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Association of ambient particulate matter pollution and stroke in Indonesia 2011-2020: Insights from the global burden of disease study 2021

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ABSTRACT

Background: Ambient particulate matter ≤2.5 µm (PM2.5) is a major environmental health risk contributing to global morbidity and mortality. Although its link with cardiovascular diseases is well established, evidence on the stroke burden attributable to PM2.5 exposure remains limited in Indonesia. **Methods**: This ecological study used Global Burden of Disease (GBD) 2021 data to analyze the association between PM2.5 exposure and stroke burden, including incidence, prevalence, and mortality, across 34 Indonesian provinces from 2011 to 2020. Age-standardized rates (ASRs) were assessed using a linear mixed model, with year as a repeated measure and province as a random effect to account for spatial and temporal variations. **Findings:** Mean PM2.5 concentrations ranged from 16.96 to 20.10 µg/m^3, exceeding WHO and national air quality standards. Despite minor annual fluctuations in PM2.5, stroke mortality attributable to air pollution showed an increasing trend. Higher PM2.5 levels were significantly associated with ischemic stroke (IS) incidence (β = -0.117, p <0.001) and mortality (β = 0.152, p <0.001), as well as intracerebral hemorrhage (ICH) incidence (β = 0.017, p = 0.015), prevalence (β = 1.641, p <0.001), and mortality (β = 0.773, p = 0.004). The effect of PM2.5 exposure was greater for ICH than for IS. **Conclusion**: Long-term exposure to PM2.5 is significantly associated with stroke burden in Indonesia, particularly for ICH. Strengthening air quality management and stroke prevention policies is crucial, especially in high-risk regions. **Novelty/Originality of this article:** This study is the first to comprehensively assess the long-term association between PM2.5 and stroke subtypes using national-level GBD data across all Indonesian provinces, providing spatially and temporally robust evidence for public health policy in low- and middle-income tropical settings.

KEYWORDS: air pollution; global burden of disease; intracerebral hemorrhage; ischemic stroke; stroke.

1. Introduction

As one of the significant environmental contributors to global mortality, ambient particulate matter pollution was responsible for an estimated 7.83 million deaths in 2021 (Fang et al., 2025). Globally, the epidemiological transition from communicable to noncommunicable diseases has placed air pollution among the top two modifiable risks for premature death (Health Effects Institute, 2024). This form of pollution is characterized by the presence of fine particles with an aerodynamic diameter below 2.5 micrometres per cubic metre of air, commonly referred to as particulate matter 2.5 (PM2.5) (Institute for Health Metrics and Evaluation (IHME), 2021). The global population-weighted estimate of

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PM2.5 concentration averaged 32.8 μg/m^3 from 2000 to 2019 (Yu et al., 2023), exceeding the World Health Organization's (WHO) 2021 annual air quality guideline by more than sixfold (World Health Organization, 2021). In 2019 globally, more than 70% of days still had PM2.5 concentrations higher than the WHO limit (Yu et al., 2023).

In the Indonesian context, Government Regulation Number 22 of 2021 on the Implementation of Environmental Protection and Management sets PM2.5 thresholds at 55 μg/m^3 for the 24-hour average and 15 μg/m^3 for the annual average, representing a policy advance toward closer alignment with international standards. Previously, Government Regulation Number 41 of 1999 on the Air Pollution Control established higher limits of 65 μg/m^3 for the 24-hour average and 15 μg/m^3 for the annual average. By comparison, the World Health Organization (WHO) guideline in 2005 recommended PM2.5 limits of 25 μg/m^3 for the 24-hour average and 10 μg/m^3 for the annual average. The WHO later revised these guidelines, lowering the thresholds to 15 μg/m^3 for the 24-hour average and 5 μg/m^3 for the annual average (World Health Organization, 2021). Despite these regulatory improvements, PM2.5 exposure remains a major public health concern due to its well-established effects on health.

Persistent exposure to PM2.5 elevated concentrations poses significant risks to human health, as fine particulate matter can penetrate deep into the body. Not only can it enter the respiratory system, but it can also enter the systemic system. Systemic inflammation caused by PM2.5 can lead to thrombosis or endothelial damage, resulting in cardiovascular diseases such as stroke (Krittanawong et al., 2023; Kulick et al., 2023; Schraufnagel et al., 2019). Stroke includes two major types: ischemic and hemorrhagic. Ischemic stroke (IS) occurs when a blood vessel becomes blocked, whereas hemorrhagic stroke results from the rupture of a blood vessel. Hemorrhagic strokes are further divided into intracerebral hemorrhage (ICH) and subarachnoid hemorrhage (SAH) (Sacco et al., 2013). Globally, stroke ranks as the third leading cause of death (Feigin et al., 2024). Each year, around 7 million people die from stroke, and 33% of these deaths occur in people under 70 years of age (Feigin et al., 2025). Given these biological mechanisms linking PM2.5 exposure to vascular injury and thrombosis, epidemiological studies have increasingly explored its population-level impacts on stroke incidence and mortality.

In relation to PM2.5, the State of Global Air Report 2024 reported that 27% of IS deaths are attributed to air pollution (Health Effects Institute, 2024). A study in China found that the overall stroke burden increased along with rising PM2.5 concentration (Su et al., 2025). Moreover, research has indicated that prolonged exposure (≥ 1 year) to PM2.5 poses a greater risk of cardiovascular-related mortality compared to short-term exposure (a few days) (Alexeeff et al., 2021). In Indonesia, Siregar et al. (2024) reported that long-term exposure to PM2.5 in Sumatra was linked to a higher risk of cardiovascular mortality with every 10 μg/m^3 rise in PM2.5 concentration. However, despite being a recognized risk factor, the burden of stroke attributable to ambient particulate matter pollution has not been adequately examined in Indonesia. The Global Burden of Disease (GBD) study provides standardized estimates of mortality, incidence, and prevalence, allowing consistent comparisons across regions and over time by integrating multiple data sources and applying comparable methodologies. This approach is particularly important in Indonesia, where substantial provincial differences may contribute to regional disparities in PM2.5 exposure and stroke burden. Understanding this relationship is essential for shaping effective air quality management and strategies to mitigate stroke risks associated with PM2.5 exposure and its adverse health impacts. Therefore, this study aims to analyze the association between ambient PM2.5 pollution and stroke burden in Indonesia by assessing its impacts on stroke mortality, incidence, and prevalence from 2011 to 2020.

2. Methods

2.1 Data source and quality control

All data in this study were retrieved from the GBD 2021 (https://www.healthdata.org/research-analysis/gbd-data). This study provides estimates on 88 risk factors and 288 causes of death from 204 countries from 1990 to 2021. Data from 56,604 sources around the world were obtained, including vital registrations, surveys, censuses, surveillance systems, and cancer registries. To ensure comparability across locations and time periods, the Institute for Health Metrics and Evaluation (IHME) applies standardized procedures, including data harmonization, correction for missing or inconsistent records, and redistribution of ill-defined causes of death through statistical modeling approaches. The GBD also quantifies uncertainty using 500 posterior draws and reports 95% uncertainty intervals (UIs) based on the 2.5th and 97.5th percentiles of the simulated distributions. These approaches provide spatially and temporally comparable estimates, enabling robust assessment of regional and longitudinal variations in PM2.5-attributable stroke burden across Indonesia's 34 provinces from 2011 to 2020 (Brauer et al., 2024).

Ambient particulate matter pollution is classified as a level 4 risk factor, while stroke is categorized as a level 3 cause of death. Stroke is further divided into IS, ICH, and SAH, which are classified as level 4 causes of death (Brauer et al., 2024; Naghavi et al., 2024). In the present analysis, only IS and ICH were included. These stroke subtypes were selected because they represent the majority of stroke cases in Indonesia. SAH was excluded due to its relatively low incidence and limited evidence of association with environmental factors.

In this study, we included the mean age-standardized death rates, incidence rates, and prevalence rates per 100,000 population, along with their 95% uncertainty intervals (UIs). These data were used to estimate the stroke burden attributable to PM2.5 exposure in Indonesia and its 34 provinces from 2011 to 2020. The burden of stroke associated with PM2.5 was quantified using these ASRs, with estimates for all metrics calculated as the mean values across 500 draws. The 95% UIs were defined by the 2.5th and 97.5th percentiles of the resulting distribution. The study population comprised individuals from the age of 25, grouped into 20 five-year age categories. The cleaned dataset, including Indonesia's mean PM2.5 levels, stroke burden, and stroke deaths attributable to PM2.5 across all provinces, is available at: https://bit.ly/PM25StrokeIndonesiaGBD2021.

2.2 Statistical analysis

Data distributions were examined for outliers and temporal consistency. Normality tests were conducted using the Kolmogorov-Smirnov or the Shapiro-Wilk test. Descriptive statistics were computed to describe the stroke burden and mean PM2.5 from 2011 to 2020. To investigate the association between PM2.5 and stroke mortality, incidence, and prevalence, the linear mixed model was used. The linear mixed model was chosen because it accommodates hierarchical data structures and repeated measures over time, which are inherent in multi-provincial ecological data. In this model, year was treated as a repeated measure, provinces were defined as subjects, and the mean PM2.5 concentration was included as a fixed effect. To account for the spatial variation across provinces, the model included province as a random effect. This approach allows the model to capture unobserved regional differences and control for spatially correlated variations in stroke burden. This modeling approach was chosen to account for repeated observations over time within each province and to capture variability both within and between provinces. Statistical Package for the Social Sciences (SPSS) version 25 was used to carry on with the analysis.

3. Results and Discussion

3.1 PM2.5 concentration in Indonesia

Figure 1 shows the annual average of PM2.5 concentration in Indonesia from 2011 to 2020. During the study period, the average PM2.5 levels ranged from 16.96 µg/m^3 in 2017 to 20.10 µg/m^3 in 2013, with only minor fluctuations observed. Importantly, these values consistently exceeded Indonesia's air quality standard (15.5 µg/m^3) and the WHO's (5 µg/m^3) (Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2025; World Health Organization, 2021). These persistent values reflect a wider global pattern, where it is estimated that 99% of the world's population lives in areas where air pollution levels surpass the WHO-recommended limits (World Health Organization, 2025). For comparison, in four-season countries like China and South Korea, despite a >20% decline in PM2.5 concentrations between 2016 and 2020, levels remain considerably higher than the WHO standard and Indonesia's average concentrations. In China, the annual mean PM2.5 levels declined from 48.80 µg/m^3 in 2016 to 37.22 µg/m^3 in 2020. Similarly, South Korea's mean concentrations in the winter dropped from 29.45 µg/m^3 in 2016 to 23.72 µg/m^3 in 2020 (Cha et al., 2023). The persistence of high PM2.5 levels, both domestically and internationally, underscores the urgency of addressing air quality as a public health priority.

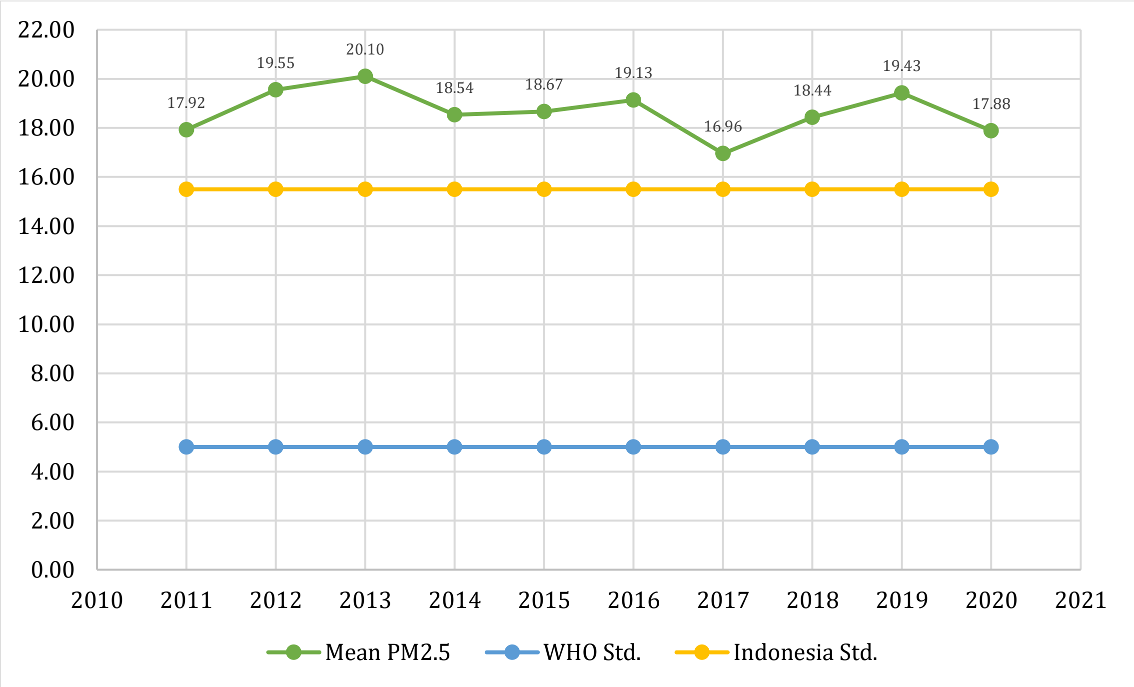

Fig. 1. Trends in mean annual PM2.5 concentration in Indonesia from 2011 to 2020 in comparison with the WHO guideline (5 µg/m^3) and Indonesia's national air quality standard (15.5 µg/m^3) (Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2025; Institute for Health Metrics and Evaluation (IHME), 2025; World Health Organization, 2021)

Within Indonesia, provincial data mirror these national challenges. Over the 10 years, 58.9% of recorded PM2.5 concentrations in all provinces were above Indonesia's air quality threshold. The lowest recorded concentration was observed in Riau in 2017 (8.357 µg/m^3), while the highest was in Jakarta in 2016 (31.282 µg/m^3). Although certain provinces have experienced temporary improvements in air quality, the overall trend remains concerning. In a recent study, Rahmatikal Wasi'ah et al. (2025) conducted a study using secondary data from the United States' embassy in six urban cities across Southeast Asian countries (Indonesia, Myanmar, Laos, and Vietnam). The annual concentration in these cities also surpassed the WHO's and their respective air quality standard, highlighting a broader regional challenge.

Provinces such as Jakarta, Banten, and West Java recorded the highest concentrations over the decade, with averages of 27.85 μg/m^3, 23.97 μg/m^3, and 22.34 μg/m^3, respectively. These provinces are located on the island of Java, where more than half of Indonesia's population resides. With an area accounting for only 7% total landmass but home to approximately 151.59 million people, Java Island faces severe air quality stress (BPS-Statistics Indonesia, 2021; Lukman et al., 2025). Jakarta's role as the nation's economic center drives daily mass commuting, mostly from Banten and West Java, with approximately 72% relying on private vehicles and only a minority opting for public transportation (BPS-Statistics Indonesia, 2019). The predominant use of private motorized transport, driven by perceptions that public transit is inefficient, directly contributes to increased vehicular emissions, a significant source of PM2.5 in densely populated areas. As a result, daily commuting activities not only exacerbate traffic congestion but also intensify exposure to air pollution for both commuters and urban residents, further elevating the health risks associated with chronic PM2.5 inhalation.

A notable exception to this decade-long trend occurred during the COVID-19 pandemic in 2020, when national PM2.5 concentrations decreased sharply. Nationally, the mean PM2.5 dropped by approximately 1.55 μg/m^3 compared to 2019. Even in Jakarta, the province with the highest PM2.5 levels over the decade, a four μg/m^3 decrease was observed in 2020. This air quality improvement can be attributed to the rise in COVID-19 cases towards the end of 2019, which prompted national lockdowns, reduced industrial and traffic activities (Lukman et al., 2025). Despite the observed decreases in most provinces, Southeast Sulawesi, Maluku, West Papua, and Papua exhibited slight increases in PM2.5 concentrations, although these changes were relatively minor. In line with these results, Kazakos et al. (2021) reported a 15.7% ± 4.1% reduction in PM2.5 average population-weighted mean exposure in the United Kingdom during the COVID-19 lockdown. However, this reduction could not be directly linked to a reduction in urban traffic. The effect of air quality improvement during the pandemic was short-lived. This suggests that sustained, policy-driven interventions targeting industrial emissions, energy production, and land use activities are essential to achieving long-term reductions in PM2.5 exposure.

3.2 Stroke burden attributable to PM2.5 in Indonesia

Table 1 summarizes the age-standardized stroke mortality rates attributable to PM2.5 across Indonesian provinces from 2011 to 2020. Nationally, the mean mortality rate attributable to PM2.5 exposure was 13.28 per 100,000 population during the study period, with relatively stable annual values ranging from 12.76 per 100,000 in 2011 to 13.00 per 100,000 in 2020. Considerable geographical variation was observed across provinces. The highest mean mortality rates were recorded in South Kalimantan (19.77 per 100,000), Bangka Belitung Islands (19.49 per 100,000), Banten (18.83 per 100,000), East Kalimantan (17.47 per 100,000), and Papua (17.36 per 100,000). In contrast, North Maluku exhibited the lowest mean mortality rate (4.49 per 100,000), followed by East Nusa Tenggara (5.30 per 100,000), North Kalimantan (7.12 per 100,000), Gorontalo (7.66 per 100,000), and Maluku (7.92 per 100,000). These findings suggest substantial interprovincial variation in the burden of stroke attributable to PM2.5 exposure in Indonesia.

The national trends of age-standardized incidence, prevalence, and mortality of IS and ICH in Indonesia from 2011 to 2020 are presented in Figure 2. As shown in Figure 2(a), the mean IS incidence increased gradually from 139.14 to 142.32 per 100,000 in 2019, and then decreased to 141.61 per 100,000 in 2020. Meanwhile, the mean number of new ICH cases showed a lower rate than IS and a consistent downward trend, decreasing from 98.23 per 100,000 in 2011. From 2015 to 2019, the results showed a stable range of ±92 new cases per 100,000, before declining further to below 90 cases per 100,000 in 2020. Regarding prevalence, they followed a pattern similar to that of incidence for both IS and ICH. The mean prevalence of IS saw a +4.11 increase from 2011 to 2020.

Table 1. Summary of stroke deaths attributable to PM2.5 by province cluster from 2011 to 2020 (age-standardized rate, per 100,000)

Provinces	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Mean
Aceh	16.02	16.24	16.32	16.40	17.13	17.28	17.64	17.87	17.86	17.33	17.01
Bali	12.17	12.08	11.99	11.96	12.03	12.33	12.70	13.10	13.20	12.68	12.42
Bangka-Belitung Islands	18.51	19.23	20.16	20.86	20.94	20.37	19.96	19.35	18.77	16.72	19.49
Banten	17.69	17.78	17.94	18.20	18.74	19.12	19.82	20.41	20.46	18.14	18.83
Bengkulu	8.94	9.67	10.55	11.44	11.91	12.41	12.90	13.30	13.33	12.90	11.73
Central Java	10.68	10.77	10.84	11.02	11.15	11.43	11.95	12.34	12.45	11.51	11.41
Central Kalimantan	7.87	8.83	9.94	10.81	11.18	11.05	10.90	10.73	10.52	9.88	10.17
Central Sulawesi	9.20	9.47	9.94	10.42	10.71	11.11	11.62	12.03	12.13	11.86	10.85
East Java	13.36	13.26	13.07	12.96	12.89	12.95	13.09	13.20	13.17	12.42	13.04
East Kalimantan	17.93	18.30	18.73	18.90	18.81	18.20	17.60	16.56	15.54	14.18	17.47
East Nusa Tenggara	4.31	4.50	4.60	4.79	5.05	5.28	5.75	6.19	6.35	6.21	5.30
Gorontalo	6.38	6.63	6.89	7.17	7.45	7.77	8.14	8.53	8.77	8.84	7.66
Jakarta	19.75	18.69	17.62	16.84	16.72	16.39	16.34	16.29	16.11	13.87	16.86
Jakarta	19.75	18.69	17.62	16.84	16.72	16.39	16.34	16.29	16.11	13.87	16.86
Jambi	11.55	12.48	13.70	14.76	15.25	15.73	16.02	16.19	16.20	14.81	14.67
Lampung	8.24	8.62	9.45	10.32	11.14	11.61	12.23	12.72	12.91	12.87	11.01
Maluku	6.80	6.96	7.14	7.36	7.65	7.88	8.28	8.69	9.05	9.38	7.92
North Kalimantan	7.51	7.55	7.49	7.42	7.34	7.15	6.98	6.78	6.56	6.42	7.12
North Maluku	4.11	4.15	4.21	4.33	4.33	4.44	4.59	4.76	4.90	5.06	4.49
North Sulawesi	12.95	13.02	13.19	13.41	13.40	13.54	13.79	13.99	14.05	13.87	13.52
North Sumatra	18.75	18.82	19.33	19.85	20.10	20.26	20.44	20.50	20.33	19.27	19.77
Papua	18.59	18.20	17.85	17.47	17.51	17.21	16.85	16.50	16.28	17.14	17.36
Riau	8.83	9.06	9.33	9.51	9.55	9.51	9.32	9.13	8.95	8.02	9.12
Riau Islands	15.19	15.06	15.01	14.98	14.84	14.79	14.80	14.93	14.85	11.88	14.63
South Kalimantan	11.68	12.66	13.89	14.92	15.37	15.39	15.55	15.49	15.28	14.12	14.43
South Sulawesi	9.29	9.65	9.98	10.44	10.86	11.27	11.84	12.34	12.51	12.47	11.07
South Sumatra	12.46	13.41	14.38	15.24	15.71	15.58	15.57	15.46	15.31	14.34	14.75
Southeast Sulawesi	10.88	11.12	11.36	11.73	12.17	12.70	13.51	14.28	14.70	14.88	12.73
West Java	15.41	15.15	14.87	14.67	14.69	14.78	15.19	15.45	15.49	13.68	14.94
West Kalimantan	9.31	10.01	10.97	11.87	12.44	12.88	13.19	13.46	13.44	12.15	11.97
West Nusa Tenggara	9.69	10.05	10.37	10.76	11.19	11.79	12.71	13.49	13.74	13.44	11.72
West Papua	14.83	14.90	14.83	14.75	14.61	14.19	13.87	13.61	13.43	13.39	14.24
West Sulawesi	7.16	7.50	7.95	8.54	8.97	9.58	10.46	11.17	11.44	11.24	9.40
West Sumatra	8.82	9.45	10.29	10.91	11.14	11.18	11.16	11.06	10.96	10.29	10.53
Yogyakarta	9.42	9.49	9.53	9.59	9.69	9.95	10.45	10.58	10.56	10.00	9.93
Indonesia	12.76	12.83	12.91	13.05	13.22	13.39	13.73	13.96	13.98	13.00	13.28

(Institute for Health Metrics and Evaluation (IHME), 2025)

In contrast, ICH's mean prevalence decreased substantially from 361.82 to 325.20 cases per 100,000 (Figure 2(b)). The IS mortality rate throughout the decade is relatively stagnant, with only a minor decrease of 1.78 cases from 2011 to 2020, as shown in Figure 2(c). Likewise, ICH mortality declined from 129.79 deaths per 100,000 in 2011 to 114.09 deaths per 100,000 in 2020. Throughout the decade, East Kalimantan consistently ranked highest in the burden of IS. The province recorded the highest incidence of IS in 2019, with 182.77 cases per 100,000 population. Additionally, East Kalimantan had the highest prevalence of IS in 2011, at 1587.11 per 100,000, and the highest mortality rate, at 137.75 per 100,000, in the same year. In contrast, Papua had the highest ICH incidence in 2011, reaching 129.78 cases per 100,000. East Kalimantan also recorded the highest prevalence of ICH in 2011, with 510.69 cases per 100,000, while Maluku experienced the highest ICH mortality that year, at 201.45 deaths per 100,000. On the other hand, North Kalimantan consistently showed the lowest rates for several indicators. It had the lowest IS incidence rate of 97.14 per 100,000 in 2015 and mortality rate of 70.63 deaths per 100,000 in 2020. Regarding ICH, it recorded the lowest incidence rate of 51.06 per 100,000 in 2016, along with the lowest prevalence and mortality rates of 231.34 and 71.96 per 100,000, respectively, in 2020. Central Kalimantan and Bali reported the lowest IS prevalence in 2011, at 825.38 and 825.56 cases per 100,000, respectively.

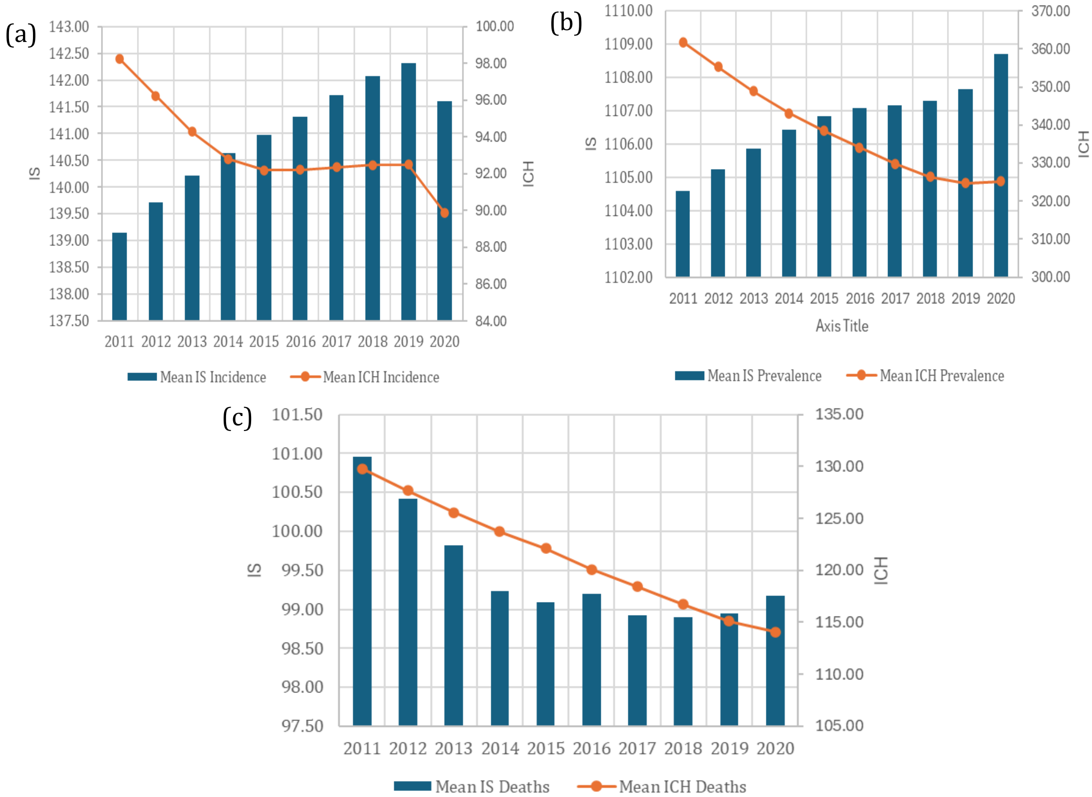

Fig. 2. Trends in mean annual stroke burden in Indonesia from 2011 to 2020 (age-standardized rate, per 100,000): (a) mean ischemic stroke and intracereblal hemorrhage incidence; (b) mean ischemic stroke and intracereblal hemorrhage prevalence; (c) mean ischemic stroke and intracereblal hemorrhage deaths
(Institute for Health Metrics and Evaluation (IHME), 2025)

Globally, there are approximately 12 million new cases of stroke each year. Approximately 94 million people in the world are currently living with the long-term consequences of stroke. Compared with the global estimates, Indonesia's incidence and mortality rates for both IS and ICH are considerably higher than international averages. The global age-standardized incidence rate for IS is approximately 92 per 100,000 population, whereas ICH has a lower incidence rate (41 per 100,000). In terms of prevalence, IS affects an estimated 819 individuals per 100,000, while ICH affects about 195 per 100,000. The global mortality rates are 44 per 100,000 for IS and 39 per 100,000 for ICH (Feigin et al., 2024, 2025). The persistence of high stroke burden in Indonesia, particularly in the eastern region, highlights critical regional disparities. A study conducted in remote areas of Indonesia found a lack of facilities in primary healthcare centers. Although hypertension, one of the major stroke risk factors, is closely monitored in these settings, problems such as limited accessibility to healthcare services, short operating hours, and a shortage of health workers contribute significantly to the ongoing burden (Soewondo et al., 2019).

Given the persistently high burden of stroke across Indonesia, it becomes crucial to examine the role of environmental risk factors, especially PM2.5, which has been increasingly recognized as a significant contributor to stroke mortality. Figure 3 presents the age-adjusted mortality rate attributable to PM2.5 pollution for IS and ICH in Indonesia from 2011 to 2020. The IS mortality rate attributable to PM2.5 exposure ranged from 10.33 to 12.30 per 100,000, while the ICH rate was slightly higher, ranging from 12.76 to 13.98 per 100,000. In line with this result, a recent study in China revealed that stroke burden from air pollution was higher in individuals with ICH than in those with IS (Su et al., 2025).

Generally, both IS and ICH rates remained consistently elevated across the decade, with ICH showing slightly higher rates than IS in all observed years.

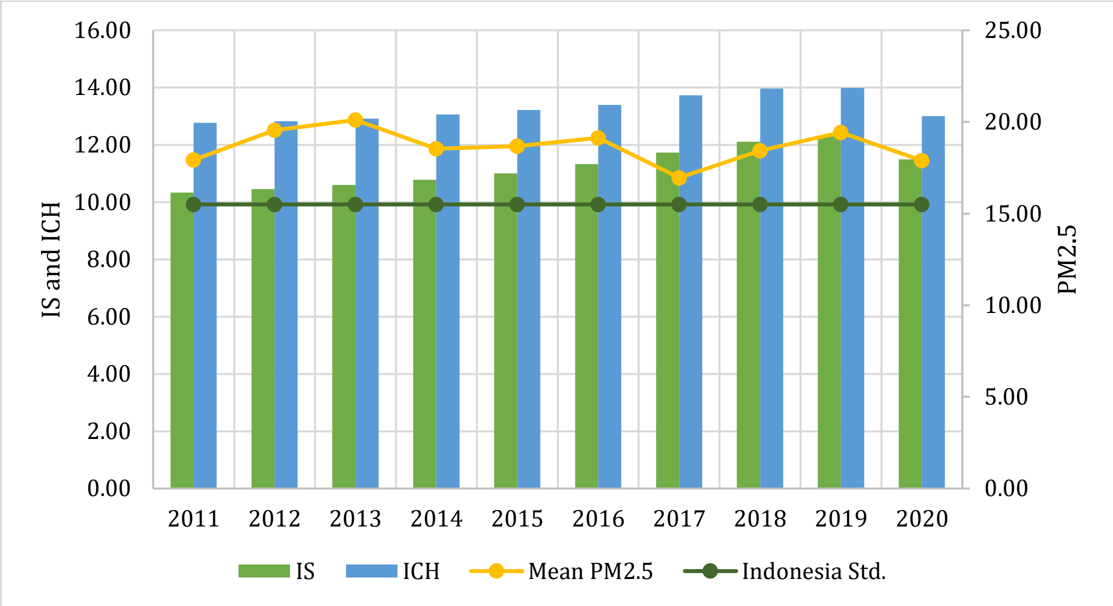

Fig. 3. IS and ICH deaths attributable to ambient particulate matter pollution (age-standardized rate, per 100,000), in comparison with the mean PM2.5 concentrations in Indonesia from 2011 to 2020
(Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2025; Institute for Health Metrics and Evaluation (IHME), 2025)

Provincially, South Kalimantan recorded the highest IS mortality rates attributable to PM2.5 in 2014, 2015, and 2016, with rates of 17.87, 16.60, and 16.35 per 100,000, respectively. Conversely, East Nusa Tenggara had the lowest IS deaths from PM2.5 exposure in 2011 and 2012, with 1.68 and 1.91 deaths per 100,000. For ICH, South Kalimantan also showed the highest mortality rates related to PM2.5 in 2014, 2015, and 2016, at 30.17, 28.27, and 27.83 per 100,000, whereas East Nusa Tenggara had the lowest ICH deaths from ambient particulate matter, with 3.16 per 100,000. Overlaying these data with the mean annual PM2.5 levels, although PM2.5 concentrations fluctuated across the years, the number of deaths attributable to PM2.5 exposure continued to rise steadily. The highest attributable mortality for both IS and ICH was observed toward the end of the study period (2018-2019).

In 2019, the global ambient particulate matter pollution-related stroke mortality exhibited an increasing trend from 1990 (Bo et al., 2023). The similar rates were also observed in China, where Su et al. (2025) reported an increase in the age-adjusted ICH and IS death rate attributable to PM2.5 from 1990 to 2016, followed by a gradual decline up to 2021. In Portugal between 2011 and 2021, an estimated 28,537 stroke deaths were associated with PM2.5 exposure, with the number of years of life lost (YLL) due to stroke and PM2.5 increased with age (Corda et al., 2024). These international findings highlight that the health impact of PM2.5 exposure on stroke mortality is not only persistent over time but may also vary by demographic characteristics, including age. Older populations tend to accumulate greater exposure to ambient particulate matter due to prolonged residence in polluted environments and higher baseline vulnerability to cardiovascular and cerebrovascular stressors. Consistent with these observations, our analysis further explored age-specific mortality patterns to better understand how PM2.5-related stroke deaths are distributed across different age groups in Indonesia.

From our data, stroke deaths attributable to ambient particulate matter indicate a clear age-related increase in mortality rates (Figure 4). In both years, younger age groups (25-34 years) have lower mortality rates, ranging from 0.12 to 0.23 per 100,000 for IS and from

0.70 to 1.58 per 100,000 for ICH. Mortality rates begin to rise significantly from the 40-44 year age group onward. For IS, the number of deaths in 2011 and 2020 approximately doubled from the previous age bracket, reflecting a consistent and significant upward trend. The increase is even more pronounced for ICH, where the 50-54 year group showed mortality rates caused by PM2.5 of 19.46 per 100,000 in 2011 and 21.16 per 100,000 in 2020, figures nearly 30 times higher than those in the 25–29 year group. This finding is in line with Chen et al.'s study (2022), where IS and ICH also demonstrated increasing mortality trends attributable to PM2.5 (2.5% and 0.5%, respectively), particularly in the 55–60 age group, suggesting that older adults are more vulnerable to the adverse effects of ambient particulate pollution. Aside from older age, the significant increase in mortality rates associated with PM2.5 levels was demonstrated in the low, low-middle, and middle sociodemographic index (SDI) regions, and for ICH (Bo et al., 2023). Understanding these patterns is essential, particularly as dynamic shifts in air quality are driven by public health interventions and social changes, as observed during the COVID-19 pandemic.

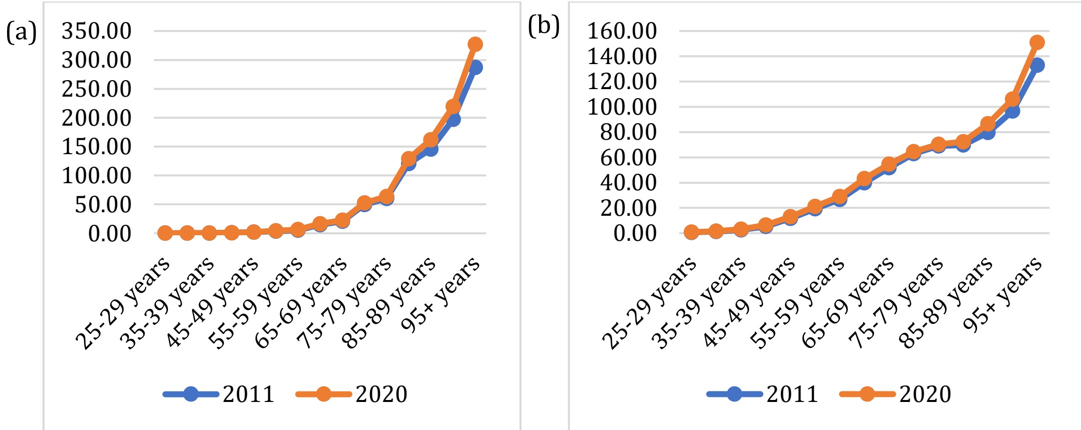

Fig. 4. Comparison of IS and ICH deaths attributable to ambient particulate matter pollution (age-standardized rate, per 100,000) in Indonesia in 2011 and 2020, grouped by age: (a) Ischemic Stroke Deaths Attributable to PM2.5; (b) Ischemic Hemorrhage Deaths Attributable to PM2.5 (Institute for Health Metrics and Evaluation (IHME), 2025)

Notably, during the COVID-19 pandemic, there was not only a decrease in mean PM2.5 concentrations but also a decline in age-standardized deaths from IS and ICH attributable to ambient particulate matter pollution. Hameed et al. (2021) found a positive correlation between reduced air pollution and stroke admissions in Pakistan, suggesting that improved air quality may have contributed to a real reduction in stroke incidence. Corda et al. (2024) also proposed that COVID-19 might have a positive effect on reducing the stroke mortality burden attributed to PM2.5 exposure, due to mobility restrictions. The decrease in stroke-related mortality during the COVID-19 pandemic might also be partly attributed to underreporting of stroke cases. Many patients were reluctant to visit hospitals due to fear of infection, leading to reduced hospital admissions (Chang et al., 2025; Sari et al., 2022). For example, the number of stroke patients who were admitted to the Dr. Soetomo Hospital Surabaya dropped by 52.4% in 2020 (Sari et al., 2022). This decline in admissions may have contributed to an apparent reduction in stroke incidence and mortality, rather than a true decrease in disease occurrence.

3.3 Association between stroke burden and PM2.5 concentration in Indonesia

The correlation between IS and ICH burden (incidence, prevalence, and mortality) and mean PM2.5 in Indonesia from 2011 to 2020 is shown in Table 2. Using a linear mixed model, mean PM2.5 levels showed significant relationships with IS incidence ($\beta = -0.117$, $p < 0.001$) and IS mortality ($\beta = 0.152$, $p < 0.001$), but not with prevalence ($p = 0.241$). The negative coefficient for incidence indicates that, as PM2.5 concentrations increased, the incidence of IS declined slightly. In contrast, the positive association with mortality suggests that higher PM2.5 exposure may contribute to an increased risk of fatal outcomes in IS patients. These results suggest more complex dynamics in PM2.5 exposure affecting IS risk and fatality.

For ICH, mean PM2.5 concentrations were significantly associated with incidence (β = 0.017, p = 0.015), prevalence (β = 1.641, p <0.001), and deaths (β = 0.773, p = 0.004). These positive associations indicate that higher PM2.5 levels are consistently linked with increased ICH occurrence and mortality. The strength of the coefficients, particularly for prevalence and deaths, suggests that particulate matter pollution plays a substantial role in worsening hemorrhagic stroke outcomes. Compared to IS, ICH demonstrates a more consistent and pronounced relationship with PM2.5 exposure.

The observed association between stroke and PM2.5 concentration aligns with growing evidence linking air pollution to cerebrovascular diseases. In 2021, stroke ranked as the highest age-standardized death rate attributable to PM2.5 pollution (34.1 per 100,000), followed by ischaemic heart disease (32.3 per 100,000), chronic obstructive pulmonary disease (COPD) (22.1 per 100,000), tracheal, bronchus, and lung cancer (8.5 per 100,000), and lower respiratory infections (3.1 per 100,000) (T. Yu et al., 2025). Interestingly, despite PM2.5 exposure being primarily associated with respiratory diseases, its impact on respiratory mortality has become less pronounced compared to its growing influence on stroke-related deaths (Fang et al., 2025). This represents a notable epidemiological shift, as COPD was the leading cause of PM2.5 attributable deaths in 1990, whereas stroke has now become the foremost contributor (Yu et al., 2025).

In the Reasons for Geographic And Racial Differences in Stroke (REGARDS) cohort study, they did not find a correlation between short-term PM2.5 exposure and stroke incidence at the individual level. Nevertheless, a correlation was found when examined using a large, geographically and racially diverse population, incorporating a novel PM2.5 exposure metric while adjusting for environmental factors such as temperature and humidity (McClure et al., 2017). Similarly, our analysis, which is based on GBD 2021 data, utilized a larger and more geographically diverse population across Indonesia, encompassing both urban and rural settings over 10 years.

Table 2. Association of stroke burden with mean PM2.5 concentrations in Indonesia from 2011 to 2020 using linear mixed model analysis.

Dependent Variable	Estimate (β)	Standard Error	Test (df)	*p*
IS Incidence				
Intercept	140.028	376.720	0.372 (1.201)	0.710
Incidence	-0.117	0.024	-4.900 (33.075)	<0.001*
IS Prevalence				
Intercept	1100.784	21885.606	0.050 (6179.457)	0.960
Prevalence	0.155	0.132	1.180 (101.662)	0.241
IS Deaths				
Intercept	98.877	2.248	43.970 (39.682)	<0.001*
Deaths	0.152	0.037	4.017 (116.664)	<0.001*
ICH Incidence				
Intercept	95.905	2.449	39.156 (<0.001)	1.000
Incidence	0.017	0.006	3.040 (8.355)	0.015*
ICH Prevalence				
Intercept	321.994	3480.888	0.093 (<0.001)	1.000
Prevalence	1.641	0.218	7.516 (63.595)	<0.001*
ICH Deaths				
Intercept	119.708	4.717	25.377 (<0.001)	0.996
Deaths	0.773	0.112	6.890 (3.496)	0.004*

Note: fixed effect: mean PM2.5; random effect: provinces; subject: provinces; repeated measure: year; *: significant.

This broader scope may have allowed for a more comprehensive assessment of long-term PM2.5 exposure effects on stroke burden, capturing spatial and temporal variations that smaller cohort studies might overlook. In line with our result, a meta-analysis comprised of 16 cohort studies with more than 2.2 million people reported that long-term exposure to PM2.5 can increase the incidence and mortality of stroke, with a pooled hazard ratio (HR) of 1.11 (95% CI: 1.05-1.17) for every five $\mu g/m^3$ increment (Yuan et al., 2019). Our study revealed that the effect of PM2.5 on stroke was greater in ICH. Similarly, an ecological study reported that for every 10 μg/m3 increase in PM2.5 concentration, mortality from IS increased by 0.27% (95% CI: 0.12-0.43%), while mortality from ICH increased by 0.37% (95% CI: 0.04-0.42%). However, this association was observed only with short-term PM2.5 exposure, whereas in long-term exposure, the relationship was significant only for IS mortality attributed to PM2.5 levels (Zhang et al., 2018).

Another study also contrasted our results, where they found that short-term air pollution was more closely linked to IS than ICH (Liao et al., 2025). One meta-analysis study found that long-term PM2.5 exposure may have a stronger association with risk of incident IS (HR = 1.18; 95% CI: 1.14-1.22) than ICH (HR = 1.10; 95% CI: 1.05–1.16) (Alexeeff et al., 2021). This differs from our findings, which showed a stronger relationship for ICH. The discrepancy may be attributed to differences in study populations and environmental settings, since previous research was conducted on different demographic and ecological profiles. Regionally, Asian regions (East, South, and Southeast Asia) have reported the highest death counts of ICH attributable to PM2.5 exposure, further supporting the regional vulnerability observed in our findings (Wu et al., 2025).

The detrimental effects of PM2.5 on human health are primarily mediated through mechanisms such as increased oxidative stress, immune system inflammatory responses, and stimulation of the autonomic nervous system (Krittanawong et al., 2023). These processes collectively contribute to endothelial dysfunction, systemic inflammation, and atherosclerosis (Sangkham et al., 2024). It has been established that atherosclerosis is the major vascular risk factor of stroke, particularly IS, by promoting plaque formation and subsequent vessel occlusion (Tsivgoulis et al., 2018). Prolonged exposure to elevated PM2.5 levels can further aggravate atherosclerotic progression by directly damaging the vascular endothelium, promoting lipoprotein cholesterol uptake in vascular cells, and disrupting coagulation pathways, thereby accelerating thrombus formation and vascular narrowing (Niu et al., 2025). The clot formed in the vessel can also trigger an inflammatory response, induced by biological changes in cells caused by PM2.5 exposure. This clot can raise the risk of cardiovascular disease, such as IS, ICH, heart attack, and heart failure (Sangkham et al., 2024).

Importantly, PM2.5 affects IS and ICH through distinct pathophysiological mechanisms (Wu et al., 2025). A study indicates that PM2.5 disrupts endothelial cell integrity, leading to increased permeability of the blood–brain barrier and triggering prolonged inflammatory responses, thereby heightening the risk of blood vessel rupture in the brain and contributing to ICH (Liu et al., 2017). In contrast, PM2.5 primarily influences IS through processes such as PM2.5-induced atherogenesis and thrombogenesis. These processes involve systemic inflammation leading to endothelial injury and arterial plaque formation and occlusion, which can occlude cerebral vessels and cause ischemic strokes (Wu et al., 2025). The complex interactions between PM2.5 and other temporal risk factors, such as temperature and co-pollutants, may differentially affect IS and ICH, necessitating further investigation into subtype-specific exposure-response relationships and vulnerable populations.

Furthermore, the negative association observed between PM2.5 and IS incidence warrants further exploration. This unexpected trend may reflect regional confounding factors such as disparities in healthcare access, underreporting of stroke cases, or the influence of prevention programs, such as increased antihypertensive medication use, that might offset incidence despite persistent exposure. Alternatively, this pattern may partly result from data smoothing within the GBD modeling framework, particularly in regions with limited stroke surveillance infrastructure. Overall, these findings emphasize the importance of refining epidemiological approaches to better capture subtype-specific risks and contextual determinants of stroke associated with particulate pollution.

Beyond direct vascular effects, several indirect pathways may mediate the link between PM2.5 and stroke, with hypertension being one of the most important. Hypertension is a well-established risk factor for both IS and ICH (Hägg-Holmberg et al., 2019; Li et al., 2022). Lv et al. (2023) reported that long-term exposure to PM2.5 is associated with hypertension prevalence. In their study, male sex and older people were more susceptible to the damaging effects of PM2.5. In Indonesia, one cross-sectional study identified a correlation between PM2.5 and higher blood pressure levels. In the overall population, a significant correlation was found between monthly PM2.5 concentration and diastolic blood pressure ($\beta = 0.234$, 95% CI: 0.003-0.464), with stronger effects observed among individuals aged 65 years and older (Madrigano et al., 2024). Given Indonesia's aging population and the high prevalence of uncontrolled hypertension (30.8%) (Badan Kebijakan Pembangunan Kesehatan, 2023), chronic exposure to ambient particulate pollution may amplify the national burden of stroke through indirect pathways mediated by elevated blood pressure.

In response to provincial disparities observed in our analysis, several high-pollution provinces showed notably higher stroke incidence and mortality, and this pattern can be explained by region-specific emission sources and the resulting PM2.5 composition. Several provinces in the island of Kalimantan recorded the highest PM2.5-attributable stroke mortality, for all types of stroke and each individual type. These provinces coincide with intensive industrial activities and recurrent forest and peatland fires. One of the most severe fire episodes occurred in 2015, when approximately 2.6 million hectares of land were affected by wildfires. The event resulted in substantial health impacts, including respiratory-related illnesses affecting hundreds of thousands of individuals and multiple reported fatalities (Nur'Aini & Ananta, 2025). Not only that, large-scale coal mining and coal-fired power plants emit PM2.5 enriched with black carbon and trace metals such as iron, zinc, and lead (Kartikasari et al., 2019; Ogwu et al., 2025). Emerging evidence suggests that the health effects of PM2.5 vary according to its chemical composition, with different components exhibiting unequal neurotoxic properties. In mining-intensive areas, exposure to heavy metal-containing particulate matter may be particularly relevant because these metals can persist in the environment and accumulate in biological systems. Previous studies have demonstrated associations between heavy metal exposure and cerebrovascular diseases, suggesting that inhaled metals may enter the body through respiratory pathways and subsequently contribute to vascular injury. Mechanistically, heavy metals disrupt cellular redox homeostasis through multiple interconnected pathways, inducing oxidative stress, systemic inflammation, endothelial dysfunction, and neurotoxicity. These biological responses may promote vascular fragility and increase susceptibility to cerebrovascular events, potentially contributing to the elevated burden of hemorrhagic and ischemic stroke observed in high-pollution provinces (Jamebozorgi et al., 2025; Liu & Wu, 2025; Lu et al., 2023).

The distinction in particulate composition between industrial-dominated and fire-dominated regions helps explain why stroke burden is not uniformly distributed across Indonesia. While Jakarta and West Java have high PM2.5 levels due to vehicular and industrial emissions, the chemical profile of their PM2.5 differs from that of peat smoke. Urban PM2.5 tends to have higher proportions of nitrate, sulfate, and combustion-derived ultrafine particles, which are more strongly linked to ischemic mechanisms such as atherogenesis and thrombosis (Azizah et al., 2024). In contrast, peat smoke particles are often larger and carry higher organic carbon loads, which may preferentially affect blood pressure regulation and increase hemorrhagic risk, even though only in the rat model (Martin et al., 2020). This source-specific pathophysiology is consistent with our finding that PM2.5 shows a stronger and more consistent positive association with ICH incidence, prevalence, and mortality compared to IS.

These findings have important implications for public health policy. Reducing stroke burden in provinces like Kalimantan requires source-specific interventions. For industrial provinces, stricter emission controls for coal-fired plants, improved dust suppression in mining areas, and a transition to cleaner energy sources would directly reduce metal-rich

PM2.5. For fire-prone provinces, strengthening peatland restoration, enforcing fire bans, and improving early warning systems for smoke episodes could mitigate episodic exposure spikes. Additionally, targeted hypertension screening and management in high-pollution provinces may reduce the population's vulnerability to PM2.5-related stroke.

This study has several strengths. First, it utilizes data from the GBD 2021, which provides a comprehensive and standardized dataset across all Indonesian provinces over a 10-year period (2011–2020). This allowed for a longitudinal and geographically diverse analysis of the relationship between PM2.5 exposure and stroke burden. The use of a linear mixed model also enabled consideration of spatial and temporal variations across different years within the same province, thereby improving the robustness of the statistical inference. Additionally, this is one of the few studies to assess the provincial-level association between PM2.5 and stroke subtypes in Indonesia, offering valuable insights for targeted public health strategies in low- and middle-income tropical settings. The inclusion of both ischemic and hemorrhagic stroke subtypes further strengthens the analytical depth of this study, allowing for a more nuanced understanding of how particulate pollution may differentially affect cerebrovascular outcomes.

Despite these strengths, several limitations should be acknowledged. First, as an ecological study, the analysis was based on aggregated secondary data, which may introduce ecological fallacy and limit causal inference at the individual level. Second, the GBD estimates are derived from modeled data that integrate multiple sources, which may introduce measurement uncertainty, particularly in regions with limited air monitoring infrastructure. The absence of direct ground-based air quality measurements in several provinces may also affect the accuracy of PM2.5 exposure estimates, particularly in remote or rural areas. Third, potential confounding variables, such as socioeconomic status, healthcare access, smoking, and comorbidities, were not directly controlled for, which may have influenced the observed associations. These unmeasured variables could also partly explain interprovincial variations in stroke burden that are not fully captured by PM2.5 levels alone. Moreover, PM2.5 was treated as an annual mean exposure, failing to account for seasonal variations or short-term exposure peaks that could have acute health impacts. Given Indonesia's tropical climate, seasonal forest fires, land-use changes, and meteorological conditions (e.g., humidity and temperature) may significantly influence temporal fluctuations in PM2.5 levels and their health effects.

Future research should focus on longitudinal cohort or case-crossover studies using individual-level exposure data. Incorporating meteorological parameters, lifestyle factors, and comorbid conditions will enhance understanding of causal mechanisms linking PM2.5 exposure to stroke subtypes. Furthermore, integrating air quality data with clinical registries, hospital admissions, and national health survey datasets would allow for more precise quantification of the exposure-response relationship. Ultimately, multi-level analyses that link environmental, behavioral, and healthcare system factors could provide a more holistic understanding of how PM2.5 pollution translates into cerebrovascular health outcomes in Indonesia and similar settings.

4. Conclusions

This study provides robust national-level evidence linking long-term ambient PM2.5 exposure with stroke burden, particularly IS (incidence and death) and ICH (incidence, prevalence, and death), with a more pronounced effect observed in ICH than in IS. Despite fluctuations in mean PM2.5 concentrations throughout the decade, stroke mortality attributable to air pollution continued to rise, indicating the long-term health consequences of chronic exposure. The findings highlight the urgent need for integrated air quality management, strengthened stroke prevention programs, and health system preparedness. Reducing PM2.5 exposure through sustainable energy, transport, and land-use policies could substantially lower Indonesia's growing burden of stroke and improve population health outcomes.

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Author Contribution
Conceptualization, S.D.R.; Methodology, S.D.R.; Software, S.D.R.; Validation, S.D.R.; Formal Analysis, S.D.R; Investigation, S.D.R.; Resources, S.D.R.; Data Curation, S.D.R.; Writing Original Draft Preparation, S.D.R.; Writing, Review & Editing, S.D.R.; Visualization, S.D.R.; Supervision, S.D.R.

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Conflicts of Interest
The author declares no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the author used Grammarly to improve the grammar, clarity, and academic tone of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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