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Air Pollution and Risk of Stroke: A Multi-Year Analysis of $PM_{2.5}$ and Other Pollutants in Tabriz, Iran

Fereshteh Asadi [a], **Fatemeh Masaebi** [b], **Mahdi Maqboli** [c], **Mehdi Farhoudi** [d], **Mohammad Reza Mehrasbi** [a*]

a. Department of Environmental Health, Faculty of Public Health, Zanjan University of Medical Sciences, Zanjan, Iran.
b. Health and Environment Research Center, Zanjan University of Medical Sciences, Zanjan, Iran.
c. Department of Neurology, Medical Faculty, Zanjan University of Medical Sciences, Zanjan, Iran.
d. Neurosciences Research Center, Aging Research Institute, Tabriz University of Medical Sciences, Tabriz, Iran.

***Corresponding author:** Department of Environmental Health, Faculty of Public Health, Zanjan University of Medical Sciences, Zanjan, Iran. Postal Code: 4515786349. E-mail: zmehr@zums.ac.ir

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A B S T R A C T

Background: This study examined the relationship between urban air pollution indices and daily stroke.
Methods: This study was conducted between 2020 and 2023 at Imam Reza Hospital in Tabriz. Data on stroke patients were collected from the Tabriz Stroke Registry, and daily air pollutant data were obtained from the Environmental Protection Agency website. Descriptive statistical analyses, along with Poisson and negative binomial regression models, were used to assess the association between air pollutant exposure and stroke incidence.
Results: $PM_{2.5}$ was identified as the primary pollutant during 89.30% of the study period. The mean daily stroke incidence was 1.35 (SD: 1.17), with the highest incidence observed on days dominated by SO_2 (1.91, SD: 0.83) and the lowest on days dominated by O_3 (1.21, SD: 1.27). SO_2 had the highest mean Air Quality Index (AQI) value (mean: 84, SD: 36), whereas O_3 showed the lowest (mean: 42, SD: 13). $PM_{2.5}$ showed a significant positive association with stroke incidence (IRR: 1.003, 95% CI: 1.001-1.005, $P < 0.001$), corresponding to a 0.3% increase in stroke incidence per unit rise in $PM_{2.5}$-related AQI. No statistically significant associations were observed for the other air pollutants.
Conclusion: Elevated $PM_{2.5}$ levels were associated with increased stroke incidence, while other air pollutants showed no significant correlations. These findings underscore the importance of effective management of particulate matter sources and the strengthening of air quality monitoring systems to mitigate stroke risk.

1. Introduction

Stroke is defined by a sudden disruption in cerebral blood flow, resulting from either an abrupt interruption of blood supply to the brain or the rupture of intracranial blood vessels, which may subsequently lead to neurological deficits (Han et al., 2015). As a leading cause of global mortality and long-term disability (Alavian, 2019; Amini et al., 2020), stroke accounted for 6.79 million deaths globally in 2023 (Global Burden of Cardiovascular Diseases and Risks 2023 Collaborators, 2025). Beyond causing permanent disabilities that severely impact the quality of life for patients and their families, stroke imposes a significant economic burden on both individuals and society (Niknam Azodi et al., 2022; Sun et al., 2019).

The incidence of stroke is multifactorial, involving cardiovascular diseases, advanced age, smoking habits, hypertension, diabetes, and hyperlipidemia. Crucially, some of these risk factors can be mitigated through appropriate medical treatments and lifestyle modifications (Fiouji et al., 2020; Lee et al., 2018; Zhou et al., 2019). Furthermore, air pollution has emerged as a substantial and preventable risk

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factor. Exposure to ambient air pollution affects the general populace and is directly responsible for 14% of stroke-related mortality (Fan et al., 2024; Verhoeven et al., 2021). In major industrial cities, air pollution primarily consists of particulate matter (PM_{10} and $PM_{2.5}$) and toxic gases (O_3, SO_2, CO, NO_2, and NO), which enter the bloodstream and cause vascular inflammation and damage (Lee et al., 2018; Taimuri et al., 2022). Reflecting this impact, the absolute number of global stroke deaths attributable to air pollution increased by 13.4% to reach 1,989,686 cases in 2021 (Fan et al., 2024).

Considering that air pollution is a modifiable risk factor associated with elevated stroke incidence, investigating the precise relationship between ambient air pollutants and stroke occurrence is of paramount importance. Although a substantial body of research, both globally and specifically within Tehran, has confirmed this association (Alimohammadi et al., 2016; Gholizadeh & Darand, 2009; Shah et al., 2015; Taimuri et al., 2022), several other studies have yielded equivocal findings or failed to demonstrate a statistically significant correlation (Ljungman & Mittleman, 2014; Wellenius et al., 2012; Wolf et al., 2021). Notwithstanding the extensive literature, localized studies focusing on the specific composition of pollutants in the megacity of Tabriz are rare. Tabriz's unique setting within a broad valley, coupled with numerous industrial centers and distinctive meteorological phenomena, including seasonal temperature inversions, trans-regional and local particulate matter (PM) events, and prevailing air mass types that exacerbate pollution, has designated it as one of Iran's most heavily polluted cities (Asakereh, 2019).

This study is specifically designed to address this critical gap by quantifying the effects of major air pollutants on stroke incidence, utilizing Poisson regression models to derive region-specific risk estimates that are vital for local health planning. Air quality surveillance is conventionally performed via the air quality index (AQI), which furnishes a simple yet comprehensive assessment of pollution levels by assigning weighted values to diverse pollutants to extract a dimensionless index (Safavy et al., 2016).

The outcomes of this investigation hold significant potential to inform policymakers in formulating targeted interventions aimed at mitigating air pollution, thereby reducing the overall societal burden of stroke. Moreover, enhancing public awareness regarding the deleterious health consequences of air pollution can create the necessary impetus for legislators to enact more stringent regulations and afford this public health challenge the requisite priority. Due to the diverse effects of air pollution on human health, the main goal of the study was to investigate the relationship between urban air pollution indices and daily stroke.

2. Materials and Methods

2.1 Study Area

This study was conducted in the city of Tabriz, one of Iran's major metropolises and an important industrial hub (Safavy et al., 2016), during the period from 2020 to 2023. Tabriz, with an estimated population of approximately 1.5 million inhabitants (Gorbani & Shorkri Firoozjah, 2012) and an area of about 324 square kilometers, has been persistently affected by severe air pollution due to its extensive industrial activities and distinctive topographical conditions (Safavy et al., 2016). These challenges stem from several factors, including low annual precipitation (average: 330.1 mm), limited natural ventilation due to surrounding mountainous terrain, low wind speeds, and frequent temperature inversions characterized by high atmospheric stability. Collectively, these conditions significantly facilitate pollutant trapping and accumulation (Asakereh, 2019; Khorshiddoust et al., 2018). The primary sources of air pollution in the area include motor vehicle emissions, fuel oil combustion at the thermal power plant, recycling facilities, and various large-scale industries located on the city's periphery (Safavy et al., 2016). Furthermore, air quality is significantly exacerbated by both regional and local dust storms (Asakereh, 2019).

2.2 Stroke Data

Daily stroke incidence data were systematically collected from the Tabriz Stroke Registry, encompassing patients admitted to Imam Reza Hospital, primarily within the Stroke Care Unit (SCU), in Tabriz between March 2020 and March 2023. Imam Reza Training Hospital serves as the primary and tertiary referral center in Tabriz for acute stroke cases, and all included cases had confirmed stroke diagnoses.

The SCU provides comprehensive stroke care, which includes standardized monitoring and nursing protocols, intravenous thrombolytic therapy, mechanical thrombectomy, essential medical management, and specialized rehabilitation services.

This centralized care model, managed by the established Tabriz Stroke Registry, ensures the complete and systematic documentation of all medical records, thereby establishing hospitalized stroke patients as an ideal study population for this investigation. Only patients whose residential address at the time of admission was within Tabriz city were included in the study. Consequently, hospitalized stroke patients residing outside Tabriz were excluded to ensure accurate alignment between patient location and air pollutant exposure assessment, which was based exclusively on data from air quality monitoring stations within Tabriz.

2.3 Air Quality Data

Air pollutant measurements were performed by the Provincial Department of Environmental Protection utilizing eight dedicated monitoring stations. These stations assessed the following: (1) Particulate matter (PM_{10} and $PM_{2.5}$); (2) Gaseous pollutants (CO, SO_2, NO_2, and O_3).

Daily AQI values corresponding to the predominant pollutants in Tabriz were retrieved from the official website of the East Azerbaijan Environmental Protection Organization throughout the study period. The utilization of data sourced from an official and authoritative reference was established as the basis for all calculations to preclude potential errors and ensure the highest degree of result validity. We opted to use the AQI as the primary exposure metric because it provides a standardized, real-time measure of the most immediate health risk posed by the dominant pollutant, which aligns with our study's objective of assessing acute stroke risk. Following data compilation and organization, the concentration levels of each air pollutant were temporally correlated with the incidence of stroke cases. Subsequently, patients residing in Tabriz were identified based on their residential addresses, and the resulting dataset was analyzed using Poisson and negative binomial regression models.

This investigation specifically examined the association between ambient air pollutant exposure and stroke incidence among patients admitted to the SCU at Imam Reza Hospital in Tabriz.

2.4 Exposure Assessment

Population exposure was quantified by deriving the daily reference value through the Dominant Pollutant Index (AQI), which inherently reflects the most critical health threat, and subsequently applying a Uniform Spatial Allocation across the study domain. This approach robustly captures the maximum potential daily health risk associated with broad, acute regional air quality episodes.

2.5 Statistical Methods

The study employed a descriptive-longitudinal design. The primary objective of this study was to investigate the association between AQI and stroke incidence count. The analytical process began with descriptive statistics for both stroke incidence and AQI values, stratified by the day's dominant air pollutant. Categorical variables, specifically the number of days each pollutant was dominant, were summarized using frequencies and their corresponding proportions. Continuous variables, namely stroke incidence and AQI values of pollutants, were described using measures of central tendency (mean, median) and dispersion (standard deviation, interquartile range). The distributional characteristics of air pollution data were visualized using Violin plots conditioned on AQI values of pollutants. To assess the association between specific air pollutants and stroke incidence, Poisson and negative binomial regression models were employed, selected based on the distributional properties of the outcome variable. Rate Ratios (RR) with accompanying 95% confidence intervals were derived from the exponentiated regression coefficients. A statistical significance level of 0.05 was established for all tests. All statistical analyses were performed using SPSS software (version 21) and R statistical software (version 4.4.1).

3. Results and Discussion

This study investigated the association between exposure to air pollution and stroke cases, a major global health concern that contributes significantly to mortality and long-term disability. Our analytical approach integrated descriptive statistics to characterize the air pollution variables and stroke counts, subsequently employing generalized linear models, specifically Poisson regression and negative binomial regression, to quantify potential risks.

Among 3,021 patients admitted to the SCU of Imam Reza Hospital in Tabriz, a total of 1,485 medical records of stroke patients residing in Tabriz were included in the analysis during the study period (March 2020 to March 2023). Of these, 55% (n = 811) were male. Regarding age distribution, 55% of patients (n = 823) were older than 65 years, 39% (n = 579) were aged between 41 and 65 years, and 6% (n = 83) were younger than 40 years.

This demographic pattern (particularly the predominance of cases among older adults > 65 years) underscores advanced age as a well-established risk factor for stroke. The nearly equal incidence across sexes suggests that stroke vulnerability is widespread and not strongly sex-dependent, although differences may appear across populations.

Analysis of AQI over 1,096 consecutive days revealed $PM_{2.5}$ as the dominant pollutant on 994 days (89.30% of observation days), while SO_2 (1 %, n = 11) and CO (1.40%, n = 16) showed the lowest frequency as primary pollutants. Other pollutants, including PM_{10} (2.70%, n = 30), O_3 (3%, n = 33), and NO_2 (2.60%, n = 29), demonstrated relatively minor contributions to air pollution (Table 1). The pronounced prevalence of $PM_{2.5}$ (89.30%) represents a crucial environmental finding, emphasizing the necessity for region-specific air quality management strategies heavily focused on fine particulate matter control. Additionally, episodes marked by extreme PM_{10} concentrations (corresponding to AQI values ranging from 187-420, primarily observed in June 2021), were clearly associated with documented regional dust storm events originating from arid areas neighboring Tabriz and atmospheric instability. This clearly illustrates the significant influence of local geography and prevailing wind patterns on short-term air quality deterioration, where regional dust transport becomes the dominant factor in summer.

Descriptive statistics for daily stroke counts and AQI values stratified by the dominant pollutant type revealed an overall mean (SD) stroke count of 1.35 (1.17). The highest average stroke incidence (mean: 1.91, SD: 0.83) occurred during SO_2-dominant days, whereas the lowest value (1.21, SD: 1.27) was recorded during O_3-dominant periods. Corresponding mean AQI values (SD) were 85 (36) for SO_2 and 70 (27) for $PM_{2.5}$, while CO-dominant (41, SD: 13) and O_3-(42, SD: 13) days showed the least variability. NO_2-dominant days exhibited AQI values of 46 (14), and PM_{10}-dominant days averaged 76 (71). Figure 1 presents a violin plot that visually illustrates the distribution of AQI values for each pollutant responsible for air pollution during the study period, thereby corroborating the findings presented in Table 1. As is evident, the pollutants $PM_{2.5}$ and PM_{10} exhibit more pronounced fluctuations in their AQI values compared to the other contaminants. This observation strongly suggests the occurrence of sudden escalations in the concentration of these particulate matters on specific days within the study timeframe. Conversely, the more compressed distribution observed for NO_2, O_3, and CO indicates a relative stability and a more constrained range of variation in the AQI for these specific pollutants throughout the measurement duration. About SO_2, both abrupt increases on certain days and notable decreases in AQI values on other days are discernible. This direct source-receptor relationship is further evidenced by the exceptionally high SO_2-related AQI values (>150) recorded in January 2022, which directly coincided with the increased use of fuel-oil combustion at the Tabriz Thermal Power Plant during peak winter demand. $PM_{2.5}$-dominant days consistently showed AQI > 100 during December-February of each year. This severe seasonal pattern is a direct consequence of the local meteorological conditions in Tabriz, specifically the frequent temperature inversions common in the valley where the city is situated, which trap pollutants. Furthermore, the increased use of fossil fuels (such as heating oil) for industrial heating during the cold months significantly contributes to this combustion-related particulate matter.

As detailed in the Poisson regression models (Table 2), $PM_{2.5}$ exhibited a statistically significant positive association with stroke incidence. Specifically, for every one-unit increase in the $PM_{2.5}$-related AQI, the incidence rate ratio (IRR or Exp(β)) was 1.003 (95% CI: 1.001-1.005), indicating an approximate 0.3% increase in stroke incidence ($P < 0.001$). This finding represents a key outcome of our study. Furthermore, this observed significant positive link (IRR = 1.003, $P < 0.001$) corroborates prior evidence of $PM_{2.5}$ cerebrovascular toxicity, as demonstrated in Boston cross-sectional studies (Wellenius et al., 2012) and Chinese cohort data (Huang et al., 2019). Mechanistically, the combustion-derived nanoparticles composing $PM_{2.5}$ (originating from fossil fuels and industrial emissions) are known to achieve enhanced pulmonary deposition and systemic translocation, thereby triggering neuroinflammatory cascades that accelerate cerebral vasculopathy and neuronal dysfunction. (Kulick et al., 2023; Verhoeven et al., 2021).

Conversely, SO_2 (IRR: 1.001, 95% CI: 0.989-1.014, P: 0.821) and PM_{10} (IRR: 0.992, 95% CI: 0.984-1.003, P: 0.204) showed no statistically significant associations with stroke incidence in the primary Poisson models. Similarly, models incorporating O_3 (IRR: 1.013, 95% CI: 0.976-1.050, P: 0.502), NO_2 (IRR: 1.011, 95% CI: 0.976-1.047, P: 0.538), and CO (IRR: 1.008, 95% CI: 0.957-1.062, P: 0.756)-estimated using Negative Binomial Regression due to observed overdispersion (mean variance > 1)-also yielded non-significant results (all $P > 0.05$). The robustness of our statistical framework was confirmed by Durbin-Watson statistics, which supported the independence assumption required for the Poisson model application. Ultimately, this analysis emphasizes that while multiple pollutants affect air quality, only $PM_{2.5}$ demonstrated a direct and statistically significant impact on stroke incidence within our study population.

Several potential factors appear to be implicated in rendering these findings "non-significant," potentially distinguishing them from the much stronger association observed with $PM_{2.5}$ and offering plausible mechanisms for this observed lack of acute impact. Initially, the observed statistical insignificance for pollutants such as O_3, NO_2, and CO may be attributed to their limited presence and low concentrations throughout the study period. Descriptive statistics suggest that these pollutants consistently maintained an AQI below 50, collectively contributing only a negligible fraction of the polluted days. This implies that their ambient concentrations rarely exceeded the physiological sensitivity thresholds required to induce an acute stroke response in the general population. Conversely, $PM_{2.5}$, even with a mean AQI of 70, remained consistently within an influential range, accounting for 89.30% of the polluted days. Similarly, a cross-sectional study conducted in Boston reported a positive association between increased $PM_{2.5}$ levels and the risk of stroke; however, no significant correlations were found between O_3, SO_2, and CO concentrations and the likelihood of stroke occurrence (Huang et al., 2019; Wellenius et al., 2012).

Furthermore, the pronounced dominance of $PM_{2.5}$, accounting for 89.30% of polluted days during the study period, likely introduced collinearity into the multivariate regression models. The robust effect of $PM_{2.5}$-known for its deep penetration into the lungs and systemic inflammatory mechanisms (Lee et al., 2018)-may have overshadowed the acute effects of other pollutants, particularly those sharing common combustion sources; this environmental prevalence can potentially obscure the less frequent or weaker effects of other contaminants. Despite its lack of overall statistical association in the primary models, SO_2 registered the highest mean AQI (85) and was linked to the highest mean stroke incidence on the rare days (1% of polluted days) when it was the sole dominant pollutant. This indicates that although SO_2 pollution events were infrequent, they were accompanied by high intensity, suggesting a potent acute toxicity potential during peak exposures. However, the rarity of these severe events (low statistical power), coupled with the pervasive background noise from $PM_{2.5}$, likely attenuated its statistical significance in models focused on overall mean effects; the distinct toxicological pathway of SO_2 also complicates its detection in models designed for chronic exposure assessments.

The lack of a significant association for PM_{10} (contributing to a small 3% of polluted days, with a mean AQI of 76) is likely linked to its primary origin and particle characteristics. Given that severe PM_{10} events in Tabriz were predominantly associated with natural phenomena like regional dust storms, these larger particles possess a lower capacity for penetrating the pulmonary barrier and exerting a direct influence on stroke pathophysiology compared to the fine nanoparticles of $PM_{2.5}$. This aligns with literature reporting PM_{10} health effects to be more related to respiratory irritation than direct systemic cardiovascular impact. Consistent with findings from a study in China, only exposure to $PM_{2.5}$ was significantly associated with post-stroke mortality risk, whereas PM_{10} exhibited no statistically significant relationship (Chen et al., 2019).

Table 1. Descriptive statistics of air pollutants, stroke incidence, and AQI values

Pollutant	Days as Dominant Pollutant (n)	Percentage of Polluted Days (%)	Stroke Incidence				AQI Values			
			Mean	SD	Median	IQR	Mean	SD	Median	IQR
SO_2	11	1.00	1.91	0.83	2.00	1.00	85	36	80	34
$PM_{2.5}$	994	89.30	1.36	1.17	1.00	2.00	70	27	63	29
PM_{10}	30	2.70	1.22	0.99	1.00	1.00	76	71	59	28
O_3	33	3.00	1.21	1.27	1.00	3.00	42	13	39	25
NO_2	29	2.60	1.28	1.36	1.00	2.00	46	14	43	19
CO	16	1.40	1.38	1.36	1.50	2.00	41	13	40	13

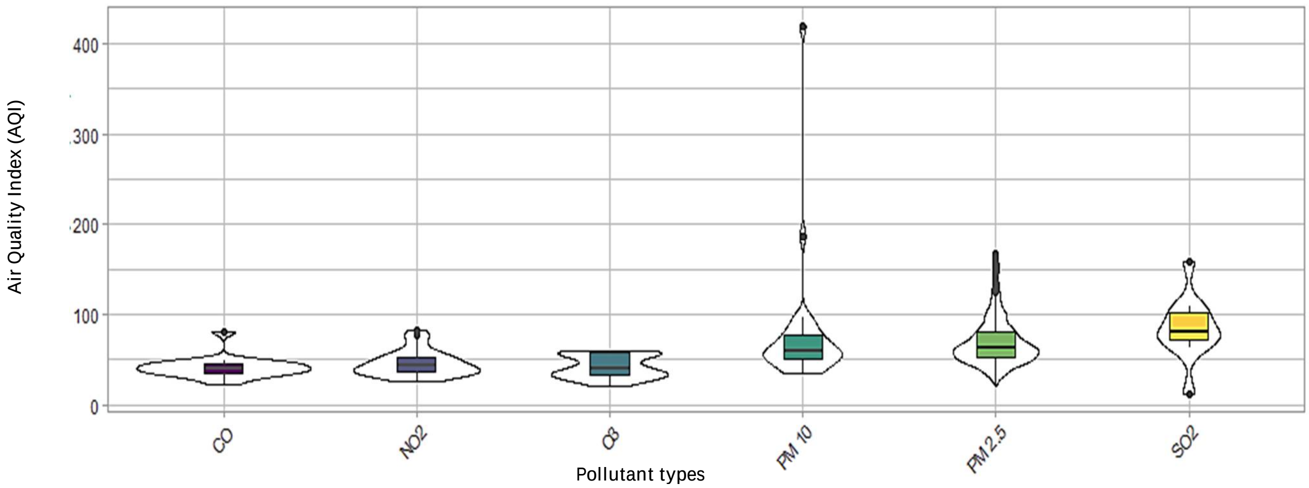

Figure 1. Violin plot diagram

In contrast to our findings, another study conducted in Iran investigated the impact of various pollutants (gaseous and particulate matter) on the risk of emergency department admission for stroke across different time frames (short-term and long-term). This research demonstrated that all examined pollutants (including CO, O_3, NO_2, SO_2, PM_{10}, and $PM_{2.5}$) were significantly associated with emergency stroke admission; however, this association varied for each pollutant depending on the temporal scale (short-term versus long-term) (Taimuri et al., 2022). Furthermore, other studies have indicated that pollutants beyond $PM_{2.5}$ also exert an effect on stroke (Wolf et al., 2021). Conversely, separate studies in the United States and Canada failed to find a strong association between pollutants and cerebral strokes (Sun et al., 2019; Villeneuve et al., 2006). This disparity in findings compared to other studies is likely attributable to differences across several aspects, including variations in the study population, sample size, study design, and methodology. Consequently, while multiple pollutants contribute to air quality degradation, our analysis demonstrates that the discernible acute impact on stroke incidence is predominantly and significantly attributable to $PM_{2.5}$, with specific statistical and environmental factors influencing the observed lack of statistical significance for other pollutants. The South Asian context remains particularly vulnerable, with approximately 85% of global stroke cases occurring in low-and middle-income countries undergoing rapid industrialization and ecological degradation (Taimuri et al., 2022). In Iran, energy-intensive development patterns have further aggravated particulate matter (PM) and NO_x/SO_x emissions, thereby reinforcing the regional relevance of our findings.

Table 2. Results of Poisson and Negative Binomial Regression Models Assessing the Association Between AQI and Stroke Incidence Across Dominant Air Pollutants

Pollutant	Parameter	β	SE	RR	*P-value*	CI (95%)
			Poisson Regression			
SO_2	Constant value	0.524	0.589	-	0.373	
	AQI	0.001	0.006	1.001	0.821	0.989-1.014
$PM_{2.5}$	Constant value	0.082	0.075	-	0.273	
	AQI	0.003	0.001	1.003	<0.001	1.001-1.005
PM_{10}	Constant value	0.702	0.356	-	0.048	
	AQI	-0.007	0.005	0.992	0.204	0.984-1.003
			Negative Binomial Regression			
O_3	Constant value	-0.384	0.834	-	0.678	
	AQI	0.013	0.019	1.013	0.502	0.976-1.050
NO_2	Constant value	-0.269	0.865	-	0.756	
	AQI	0.011	0.017	1.011	0.538	0.976-1.047
CO	Constant value	-0.025	1.153	-	0.982	
	AQI	0.008	0.026	1.008	0.756	0.957-1.062

Note: Rate Ratio (RR) is expressed as Exp(β); CI indicates 95% Confidence Interval

Consistent with the World Health Organization's recognition of $PM_{2.5}$ as a modifiable risk factor for stroke, our results advocate for multifaceted intervention strategies, including: (1) Industrial controls: Adoption of high-efficiency scrubber technology at power plants and major industrial emitters. (2) Urban planning: Expansion of green belts, enhanced traffic zoning, and congestion mitigation in metropolitan areas. (3) Public health: Implementation of biomarker-guided exposure monitoring to identify and protect at-risk populations. (4) Policy reforms: Enforcement of stricter emission standards harmonized with EU/EPA benchmarks.

Proactive measures of this nature could yield substantial cerebrovascular health benefits, as evidenced by stroke incidence declines observed during COVID-19 lockdown periods (Wu et al., 2022). Future research should integrate geospatial exposure modeling with clinical biomarker profiling to refine risk stratification frameworks, particularly for susceptible demographic subgroups. Such evidence-driven approaches can strengthen regional air-quality policies, ultimately reduce the stroke burden while preserving the health advantages of outdoor activity.

3.1 Study Limitations and Recommendations

This study was conducted exclusively at a single comprehensive stroke center in Tabriz, which limits the generalizability of our findings and underscores the need for larger, nationwide studies. The use of patients' residential addresses as proxies for pollution exposure may not fully reflect individual exposure patterns in daily life. Moreover, the use of a uniform citywide exposure estimate derived from the maximum AQI value among monitoring stations may introduce exposure misclassification, as it does not capture intra-urban variability in pollutant concentrations. Reliance solely on the AQI as the primary exposure metric has limited the potential to model a continuous relationship between exposure and stroke incidence due to its discrete and threshold-based nature. This approach contrasts with the use of raw pollutant concentrations, which offer a more continuous representation of the biological dose. Consequently, while AQI is a useful tool for public communication, its application instead of ambient concentration data restricts the precision of quantifying the true impact of pollutants on stroke risk.

Another limitation is the lack of adjustment for meteorological variables-such as temperature and relative humidity-that can independently influence both air pollutant concentrations and stroke incidence. Similarly, potential temporal confounders, including seasonal variations and long-term trends in stroke occurrence unrelated to pollution, were not explicitly controlled for.

The statistical power for some pollutants was limited due to incomplete data. In particular, the regression analysis for sulfur dioxide (SO_2) relied on only 11 observation days, which substantially reduces the reliability of its estimated effects. Furthermore, the analysis focused solely on same-day (lag 0) exposure; while appropriate for capturing immediate impacts, potential delayed effects over multiple days were not explored.

Future studies should incorporate longer monitoring periods, employ more advanced exposure assessment methods, and account for relevant environmental and temporal factors. Ensuring the continuous and accurate recording of pollutant concentrations-by promptly addressing technical issues at monitoring stations-is essential for reliable environmental epidemiological research. Nevertheless, supplementary data from auxiliary citywide stations were successfully utilized to identify key pollutants and impute missing values, which strengthened the overall robustness of this study's findings.

4. Conclusion

Collectively, our findings establish a statistically significant positive association between elevated $PM_{2.5}$ (IRR: 1.003, 95% CI: 1.001-1.005, $P < 0.001$) concentrations and increased stroke incidence; specifically, each unit increment in the $PM_{2.5}$-related AQI corresponded to a measurable elevation in stroke rates. Crucially, no meaningful correlations were identified for other tested gaseous pollutants or PM_{10}. These outcomes strongly underscore the imperative for targeted particulate matter control strategies, which must be multifaceted and coordinated, encompassing: (1) stringent urban traffic management, particularly within core districts; (2) rigorous industrial emission controls across manufacturing zones; (3) the strategic expansion of urban green spaces and forested parks; and (4) the establishment of peripheral green belts to disrupt particulate dispersion pathways (Gholampour et al., 2016; Gorbani & Shorkri Firoozjah, 2012). Ultimately, achieving substantial and sustainable cerebrovascular risk reduction mandates coherent policy reform integrated across local, national, and supranational governance tiers.

Authors' Contributions

Fereshteh Asadi: Conceptualization; Data Curation; Investigation; Methodology; Writing-Original Draft Preparation; Writing-Review & Editing. **Fatemeh Masaebi:** Formal Analysis; Methodology; Visualization; review; and editing of the manuscript. **Mahdi Maqboli:** Validation; review; and editing of the manuscript. **Mehdi Farhoudi:** PI in Tabriz Stroke Registry; supervises stroke data; reviews; and editing of the manuscript. **Mohammad Reza Mehrasbi:** Conceptualization; Project Administration; Supervision; review; and editing of the manuscript. All authors reviewed and approved the final manuscript.

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Conflicts of Interest

The authors declare that they have no competing interests.

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Ethical Considerations

The confidentiality of the data used in this study was strictly maintained. This study was approved by the Ethics Committee of Zanjan University of Medical Science (Approval Code: IR.ZUMS.REC.1402.147).

Using Artificial Intelligence

Artificial intelligence was not used in this research.

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