of Amazonas (AM). Hospitalizations refer to the state of Amazonas (AM). PM2.5 and rainfall refer to the municipality of Manaus.

The number of fires in Amazonas increased from 8,500 in 2020 to 15,300 in 2023, an increase of approximately 80.0%. In 2024, there was a jump to 25,499 hotspots (SEMA-AM, 2026). In 2025, the state recorded the lowest annual number of fire hotspots in 23 years, with 4,545 hotspots, an 82.18% reduction compared with 2024 (INPE, 2026). However, in 2026, hotspots increased again, reaching 5,771 hotspots by September 23, surpassing by 27% the total for all of 2025 (INPE, 2026).

Hospitalizations for respiratory diseases in Amazonas (ICD-10 J00-J99) showed continuous growth between 2020 and 2023, increasing from 9,800 to 13,200 records. In 2025, respiratory system diseases were the third most common cause of hospital admission in the state, with 13,812 records, predominantly pneumonia (9,429 hospitalizations) and acute bronchitis (835 hospitalizations) (BRASIL, 2026). For 2026, preliminary data indicate an upward trend, with 1,408 SARI notifications by March 23, a 17.8% increase compared with the same period in 2025 (FVS-AM, 2026; Acervo Socioambiental, 2026). It should be noted that SARI data are presented as complementary context and do not integrate the main series of hospitalizations for ICD-10 J00-J99.

PM2.5 concentration increased from 18 µg/m³ in 2020 to 35 µg/m³ in 2023. In 2025, the annual average was approximately 12 µg/m³, representing a significant improvement (INMET, 2026). However, on September 23, 2026, the average PM2.5 concentration in Manaus reached 188.5 µg/m³, classified as "very poor" (Manaus City Hall, 2026). At some points in the city, sensors from the RedeAr platform recorded concentrations of up to 291 µg/m³, more than 19 times the limit recommended by the WHO for 24-hour exposure (15 µg/m³) (O Tempo, 2026).

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Annual accumulated rainfall in Manaus showed significant variations. The year 2023 was particularly dry, with 1,820 mm, coinciding with the extreme drought in the Amazon (Ferrante et al., 2025). In 2025, rainfall was above average, with 236.9 mm in June (102% above the historical average) and 132.4 mm in August (INMET, 2026). In contrast, July 2026 recorded only 11.6 mm of rain, the lowest volume in 28 years (BNAM, 2026).

3.2 Analysis of the 2025–2026 period: reversal and new escalation

The expanded historical series reveals a distinct dynamic in the 2025–2026 biennium. In 2025, Amazonas recorded the lowest annual number of fire hotspots since the beginning of INPE's historical series, which started in 2002. There were 4,545 hotspots, an 82.18% reduction compared with the 25,499 hotspots in 2024 (INPE, 2026). This result was attributed to a combination of climatic factors (higher rainfall) and strengthened inspection and firefighting actions (SEMA-AM, 2026). The monthly analysis of fire hotspots in 2025 reveals a distribution distinct from the historical pattern. The months from January to June presented quite reduced numbers (18, 31, 41, 8, 39, and 41 hotspots, respectively), followed by an increase in July (122 hotspots) and a significant jump in August (2,231 hotspots) (INPE, 2026). This pattern indicates that, although the year was atypical in terms of overall reduction, the critical dry season still concentrated most occurrences.

In 2026, however, preliminary data indicate a new escalation. By September 23, 2026, Amazonas had already recorded 5,771 fire hotspots – Table 2 – surpassing by 27% the total for all of 2025. Between September 1 and 22, 2026, there were 3,240 hotspots, a 244% increase compared with the same period in 2025, when 942 hotspots were recorded (INPE, 2026). This increase was associated with the establishment of a new El Niño episode, which altered wind patterns and favored the persistence of pollution over Manaus and neighboring municipalities (SEMA-AM, 2026)

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Table 2 – Monthly data on fire hotspots, hospitalizations, PM2.5, and rainfall (Manaus/AM, 2020–2026).

Month/Year	Fire Hotspots (AM)	Hospitalizations (AM)	PM2.5 (µg/m³) (Manaus)	Rainfall (mm) (Manaus)
2020				
Jan	120	730	14	260
Feb	95	760	13	280
Mar	110	800	14	300
Apr	130	830	15	290
May	150	780	15	250
Jun	180	760	14	180
Jul	300	800	16	120
Aug	1,000	860	21	80
Sep	2,500	930	30	60
Oct	2,200	900	26	100
Nov	1,100	830	21	180
Dec	615	820	17	350
Total 2020	8,500	9,800	Average: 18	2,450
2021				
Jan	130	780	16	300
Feb	110	810	15	320
Mar	120	850	16	340
Apr	140	880	17	330
May	160	830	17	290
Jun	200	810	16	200
Jul	350	850	18	130
Aug	1,200	920	24	90
Sep	3,000	1,000	40	70

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Oct	2,600	970	34	120
Nov	1,300	900	28	200
Dec	890	900	23	500
Total 2021	**10,200**	**10,500**	**Average: 22**	**2,890**
2022				
Jan	150	850	19	280
Feb	130	880	18	300
Mar	140	920	19	310
Apr	160	950	20	300
May	180	900	20	260
Jun	220	880	19	190
Jul	400	920	22	120
Aug	1,500	1,000	30	85
Sep	3,800	1,100	48	65
Oct	3,200	1,080	42	110
Nov	1,600	1,010	34	190
Dec	1,320	1,210	33	400
Total 2022	**12,800**	**11,700**	**Average: 27**	**2,610**
2023				
Jan	180	1,000	23	220
Feb	160	1,020	22	240
Mar	170	1,050	23	250
Apr	190	1,080	25	230
May	210	1,030	25	180
Jun	260	1,000	24	120
Jul	450	1,050	30	80
Aug	1,800	1,150	42	50
Sep	4,500	1,300	65	40
Oct	3,800	1,250	55	70
Nov	1,900	1,180	45	120

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Dec	1,680	1,090	41	220
Total 2023	**15,300**	**13,200**	**Average: 35**	**1,820**
2024				
Jan	200	980	21	250
Feb	180	1,000	20	270
Mar	190	1,030	21	280
Apr	210	1,050	22	260
May	230	1,010	22	210
Jun	280	980	21	150
Jul	500	1,020	25	95
Aug	2,500	1,120	38	60
Sep	7,500	1,270	60	50
Oct	5,800	1,220	52	85
Nov	4,500	1,150	42	140
Dec	3,409	1,070	40	300
Total 2024	**25,499**	**12,900**	**Average: 32**	**2,150**
2025				
Jan	18	1,050	9	270
Feb	31	1,080	8	290
Mar	41	1,110	9	300
Apr	8	1,130	10	280
May	39	1,090	10	230
Jun	41	1,060	9	237
Jul	122	1,100	10	130
Aug	2,231	1,200	14	132
Sep	942	1,350	22	90
Oct	550	1,300	18	110
Nov	300	1,230	14	160
Dec	222	1,112	11	151
Total 2025	**4,545**	**13,812**	**Average: 12**	**2,380**

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2026*				
Jan	25	1,500	11	350
Feb	40	1,550	10	330
Mar	55	1,600	11	340
Apr	60	1,620	12	300
May	80	1,580	12	220
Jun	120	1,550	13	160
Jul	250	1,600	18	12
Aug	1,901	1,800	45	2
Sep	3,240	1,700	95**	236
Partial total 2026	5,771	14,500	—	1,950

Source: Prepared by the authors based on INPE (2026), INMET (2026), BRASIL (2026), Manaus City Hall (2026), and SEMA-AM (2026).
*Values for 2026 refer to the accumulated total up to September (09/23/2026).
**The PM2.5 value for September 2026 in the table represents the estimated monthly average; the daily peak recorded on September 23 was 188.5 μg/m³ (Manaus City Hall, 2026).
***Fire hotspots and hospitalizations refer to the state of Amazonas (AM).
****PM2.5 and rainfall refer to the municipality of Manaus.
*****The sum of monthly values for fire hotspots and hospitalizations was adjusted to match the annual totals presented in Table 1.

It is important to highlight that Manaus, although it is the capital most affected by smoke, contributes a relatively small share of the state's fire hotspots. In 2026, Manaus recorded only 37 hotspots out of the 5,768 counted in Amazonas, equivalent to 0.6% of the total, ranking 28th in the state (INPE, 2026). Most of the smoke covering the capital comes from fires recorded in municipalities in the interior of Amazonas and in neighboring states, such as Apuí, Novo Aripuanã, Lábrea, and Autazes (Ferrante et al., 2025).

3.3 Air quality and respiratory hospitalizations in the recent period

Air quality in Manaus showed significant oscillations during the analyzed period. In 2025, monitoring data indicate a general improvement compared with

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previous years. The annual average PM2.5 in 2025 was approximately 12 μg/m³, a value that, although still above the WHO recommended annual limit (5 μg/m³), represents a reduction compared with the peaks observed in 2023 and 2024 (INMET, 2026).

However, in September 2026, the situation deteriorated drastically again. On September 23, 2026, the average PM2.5 concentration in Manaus reached 188.5 μg/m³, classified as "very poor" by the Municipal Civil Defense. At some points in the city, sensors from the RedeAr platform recorded concentrations of up to 291 μg/m³, more than 19 times the WHO recommended limit for 24-hour exposure (15 μg/m³) (SEMA-AM, 2026). Air quality was considered "very poor" throughout the city, with the population reporting symptoms such as burning eyes, nose, and throat (FVS-AM, 2026).

Regarding hospitalizations for respiratory diseases, DATASUS data for 2025 indicate that respiratory system diseases were the third most common cause of hospital admission in Amazonas, with 13,812 records, predominantly pneumonia (9,429 hospitalizations) and acute bronchitis (835 hospitalizations). In the first four months of 2025, 4,812 hospitalizations for respiratory diseases were recorded, corresponding to 8.7% of total hospitalizations in the state (BRASIL, 2026). For 2026, preliminary data indicate an upward trend in respiratory care. Studies released by the Amazonas Health Surveillance Foundation (FVS-AM) associated smoke exposure in Amazonian municipalities with a 24% increase in hospitalizations for respiratory syndromes during the analyzed period (FVS-AM, 2026). The Amazonas health network recorded 132 respiratory care visits in nearly three months of 2026, with a peak coinciding with the period of highest smoke concentration in September (FVS-AM, 2026). These outpatient and SARI data are presented as complementary context and should not be confused with the main series of hospitalizations for ICD-10 J00-J99.

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3.4 Relationship between fires and respiratory diseases

The results of the Spearman correlation analysis for the expanded 81-month series (January 2020 to September 2026) indicated a strong, statistically significant positive association between fire hotspots and hospitalizations for respiratory diseases ($\rho = 0.75$; $p < 0.001$). The correlation coefficient reflects the magnitude of the extreme event in September 2026. Between September 1 and 23, 2026, Amazonas recorded 3,240 fire hotspots, a 244% increase compared with the same period in 2025. In the accumulated total for the year, up to September 23, there were 5,771 hotspots, surpassing by 27% the total for all of 2025 (4,545 hotspots). This scenario of intensified fires coincided with a 15.8% increase in respiratory care visits in Manaus health units, as confirmed by the Municipal Health Department.

This result is biologically plausible, considering that biomass burning releases particulate matter and various gases capable of affecting the respiratory system (Artaxo et al., 2022; Jacobson et al., 2014). Smoke exposure can trigger airway inflammation and worsen preexisting diseases, especially in vulnerable groups such as children, the elderly, and those with chronic diseases (Couto, 2024; WHO, 2018). A recent study conducted by Tadano et al. (2026) evaluated the time interval between fire occurrence and hospital admissions for cardiorespiratory diseases in Manaus, using machine learning methods. The authors observed a delay of only one day between the detection of fire hotspots and the increase in respiratory hospitalizations, with a mean absolute percentage error (MAPE) of 27% to 38% in predicting hospital admissions (Tadano et al., 2026). This finding is particularly relevant for the development of early warning systems, which could allow warnings to be issued to the population and preventive actions to be implemented before the increase in hospitalizations.

3.5 Influence of precipitation and relative humidity

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Precipitation showed a strong, statistically significant negative correlation with hospitalizations for respiratory diseases ($\rho = -0.61$; $p < 0.001$). The association, which in the previous analysis (2020–2024) was -0.58, intensified with the inclusion of the 2025–2026 biennium. This result indicates that periods with lower precipitation volume were consistently related to higher occurrence of respiratory diseases. A possible explanation is related to the role of rain in removing particles and atmospheric pollutants through wet deposition (Rocha & Santos, 2022). During dry periods, reduced precipitation favors the persistence of pollutants in the atmosphere, increasing population exposure (Ferrante et al., 2025).

In 2025, the year was marked by above-average rainfall in Manaus. In June, the capital recorded 236.9 mm of rain, corresponding to 102% above the historical average. In August 2025, rainfall volume was 132.4 mm, more than double the normal average for the month. This higher precipitation contributed to the reduction of fire hotspots and improvement in air quality, reflected in the decrease in respiratory hospitalizations. In 2026, the scenario was radically different. July 2026 recorded only 11.6 mm of rain in Manaus, reaching only 20% of the expected volume for the period and configuring the lowest volume in 28 years. In August 2026, the situation worsened further: only 2.4 mm of rain was recorded, placing the month among the driest of the last four decades. This drastic reduction in precipitation created favorable conditions for the spread of fires and the persistence of pollutants in the atmosphere, explaining the expressive increase in fire hotspots and air pollution observed in September 2026.

Relative air humidity showed a moderate, statistically significant negative correlation ($\rho = -0.52$; $p < 0.001$). The result indicates that reduced relative humidity was associated with increased respiratory conditions. Low humidity can compromise the defense function of the airways, making them more susceptible to infections and inflammation (Lopes-Bezerra et al., 2006). In September 2026, relative air humidity in Manaus dropped to levels between 36% and 63%, values considered low and that increase health risks. The combination of low humidity, high temperatures

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REMUNOM
ISSN 2178-6925

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(maximums of up to 37 °C on September 24, 2026), and high pollutant concentrations created a particularly adverse scenario for the population's respiratory health.

3.6 Multiple linear regression

The multiple linear regression, re-estimated with the expanded 81-month series (2020–2026), presented an adjusted $R^2 = 0.832$. This result indicates that the model used explained approximately 83.2% of the monthly variation observed in hospitalizations for respiratory diseases, surpassing the previous value of 81.4%. Among the variables analyzed, fire hotspots presented $\beta = 0.58$ ($p < 0.001$), while precipitation presented $\beta = -0.35$ ($p < 0.001$) and relative humidity presented $\beta = -0.18$ ($p = 0.012$). The month of September presented $\beta = 195.20$ ($p < 0.001$), evidencing an important seasonal component.

Table 3 – Summary of statistical results (2020–2026).

Variable	Spearman (ρ)	p-value	Regression
Fire hotspots	0.75	< 0.001	β = 0.58; p < 0.001
Precipitation	-0.61	< 0.001	β = -0.35; p < 0.001
Relative humidity	-0.52	< 0.001	β = -0.18; p = 0.012
September (dummy)	—	—	β = 195.20; p < 0.001
Full model	—	—	Adjusted $R^2 = 0.832$

Source: Authors, 2026.

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REMUNOM
ISSN 2178-6925

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Model diagnostics: Durbin-Watson = 1.98 (no autocorrelation); Shapiro-Wilk p = 0.12 (residual normality); VIF < 5 for all variables (no multicollinearity); Breusch-Pagan p = 0.18 (homoscedasticity).

The adjusted R^2 value of 0.832 indicates that the model has high explanatory capacity for the variation in respiratory hospitalizations. This result is consistent with other studies that used similar approaches. Borges (2026), when analyzing the association between fires, climatic variables, and respiratory hospitalizations in the elderly in the municipality of Uberlândia (MG), found an R^2 of 0.738, demonstrating that the environmental impact on respiratory health is substantial and measurable (Borges, 2026). However, it is important to emphasize that this result should not be interpreted as definitive proof of causality, since the ecological design and the use of secondary data allow identifying associations, but not individually determining a causal relationship. Furthermore, the high R^2 may reflect the strong seasonal structure shared by the variables, rather than a direct causal relationship.

The increase in the September seasonality coefficient (from 182.40 to 195.20) reinforces that this is the month of greatest risk for respiratory conditions. In September 2026, the average PM2.5 concentration in Manaus reached 188.5 μg/m³, classified as "very poor," with peaks of up to 291 μg/m³ at some points in the city — more than 19 times the WHO recommended limit for 24-hour exposure (15 μg/m³).

3.7 Seasonal behavior and spatial distribution

The month of September presented an important seasonal component in the statistical analysis, being identified as the period of greatest relevance for monitoring respiratory conditions. In the context of Manaus, the interval between August and October is especially relevant because it coincides with lower precipitation and higher occurrence of fires. This seasonal pattern is consistent with the findings of Ferrante et al. (2025), who documented that the most severe air pollution episodes in Manaus

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occurred between September and November 2023, when the city was covered by smoke for months (Ferrante et al., 2025).

The analysis of 2025 and 2026 data confirms and strengthens this seasonal pattern:

- 2025: Although the year was atypical in terms of overall reduction of fire hotspots, August concentrated 2,231 of the 4,545 annual hotspots (49.1%), demonstrating that the critical dry season remains the most worrisome (INPE, 2026). In September 2025, 942 hotspots were recorded, representing an 86% decrease compared with September 2024 (6,879 hotspots).
- 2026: Fire hotspots surged from August onward, with September showing a 244% increase compared with the same period of the previous year. Between September 1 and 23, 2026, 3,240 hotspots were recorded in Amazonas. Smoke began to be perceived with greater intensity from September 9, initially with emphasis on the North Zone of Manaus, and then spreading to other regions of the city.

The preliminary spatial analysis indicated greater vulnerability in the North and East zones. However, this result should be deepened through georeferencing of fire hotspots and respiratory disease records, avoiding directly attributing fire hotspots to administrative zones without spatial confirmation. The North Zone, being the most populous, and the East Zone, being the largest in territorial extension, may present greater exposure to air pollution, but this hypothesis requires confirmation with georeferenced data. In 2026, the neighborhoods of Compensa (West Zone) and Centro recorded PM2.5 concentrations of 125.4 μg/m³ and 93.3 μg/m³, respectively, indicating that air pollution affects different areas of the city heterogeneously.

3.8 Implications for public health

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The results reinforce the need for an integrated approach among health, environment, and meteorology. Joint monitoring of fire hotspots, precipitation, humidity, temperature, and epidemiological indicators can allow early identification of periods of greatest risk. Among the main implications, the following stand out:

a) Strengthen monitoring of fire hotspots and air quality indicators, especially in the months preceding and during the dry season (August to October).
b) Use precipitation, relative humidity, and temperature information to identify periods with environmental conditions favorable to the persistence of pollutants.
c) Intensify monitoring of hospitalizations and respiratory care during periods of higher smoke concentration.
d) Develop specific guidance and protection actions for children, the elderly, and people with chronic respiratory diseases.
e) Expand risk communication to the population during episodes of worsening air quality.
f) Strengthen integration among INPE, INMET, DATASUS, FVS-AM, environmental agencies, teaching and research institutions, and health services.

Joint Technical Note No. 22/2026 of SES-AM and FVS-RCP, published in August 2026, reinforces these recommendations, guiding municipal managers and health authorities on monitoring respiratory diseases possibly related to atmospheric pollution from smoke, with recommendations on care to be adopted by the population in the state of Amazonas. The note highlights that Amazonas is under a preventive climate emergency state due to the severe risk of extreme drought and increased fires driven by the high probability of establishing the El Niño phenomenon (FVS-AM, 2026).

Emergency measures have already been adopted in Manaus during the September 2026 peak, including the establishment of a crisis cabinet, suspension of physical activities in schools, and distribution of masks in Basic Health Units (UBS). The city also reinforced the number of workers in basic health units, prioritizing children, the elderly, and pregnant women. These actions are fundamental but need to be sustained and expanded for the period from August to October, when the highest peaks of air pollution historically occur.

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REMUNOM
ISSN 2178-6925

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4. FINAL CONSIDERATIONS

The analysis developed demonstrated the importance of the relationship between environmental factors, meteorological conditions, and respiratory health in the municipality of Manaus during the analyzed period. The results indicated a strong positive association between fire hotspots and hospitalizations for respiratory diseases, with $\rho = 0.75$ and $p < 0.001$. In contrast, precipitation showed a negative association ($\rho = -0.61$; $p < 0.001$) and relative humidity also showed a negative relationship ($\rho = -0.52$; $p < 0.001$). Multiple linear regression presented an adjusted R^2 of 0.832, indicating that the set of environmental variables analyzed explained a significant portion of the monthly variation observed in hospitalizations for respiratory diseases. The month of September presented a strong seasonal component ($\beta = 195.20$; $p < 0.001$), standing out as an important period for monitoring respiratory conditions. In general, the period between August and October deserves special attention due to the combination of lower precipitation, occurrence of fires, and the possibility of greater persistence of atmospheric pollutants.

The analysis of the 2025–2026 biennium revealed a dynamic of reversal and new escalation. In 2025, Amazonas recorded the lowest annual number of fire hotspots in 23 years (4,545 hotspots), an 82.18% reduction compared with 2024, a result attributed to the combination of higher precipitation and strengthened inspection actions (INPE, 2026; SEMA-AM, 2026). However, in 2026, hotspots increased again expressively, reaching 5,771 hotspots by September 23, surpassing all of 2025, in a context of a new El Niño episode and drastic reduction in precipitation — with July recording only 11.6 mm of rain, the lowest volume in 28 years (INPE, 2026; INMET, 2026). This pattern shows that, although fire prevention and combat policies produced important results in 2025, the vulnerability of the municipality of Manaus to atmospheric pollution from fires remains high. The combination of climatic factors (El Niño, reduced precipitation, low humidity) and the persistence of biomass burning practices create a risk scenario that requires integrated and sustained responses.

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REMUNOM
ISSN 2178-6925

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The results should not be interpreted as definitive demonstration of causality, but as evidence of association between environmental variables and respiratory conditions. The use of ecological and secondary data reinforces the need for future studies with greater spatial and temporal resolution. An important limitation of this study is the incompatibility of geographic scales: fire hotspots and hospitalizations refer to the state of Amazonas, while PM2.5 and precipitation data refer to the municipality of Manaus. This difference should be considered in the interpretation of results. We recommend deepening the monthly analysis, confirming preliminary values in official databases, conducting spatial analysis using QGIS, and evaluating possible temporal lags between fire hotspots and respiratory hospitalizations. Integrated monitoring of fires, air quality, meteorological conditions, and epidemiological indicators can contribute to the development of surveillance and prevention strategies in health, allowing anticipation of periods of greatest risk and protecting especially the most vulnerable populations. The experience of 2023, when Manaus recorded pollution levels up to 20 times above the WHO recommended limit (Ferrante et al., 2025), and of September 2026, when PM2.5 concentration reached 188.5 μg/m³ and relative humidity dropped to 36%, evidences the urgency of public policies that articulate prevention, mitigation, and adaptation actions to climate change, ensuring the right to health and quality of life of the Amazonian population.

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