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Article

Macro-Regional Spatial Patterns of Ambient Air Pollution and Avoidable Hospitalizations for Community-Acquired Pneumonia in Mexico (2013–2020)

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Highligths

What are the main findings?

- Macro-regional and state-level bivariate maps reveal persistent "high–high" clusters where industrial $PM_{2.5}$ emissions and avoidable pneumonia hospitalizations coincide, particularly in the northern border corridor and the Mexico City basin.
- National industrial emissions declined from 2013 to 2020; however, several macro-regions (CDMX_Edomex, Centro, Centro Norte) exhibited increasing age- and sex-adjusted PQI 11 rates and demonstrated heterogeneous correlations between emissions and health outcomes. This underscores significant regional disparities in dose–response relationships.

What are the implications of the main findings?

- Basin-based geomatics analysis elucidates significant spatial disparities that are often overlooked by national averages, thereby offering a more appropriate evidence base for the targeted implementation of air quality regulations and healthcare interventions at regional hotspots.
- Customizing environmental and primary healthcare policies to macro-regional emission profiles and vulnerability patterns may be more effective at reducing preventable respiratory hospitalizations than applying uniform, country-wide standards.

Abstract

Ambient air pollution significantly contributes to respiratory illnesses, yet little is known about how industrial emissions are linked to preventable hospitalizations across atmospheric basins in middle-income countries. This study develops a basin-based geomatics framework to examine the spatial and temporal relationship between industrial pollutants and age- and sex-adjusted avoidable hospitalizations for community-acquired pneumonia (PQI 11) in Mexico from 2013 to 2020. Using state-level data grouped into eight macro-regions, we combine bivariate choropleth maps, Pearson correlations, linear regression, and longitudinal time-series analysis to identify spatial clusters of high risk and to estimate regional sensitivities to changes in $PM_{2.5}$, SO_2, NOx, and volatile organic compound emissions. The findings reveal notable regional differences: northern border states and the Mexico City metropolitan basin form persistent high–high clusters where elevated emissions coincide with high PQI 11 rates, while coastal and peninsular regions show lower hospitalization burdens despite medium emission levels. Although national industrial $PM_{2.5}$ emissions decreased over the study period, several macro-regions—particularly CDMX_Edomex, Centro, and Centro

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Norte—experienced significant increases in avoidable hospitalizations and decoupled emission–health patterns. Correlation matrices and regression slopes suggest that the strength and even direction of links between pollutants and PQI 11 vary across macro-regions, with emission-responsive patterns in Centro Norte and weak or inverse relationships in Peninsula and Pacifico Sur. These findings demonstrate that national averages obscure critical spatial disparities and highlight the value of basin-based geomatics approaches for regional air-quality governance, spatial decision support, and primary-care planning aimed at reducing preventable respiratory hospitalizations.

Keywords: geospatial analysis; air quality; public health; $PM_{2.5}$ emissions; avoidable Hospitalizations (PQI 11); and regional heterogeneity

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1. Introduction

Ambient air pollution has emerged as one of the principal environmental factors contributing to the global burden of respiratory diseases, with consistent correlations observed between exposure to fine particulate matter ($PM_{2.5}$) and elevated mortality and hospitalization rates for acute and chronic respiratory conditions [1–3]. Numerous cohort and time-series investigations have demonstrated that modest daily increases in $PM_{2.5}$ concentrations are associated with substantial increases in the risk of mortality from influenza and pneumonia, in addition to heightened hospital admission rates for respiratory illnesses [2,3].

Recent research in Mexico has documented short-term correlations between criteria air pollutants and respiratory health outcomes in major metropolitan regions. The findings indicate that daily increases in $PM_{2.5}$ levels are associated with higher mortality from influenza and pneumonia, as well as heightened risks of respiratory morbidity. Complementary analyses conducted in urban centers such as Monterrey have further demonstrated significant associations between ambient pollutant concentrations and hospital admissions for respiratory diseases, highlighting the susceptibility of populations residing along industrial corridors [4].

Beyond traditional mortality indicators, avoidable hospitalizations for ambulatory care–sensitive conditions have been proposed as a useful metric to assess both the effectiveness of primary care and the impact of environmental factors on hospital demand [5]. Previous studies have shown that air pollution is associated with increased avoidable hospitalizations in urban settings, especially when high pollutant exposure coincides with socioeconomic inequalities [6].

However, most studies in Mexico have focused on a limited number of metropolitan areas and short time windows and have relied on models aggregated at the national or city level that may mask spatial heterogeneity in health risks [7,8]. From the perspective of geomatics and spatial epidemiology, important gaps remain in characterizing the spatiotemporal relationship between industrial emissions and avoidable hospitalizations for community-acquired pneumonia at a macro-regional scale, as well as in identifying critical risk zones where high pollutant loads overlap with vulnerable populations [9].

Beyond quantifying associations, this study advances a geomatics-based framework that integrates industrial emission inventories, atmospheric basin delineation, and spatial epidemiological indicators to enable macro-regional risk characterization. By combining bivariate cartography [10], regression modeling [11], and longitudinal analysis [12] within a spatially explicit structure, the approach contributes a reproducible geospatial methodology for environmental–health integration [13] in emerging economies.

The remainder of this article investigates these objectives, the next section (2) presents the data sources and the methods used in analyzing the ambient air pollution and avoidable hospitalizations in Mexico. Section 3 presents the results of the study, identifying regional patterns and health risk indicators. The penultimate section (4) discusses these findings in the context of the research objectives; the final section (5) concludes the work and presents avenues for future investigation.

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2. Materials and Methods

2.1. Data Sources and Health Indicators

This study integrated two primary datasets covering the 32 federal entities of Mexico for the years 2013, 2016, 2018, and 2020. Health data consisted of avoidable hospitalization rates for community-acquired pneumonia, defined by the Prevention Quality Indicator 11 (PQI 11) of the Agency for Healthcare Research and Quality (AHRQ) [14]. These rates were age- and sex-adjusted to allow for longitudinal and cross-sectional comparisons between states with varying demographic structures [15]. Environmental data were retrieved from national emissions inventories of the Ministry of Environment and Natural Resources of Mexico, specifically focusing on annual tonnage of fine particulate matter $PM_{2.5}$, sulfur dioxide SO_2, nitrogen oxides NO_x, and volatile organic compounds *COV* [16].

2.2. Geographic Stratification

To address spatial heterogeneity, the 32 states were grouped into eight macro-regions based on the methodology of the National Health and Nutrition Survey of Mexico [17], which defined regions by adjacency, the macro-regions are: Frontera: Chihuahua, Coahuila, Nuevo León, and Tamaulipas; Pacifico Norte: Baja California, Baja California Sur, Nayarit, Sinaloa, and Sonora; Pacifico Centro: Colima, Jalisco, and Michoacán; Pacifico Sur: Guerrero, Morelos, Oaxaca, and Puebla; Centro Norte: Aguascalientes, Durango, Guanajuato, Querétaro, San Luis Potosí, and Zacatecas; Centro: Hidalgo, Tlaxcala, and Veracruz; CDMX_Edomex: Ciudad de México, and Estado de México; and Peninsula: Campeche, Chiapas, Quintana Roo, Tabasco, and Yucatán. This stratification enabled the assessment of region-specific sensitivities to industrial emissions [18].

2.3. Geospatial Data Processing and Analysis

Data cleaning and integration were performed using Stata software Version 19 [19]. The variables were merged into a panel dataset using federal entity names and geographic IDs as unique identifiers. Bivariate choropleth maps were generated using the bimap [20] and spmap [21] packages to visualize the overlap between adjusted hospitalization rates and $PM_{2.5}$ emissions. Pearson correlation coefficients (r) were calculated to determine the strength of association between the PQI 11 indicator and each pollutant [22], segmented by macro-region. Scatter plots with linear regression fits (with the Stata command lfit) were utilized to analyze the dose-response relationship [23].

2.4. Ethical Approval and Data Availability

This study utilizes de-identified, publicly available secondary open data from national health and environmental repositories; therefore, it did not require direct intervention with human subjects or specific ethical approval from an institutional review board. All processed datasets and Stata .do files used for this analysis are available in https://github.com/carloshn29/geomatics-datasets to ensure reproducibility.

2.5. Declaration on the Use of Generative AI

Generative Artificial Intelligence (GenAI) was utilized in the preparation of this manuscript. Specifically, Gemini was used to generate data visualization code (Stata scripts). The final interpretation, discussion, statistical verification, and technical writing were conducted and reviewed by the authors to ensure scientific accuracy and integrity.

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3. Results

3.1. Regional Spatiotemporal Patterns of PQI 11 and Air Quality (2013–2020)

The descriptive analysis of health and environmental indicators reveals distinct regional trajectories across the study period (Table 1). On a national scale, a general reduction in industrial emissions was observed; however, this trend was not uniformly reflected in public health outcomes, suggesting a complex, non-linear relationship between atmospheric pollution and respiratory-related hospitalizations.

Longitudinal data indicate that the Centro and Peninsula regions consistently maintained the highest industrial loads, with mean SO_2 emissions reaching 102,056.8 and 56,029.2 tons, respectively. While these regions faced high pollution levels, their hospitalization rates (PQI 11) followed relatively stable paths. In contrast, metropolitan and southern regions experienced significant volatility. For instance, Frontera and Pacifico Norte reported the highest average hospitalization rates (93.66 and 91.83 per 100,000 inhabitants), highlighting these areas as persistent hotspots for avoidable respiratory illness throughout the 2013–2020 period. Several macro-regions exhibited a clear decoupling between trends in emissions and hospitalizations. While most regions experienced a reduction in $PM_{2.5}$ emissions between 2013 and 2020, several of them showed substantial increases in age- and sex-adjusted hospitalization rates for pneumonia, indicating that improved industrial inventories did not necessarily translate into better health outcomes.

For example, CDMX_Edomex and Centro demonstrated declines in $PM_{2.5}$ levels; however, they exhibited substantial percentage increases in avoidable hospitalizations, indicating heightened population vulnerability or the influence of non-industrial sources and local atmospheric conditions. Conversely, the Peninsula region achieved reductions in both emissions and hospitalizations simultaneously. Meanwhile, Pacifico Centro experienced increases in emissions accompanied by only modest growth in hospitalization rates. These divergent percentage trajectories underscore pronounced regional heterogeneity in dose–response behavior, underscoring the importance of macro-regional and basin-based approaches to air quality and health planning.

Table 1. Regional Descriptive Statistics for Health and Air Quality Indicators (2013–2020).

Geographic Region	Mean $PM_{2.5}$ (SD) (Ton)	Mean SO_2 (SD) (Ton)	Mean Hosp. Rate (SD)	Δ $PM_{2.5}$ (%)	Δ Hosp. (%)
CDMX_Edomex	19,029.4 (15,425.5)	3,206.4 (2,333.6)	80.16 (36.37)	-17.96	+113.89
Centro	32,439.9 (28,740.0)	102,056.8 (86,641.2)	52.89 (15.07)	-23.43	+65.96
Centro Norte	15,480.9 (7,810.8)	16,683.2 (21,631.7)	69.82 (11.29)	-24.01	+8.85
Frontera	21,407.9 (8,727.4)	54,189.8 (62,336.1)	93.66 (18.18)	-25.16	+30.59
Pacifico Centro	27,813.9 (18,137.9)	20,245.9 (10,511.7)	90.60 (29.86)	+19.23	+12.32
Pacifico Norte	14,375.3 (8,973.7)	25,639.7 (29,857.3)	91.83 (30.31)	-12.42	+0.90
Pacifico Sur	24,595.3 (10,923.2)	45,398.7 (45,323.8)	42.40 (13.08)	-3.83	+20.05
Peninsula	17,221.9 (14,783.8)	56,029.2 (58,438.2)	54.53 (18.66)	-27.98	-11.11

Note: SD = Standard Deviation; Hosp. Rate = Age- and sex-adjusted hospitalization rate (PQI 11); Δ(%) = Percentage change between 2013 and 2020 baseline inventories.

Age- and sex-standardization of PQI 11 rates was performed to ensure comparability of avoidable hospitalizations across Mexican macro-regions with differing demographic structures. Using the national population by five-year age group and sex as the reference, we applied direct standardization to obtain adjusted rates per 100,000 inhabitants for each state and year [24–26]. This approach reduces confounding by demographic composition, allowing observed regional differences in pneumonia-related avoidable hospitalizations to be more directly attributable to environmental and health-system factors rather than to age or sex distributions. Consequently, the temporal and

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spatial patterns reported in subsequent sections reflect standardized risk measures suitable for longitudinal and cross-sectional studies.

The temporal trajectories of avoidable hospitalizations reveal marked heterogeneity across macro-regions over the 2013–2020 period (Figure 1). Most regions exhibit a modest increase between 2013 and 2016, followed by a transient decline in 2018 and a subsequent rebound in 2020, but the magnitude of these fluctuations varies substantially between regions.

Centro Norte and Centro display the steepest increases by 2020, with adjusted PQI 11 rates rising sharply above 2016 levels, indicating a sustained escalation of respiratory risk in these macro-regions. In contrast, Pacifico Sur and CDMX_Edomex maintain comparatively lower levels throughout the series, despite an uptick in 2020, suggesting a more moderate, though still noticeable, deterioration in hospital demand. Peninsula and Pacifico Norte follow intermediate trajectories, with smoother changes over time. Overall, the non-parallel slopes and diverging endpoints across macro-regions support the presence of region-specific temporal dynamics in avoidable hospitalizations that align with the macro-regional, basin-based approach adopted in this study.

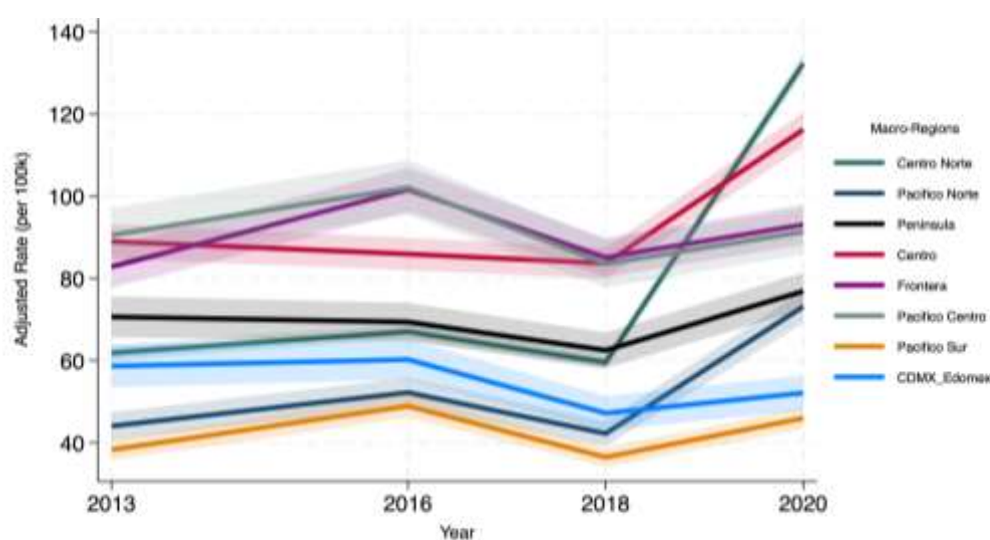

Figure 1. Temporal evolution of age- and sex-adjusted avoidable hospitalization rates for community-acquired pneumonia (PQI 11) by macro-region in Mexico, 2013–2020. Lines represent regional mean rates per 100,000 inhabitants, and shaded bands indicate 95% confidence intervals, highlighting heterogeneous trajectories and a marked post-2018 increase in several macro-regions.

3.2. Bivariate Geospatial Assessment of Health Risk and Emissions

The bivariate choropleth map (Figure 2) illustrates the combined spatial distribution of age-adjusted PQI 11 hospitalization rates and average $PM_{2.5}$ emissions across Mexican states, revealing a pronounced macro-regional structuring of environmental health vulnerability. High–high combinations of respiratory hospital burden and industrial emissions are concentrated in the northern border states and parts of the Pacifico Centro region, delineating contiguous hotspots where elevated pollution levels coincide with a high load of avoidable pneumonia admissions.

In contrast, several states in the Peninsula and Pacifico Sur regions fall into low-hospitalization classes despite medium or high $PM_{2.5}$ emissions, suggesting that coastal dispersion dynamics or differences in population susceptibility may attenuate the observable health impact of emissions. Metropolitan states in the CDMX_Edomex basin exhibit medium hospitalization levels with medium emission loads, indicating that relatively moderate industrial totals in densely populated, high-altitude environments can still translate into substantial respiratory risk. Overall, the spatial heterogeneity in bivariate classes indicates that the health impact of $PM_{2.5}$ is not solely driven by emission volume but is modulated by regional geographic, demographic, and health-system characteristics.

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Figure 2. Bivariate choropleth map displaying the joint spatial distribution of age- and sex-adjusted avoidable hospitalization rates for community-acquired pneumonia (PQI 11) and average $PM_{2.5}$ emissions by state in Mexico (2013–2020). States are categorized into combined quantile-based groups of hospitalization burden and emission levels, highlighting macro-regional hotspots where high respiratory risk coincides with elevated industrial emissions, as well as areas with unusual combinations.

The spatial distribution maps (Figure 3) illustrate the geographic variance of adjusted hospitalization rates (PQI 11) and $PM_{2.5}$ emissions across the 32 federal entities of Mexico.

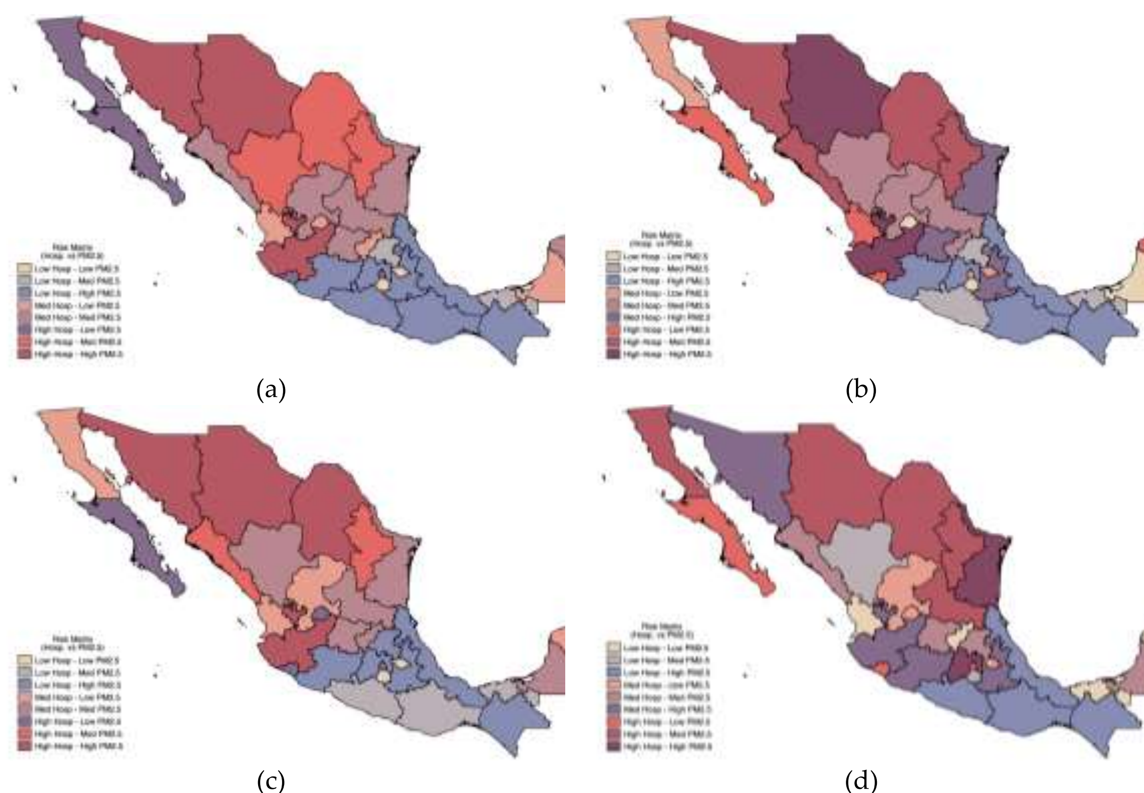

Figure 3. Spatial bivariate distribution of age- and sex-adjusted avoidable hospitalization rates for community-acquired pneumonia (PQI 11) and annual PM2.5 emissions by federal state in Mexico for (a) 2013, (b) 2016, (c) 2018, and (d) 2020. States are classified into nine risk categories based on a three-by-three matrix that combines tertiles of hospitalization burden (low, medium, high) with tertiles of PM2.5 emissions (low, medium, high), allowing identification of “high–high” hotspots, “low–high” and “high–low” atypical combinations, and temporal transitions in the joint health–pollution profile of each state over the study period.

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In 2013, high–high combinations of pneumonia hospitalizations and particulate emissions were already concentrated in the north and central industrial corridor, while much of the south and southeast fell into low-hospitalization classes despite medium or high $PM_{2.5}$ loads. By 2016 and 2018, the overall pattern became more heterogeneous, with several central and southern states shifting into medium-risk categories, indicating a gradual spread of combined environmental and health vulnerability beyond the traditional industrial hubs.

The 2020 map indicates a further escalation of risk across multiple northern and central states, with an expansion of high-hospitalization categories under medium- to high-$PM_{2.5}$ concentrations. This trend aligns with the significant rise in avoidable hospitalizations observed in the time-series analysis. Conversely, several coastal and southeastern states remain within low-hospitalization zones, even when emissions are present at non-negligible levels. This suggests that geographic, climatic, or health system factors may mitigate the translation of emissions into hospital burden in these regions. Collectively, the four snapshots emphasize the dynamic spatial reconfiguration of $PM_{2.5}$-related pneumonia risk at the state level and highlight the importance of longitudinal, geomatics-based approaches for identifying emerging hotspots and regions demonstrating relative resilience.

Including both macro-regional (Figure 2) and state-level (Figure 3) bivariate maps is crucial for capturing the multiscale nature of environmental health risk in Mexico. Macro-regional visualizations highlight broad patterns of vulnerability aligned with atmospheric basins and planning regions, supporting comparisons across large areas and informing basin-scale policy design. However, aggregating to macro-regions can conceal substantial intra-regional heterogeneity, particularly where industrial corridors, metropolitan areas, and rural municipalities coexist within the same basin. State-level bivariate maps, therefore, provide the necessary spatial resolution to detect local hotspots and pockets of resilience that would otherwise remain masked, allowing decision makers to align basin-wide strategies with targeted, sub-regional interventions and to better prioritize resources within each macro-region.

3.3. Regional Dose-Response Sensitivity: Scatter Plot Analysis

The analysis of the linear scale (Figure 4) reveals significant industrial disparities across various regions. The linear regression lines (solid lines) exhibit heterogeneous slopes, highlighting the differing levels of population vulnerability to increases in absolute emissions. While the Frontera region is positioned in the upper-right quadrant, characterized by the highest absolute emissions, the Peninsula and Pacifico Sur clusters are near the origin. Of particular significance, the variation in regional slopes suggests that for each 1,000-ton increase in $PM_{2.5}$, regions such as CDMX_Edomex experience a more substantial rise in respiratory emergencies compared to more dispersed industrial areas.

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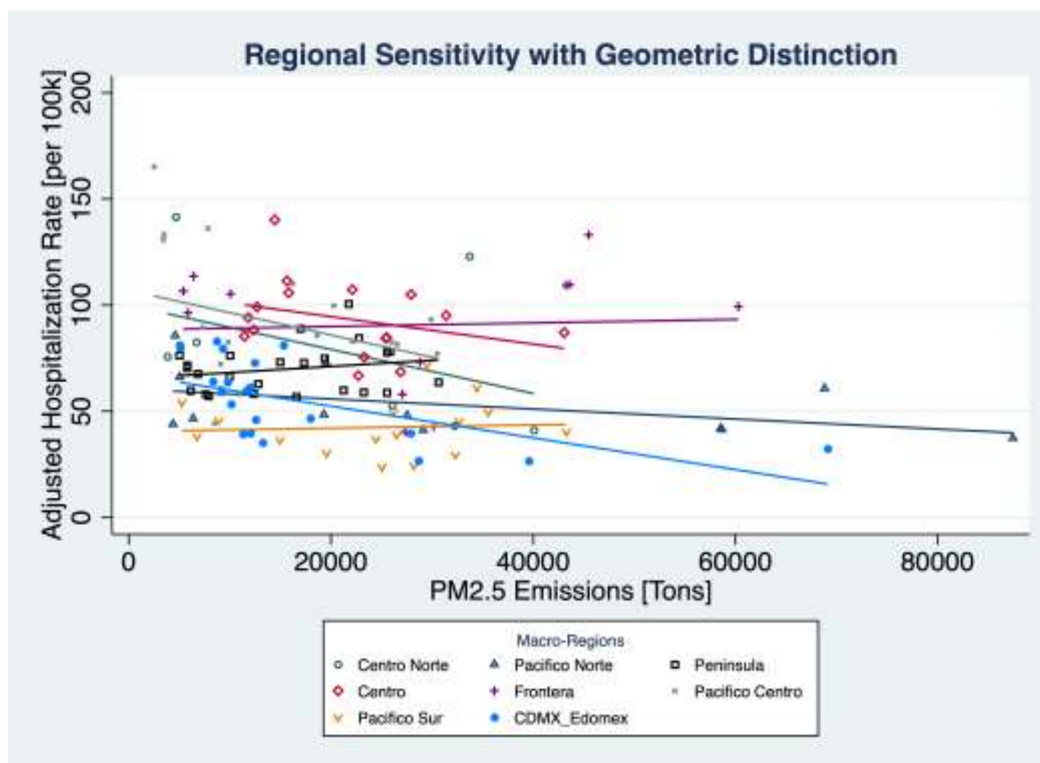

Figure 4. Regional Sensitivity Analysis: Linear Association between $PM_{2.5}$ Emissions and Adjusted Hospitalization Rates. The scatter plot illustrates the direct correlation between annual $PM_{2.5}$ emission volumes and age- and sex-adjusted hospitalization rates for community-acquired pneumonia (PQI 11) across eight Mexican macro-regions (2013–2020).

In this study, the term 'industrial areas' specifically refers to macro-regions characterized by high concentrations of manufacturing corridors, energy production complexes, and extensive logistics infrastructure. Key examples include the northern border states (Frontera) [27] and the metropolitan–industrial basins of Monterrey [28] and the Mexico City Metropolitan Area (CDMX_Edomex) [29]. These territories host dense clusters of maquiladora plants, metal-mechanical and petrochemical industries, and thermoelectric power stations, all of which contribute disproportionately to national $PM_{2.5}$ and related co-pollutant emissions inventories. Conversely, macro-regions such as the Peninsula and sections of Pacifico Sur are primarily distinguished by tourism, services, and agricultural activities, and feature fewer heavy industrial complexes as well as lower absolute industrial emissions, notwithstanding the significance of localized $PM_{2.5}$ loads. This geographic contrast underpins the interpretation that the steeper regression slopes observed in compact, high-altitude basins like CDMX_Edomex indicate increased population exposure per unit of emitted $PM_{2.5}$ compared to more spatially dispersed industrial zones.

3.4. Regional Statistical Associations: Correlation Matrix

The regional correlation matrix (Table 2) demonstrates a heterogeneous pattern of statistical relationships between industrial emissions and preventable hospitalizations for pneumonia. In several macro-regions, higher emissions are modestly linked to lower adjusted PQI 11 rates, as evidenced by negative coefficients for $PM_{2.5}$ and SO_2 in CDMX_Edomex, Centro, Frontera, Pacifico Norte, Pacifico Sur, and Peninsula. This seemingly paradoxical pattern likely reflects the combined influence of temporal trends—characterized by decreasing emissions alongside increasing hospitalization rates—as well as unmeasured confounders such as changes in healthcare access, diagnostic practices, and population vulnerability within these basins.

In contrast, Centro Norte exhibits positive correlations between PQI 11 and all pollutants, particularly *COV* (r = 0.469), suggesting that increases in emissions in this macro-region are more

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directly accompanied by higher avoidable hospitalization rates. Pacifico Centro shows near-zero correlations for $PM_{2.5}$ and SO_2 but negative associations for NO_x and *COV*, indicating a weaker and more complex linkage between industrial activity and respiratory outcomes. The Peninsula stands out with relatively strong negative correlations for both $PM_{2.5}$ ($r = -0.592$) and NO_x ($r = -0.636$), consistent with a context in which declining industrial inventories coexist with persistent or increasing hospital demand driven by non-industrial determinants.

Taken together, these contrasting correlation structures underscore that the relationship between emissions and respiratory hospitalizations is strongly region-dependent and cannot be captured by a single national coefficient. Regions such as Centro Norte behave more like "emission-responsive" systems, whereas compact metropolitan basins (CDMX_Edomex, Centro) and coastal regions (Peninsula, Pacifico Sur) show decoupled or inverse associations. This spatial variability justifies the use of a macro-regional analytical framework and supports subsequent modeling of region-specific dose–response sensitivities rather than assuming a homogeneous effect of $PM_{2.5}$ and co-pollutants across Mexico.

Table 2. Pearson Correlation Coefficients (*r*) between Adjusted Hospitalization Rates (PQI 11) and Air Pollutants by Geographic Region.

Geographic Region	$PM_{2.5}$ (*r*)	SO_2 (*r*)	NO_x (*r*)	*COV* (*r*)
CDMX_Edomex	-0.441	-0.469	-0.064	-0.193
Centro	-0.451	-0.558	-0.345	-0.308
Centro Norte	0.200	0.207	0.151	0.469
Frontera	-0.311	-0.325	0.021	-0.022
Pacifico Centro	0.050	0.044	-0.232	-0.182
Pacifico Norte	-0.310	0.315	-0.076	-0.344
Pacifico Sur	0.065	-0.452	-0.030	-0.126
Peninsula	-0.592	-0.412	-0.636	-0.225

Note: *r* = Pearson correlation coefficient. Significance levels (*p*-values) are calculated based on state-level annual observations within each macro-region (2013–2020).

4. Discussion

Our spatiotemporal analysis indicates that the burden of preventable pneumonia hospitalizations is not evenly distributed; instead, it is concentrated along specific atmospheric basins, notably within the northern industrial corridor and the Mexico City Metropolitan Area. These findings align with prior evidence suggesting that emission sources and exposure patterns in the Valley of Mexico and border cities generate highly localized health effects that are not reflected in national averages. Furthermore, our bivariate maps and temporal trajectories demonstrate that several macro-regions have experienced a decoupling between declining $PM_{2.5}$ emissions and rising PQI 11 rates, emphasizing the necessity of considering health system performance, demographic shifts, and socioeconomic vulnerability alongside air quality indicators.

From a methodological perspective, the application of bivariate choropleth mapping and macro-regional stratification extends previous utilizations of GIS and spatial epidemiology within Mexico by explicitly integrating industrial emissions with ambulatory care–sensitive outcomes. While antecedent studies have depicted mortality rates or general respiratory morbidity in relation to ambient pollution, they have seldom concentrated on avoidable hospitalizations for community-acquired pneumonia or contrasted patterns at basin and state levels. Our findings indicate that macro-region maps are effective in delineating expansive atmospheric risk zones, whereas state-level bivariate maps are essential for identifying intra-regional hotspots and pockets of resilience that might otherwise remain obscured through aggregation. This multiscale methodology is consistent with scholarly calls in the air pollution domain to transcend city-level averages and to assess spatial heterogeneity in dose–response relationships.

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The heterogeneous slopes observed in the macro-regional regression models imply that the health impact of a specific increase in $PM_{2.5}$ is heightened in compact, high-altitude urban basins such as CDMX_Edomex, where emission sources, population density, and atmospheric stability align. Conversely, regions such as the Peninsula and parts of Pacifico Sur, where economic activity predominantly centers on tourism and agriculture, exhibit weaker or inverse statistical relationships between emissions and PQI 11, despite significant $PM_{2.5}$ loads. These differences support the interpretation that regional geography, industrial composition, and ventilation conditions influence the translation of industrial tonnage into population exposure and hospital demand. They also corroborate international evidence indicating that the health effects of $PM_{2.5}$ vary geographically and are influenced by source composition, meteorological conditions, and baseline vulnerability.

Several limitations must be considered when interpreting these findings. Firstly, the analysis depends on annual emissions inventories rather than direct exposure measurements, and thus cannot capture short-term peaks or within-year variability that are significant for acute respiratory events. Secondly, PQI 11 hospitalizations may be affected by changes in clinical practices, coding procedures, healthcare access, and vaccination coverage, which were not explicitly modeled and could partly explain the inverse correlations observed in certain macro-regions. Thirdly, the ecological design and macro-regional aggregation limit inference at the individual level and may be influenced by the modifiable areal unit problem, a well-known challenge in spatial health research. Future research should incorporate higher-resolution land-use regression models, and demographic data to enhance risk assessments within urban corridors and rural–urban gradients.

Despite these limitations, the study offers several implications for environmental and health planning. The identification of high–high clusters and emission-responsive macro-regions provides an evidence base for prioritizing basin-specific mitigation strategies, such as stricter controls on industrial sources and transportation corridors in Frontera and CDMX_Edomex, combined with targeted strengthening of primary care to reduce avoidable hospitalizations. In regions where emissions have decreased but hospitalizations remain high or rising, integrated policies that address social determinants of health, indoor exposures, and health-system capacity will be needed to complement air-quality management. The geomatics framework designed in this work combined standardized PQI indicators, emissions inventories, and multiscale mapping; that can be adapted to other ambulatory care–sensitive conditions and pollutant mixtures, supporting the design of spatially differentiated policies in Mexico and other middle-income countries facing complex patterns of industrialization and urbanization.

5. Conclusions

The study demonstrates that a geomatics-based macro-regional approach is essential to uncover the spatial heterogeneity linking industrial air pollution and avoidable hospitalizations for community-acquired pneumonia (PQI 11) in Mexico. While national $PM_{2.5}$ emissions declined between 2013 and 2020, several macro-regions: CDMX_Edomex, Centro Norte, and Frontera—showed persistent or increasing standardized hospitalization rates and high–high bivariate clusters, indicating that reductions in aggregate emissions have not been sufficient to alleviate respiratory risk in key atmospheric basins. This decoupling between emissions and hospital burden underscores that the health impact of $PM_{2.5}$ is strongly modulated by regional geography, industrial structure, and population vulnerability, rather than by emission tonnage alone.

Our findings also show that the strength and direction of statistical associations between pollutants and PQI 11 differ markedly across macro-regions, with emission-responsive patterns in Centro Norte and weak or inverse correlations in coastal and tourism-oriented regions such as the Peninsula and parts of Pacifico Sur. These results imply that national-level coefficients or uniform regulatory thresholds are likely to misrepresent the realities of local context, and that environmental and health policies must be tailored to basin-specific exposure profiles and health-system conditions. The identification of macro-regional and state-level hotspots provides a decision-support framework to prioritize interventions such as stricter control of industrial and transport emissions in dense

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basins, strengthening primary care to reduce avoidable hospitalizations, and integrated planning that couples air-quality management with social and health-service investments.

Methodologically, the paper contributes a transferable geomatics workflow that integrates standardized PQI indicators, national emissions inventories, bivariate mapping, and macro-regional regression analysis to assess dose–response heterogeneity in space and time. This framework can be extended to other ambulatory care–sensitive conditions, additional pollutants, and finer spatial scales using satellite- or sensor-based exposure models, thereby enhancing the ability of researchers and policymakers to monitor environmental health inequalities in Mexico and other middle-income countries. Future research should incorporate higher-resolution exposure metrics, individual-level covariates, and scenario-based simulations to evaluate how alternative emission control strategies might reshape the geography of preventable respiratory hospitalizations under different climate and urbanization trajectories.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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Abbreviations

The following abbreviations are used in this manuscript:

PQI 11	Prevention Quality Indicator, CommunityAcquired Pneumonia Admission Rate
$PM_{2.5}$	Fine particulate, specifically particles less than 2.5 micrometers in diameter
SO_2	Sulfur Dioxide
NOx	Nitrogen Oxides (Nitric Oxide *NO* and Nitrogen Dioxides NO_2)
COV	Volatile organic compounds (VOC), in English

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