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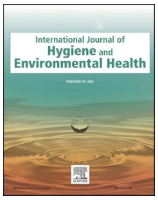

Effect of neighbourhood greenness on the association between air pollution and risk of stroke first onset: A case-crossover study in shandong province, China

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ABSTRACT

Background: Higher neighbourhood greenness is associated with beneficial health outcomes, and short-term exposure to air pollution is associated with an elevated risk of stroke onset. However, little is known about their interactions.

Methods: Daily data on stroke first onset were collected from 20 counties in Shangdong Province, China, from 2013 to 2019. The enhanced vegetation index (EVI) and concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and sulfur dioxide (SO_2) were calculated for each individual at the village or community level based on their home address to measure their neighbourhood exposure to greenness and air pollution. EVI was categorised as low or high, and a time-stratified case-crossover design was used to estimate the percent excess risk (ER%) of stroke associated with short-term exposure to air pollution. We further stratified greenness on the basis of EVI values into quartiles and introduced interaction terms between air pollutant concentrations and the median EVI values of the quartiles to assess the effect of greenness on the associations between short-term exposure and stroke.

Results: Individuals living in the high-greenness areas had weaker associations between total stroke risk and exposure to NO_2 (low greenness: ER% = 1.765% [95% CI 1.205%–2.328%]; high greenness: ER% = 0.368% [95% CI −0.252% to 0.991%]; P = 0.001), O_3 (low greenness: 0.476% [95% CI 0.246%–0.706%]; high greenness: ER% = 0.085% [95% CI −0.156% to 0.327%]; P = 0.011), and SO_2 (low greenness: 0.632% [95% CI 0.138%–1.129%]; high greenness: ER% = −0.177% [95% CI −0.782% to 0.431%]; P = 0.035).

Conclusion: Residence in areas with higher greenness was related to weaker associations between air pollution and stroke risk, suggesting that effectively planning green spaces can improve public health.

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1. Introduction

Stroke has become a major global public health problem. Although the age-standardised incidence rates of stroke decreased slightly from 1990 to 2019, the absolute number of stroke incidents worldwide grew by 70.0% during this period (GBD, 2021 Stroke Collaborators, 2021). In 2019, 12.2 million incident strokes and 101 million prevalent strokes were reported worldwide, with the majority of cases occurring in lower-income and lower-middle-income countries (GBD, 2021 Stroke Collaborators, 2021). In 2019, approximately 3.94 million new strokes occurred in China, which accounted for nearly a quarter of the global incident strokes that year (Tu et al., 2023). The annual rates of incident stroke increased between 1990 and 2019, with ischaemic stroke exhibiting the greatest increase (226.5%), followed by haemorrhagic stroke (53.2%) (Ma et al., 2021).

Air pollution is a leading risk factor for stroke (Bedada et al., 2012; Fisher et al., 2019; Liu et al., 2023; Tian et al., 2018; Verhoeven et al., 2021). Recent studies from around the world (Bedada et al., 2012; Gaines et al., 2023; Hasegawa et al., 2022; Ho et al., 2022; Liu et al., 2023; Nhung et al., 2020; Zhang et al., 2021b) have demonstrated that short-term exposure to air pollution significantly increases the risk of stroke. Although governments attempt to control air pollution, in 2019, 99% of the world's population resided in areas not meeting the World Health Organization air quality recommendations (WHO 2021). Therefore, novel and effective measures are urgently required to alleviate the risk of stroke associated with short-term air pollution.

Residential greenness has been reported to reduce the risks of diseases caused by air pollution (Crouse et al., 2017; Ji et al., 2020; Kasdagli et al., 2021; Li et al., 2022; Liu et al., 2022; Orioli et al., 2019; Song et al., 2022; Sun et al., 2020) through several mechanisms. Several studies have found that greenness could interact with exposure to air pollutants (Ji et al., 2020; Nowak et al., 2014). Greenness could filter out air pollutants aerodynamically, or there could be in-vivobiological interactions. For example, vegetation can directly filter air pollutants or improve ventilation in green areas, thereby increasing the dispersal of air pollutants and reducing health impacts. Airborne chemical evidence suggests that vegetation has the ability to capture airborne particles or make it easier for gaseous contaminants to be absorbed through leaf stomata on plant surfaces (Chen et al., 2016; Ji et al., 2020). Given that short-term exposure to air pollution increases the risk of stroke onset and that vegetation can reduce air pollution, we hypothesise that greenery mitigates the harmful effects of air pollution, specifically, their potential to increase stroke risk. However, no studies have estimated the potential effect of greenness on the association between short-term exposure to air pollution and stroke onset. To fill this gap, we comprehensively investigated the effect of greenness on the relationship between short-term exposure to air pollution and total stroke as well as the haemorrhagic and ischaemic stroke subtypes by conducting a case-crossover study in Shandong province, China.

2. Methods

2.1. Study area

Shandong, a coastal province with 17 prefecture-level cities and approximately 101.53 million people, is situated on China's eastern coast. The present study followed a previous study that used stratified random sampling to select 20 counties in Shandong (Fig. 1). These counties were then categorised into 4 regions: central Shandong (Feicheng, Huaiyin, Laiwu, Yiyuan, and Zhangdian), the Shandong Peninsula (Fushan, Gaomi, Penglai, Shouguang, and Wenden); south-western Shandong (Chengwu, Junan, Mudan, Xuecheng, Zoucheng, and Pingyi), and north-western Shandong (Bincheng, Gaotang, Leling, and Wucheng) (He et al., 2022). The research region encompasses 11 688 villages and communities, each with an average surface area of 1.848 km^2.

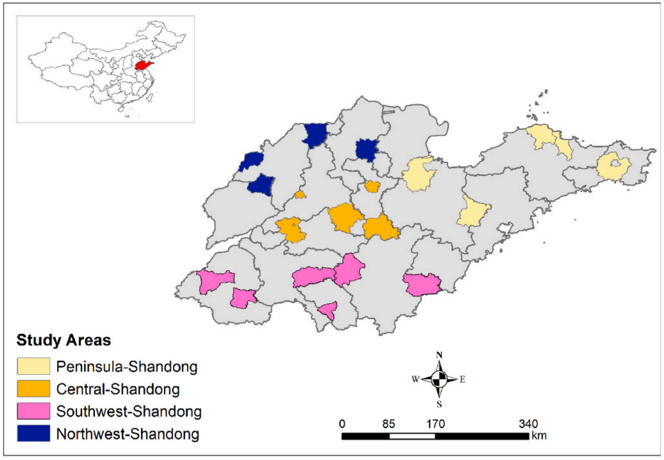

Fig. 1. Location of the study area (20 counties of Shandong province, China) and spatial distribution of the cases.

2.2. Ischaemic stroke registry data

We obtained daily stroke onset data from the noncommunicable disease registry system operated by the Shandong Center for Disease Control and Prevention (CDC); this registry was described in detail in a prior study (Wu et al., 2022),especially, the time of onset of clinical symptoms reported by the patient is recorded as the onset date by the attending physician in the incidence registry system. We identified 362 947 individuals who lived in one of the 20 selected counties in Shandong and experienced a first stroke (301 068 ischaemic strokes and 58 090 haemorrhagic strokes) between 2013 and 2019. As in previous studies (He et al., 2022; Wu et al., 2022), we analysed 3 categories of stroke on the basis of the *International Classification of Diseases,* 10th *Revision* (*ICD-10*): total stroke (codes: I60–I67), ischaemic stroke (code: I63), and haemorrhagic stroke (codes: I60–I62). Our data included sex, age, residence status, disease classification, incidence date, and *ICD-10* codes.

2.3. Air pollution assessment

We collected daily air pollution data from 2013 to 2019 in Shandong from the ChinaHighAirPollutant (CHAP) data set (available at https://weijing-rs.github.io/product.html). Using a space-time extremely randomized trees (STET) model, a new tree-based ensemble approach for regression that combines ground observation, remote sensing products, atmospheric reanalysis, and emission inventories, daily NO$_2$, O$_3$, CO, and SO$_2$ were calculated at a resolution of 10 km in space (Wei et al. 2020, 2021, 2022). We also acquired daily levels of fine particulate matter (PM$_{2.5}$) at 1-km spatial resolution from the CHAP data set. The cross-validated coefficients of determination (R^2) were 0.84, 0.87, 0.80, 0.87, 0.84, and 0.91 for NO$_2$, O$_3$, CO, SO$_2$, and PM$_{2.5}$, respectively. Residential address was available at the communities/villages level in the study. Individuals were classified into 11 688 communities/villages within the study area. By linking community/village-level addresses to the nearest grids at 1 km/10 km resolution, we match the exposures of PM$_{2.5}$/NO$_2$, SO$_2$, O$_3$, and CO to each participant. Same-day (0-d lag) and moving-average 1-day lag exposure data were used to examine the acute effects of ambient air pollution on stroke onset. Our data analyses showed that the estimated effects were representative at lag 01 day, and it was also used extensively in previous studies. Hence, lag 01 day exposure was employed as the exposure parameter in the main analyses (Li et al., 2023; Xu et al., 2022).

2.4. Greenness exposure data

We employed the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to estimate neighbourhood greenness exposure. Vegetation indices (EVI and NDVI) range from −1.0 to 1.0, with values less than zero indicating water, snow, or no vegetation and higher values suggesting the potential for more greenness (He et al., 2022; Zhang et al., 2021a). Compared to the NDVI, EVI can remove residual atmospheric contamination and is sensitive to high-density vegetation (Zhang et al., 2021a). Less than 10% cloud cover EVI and NDVI values from 2013 to 2019 were collected from the satellite images provided by the Landsat 8 Operational Land Imager (OLI), which provides images every 16 days at the 30 m resolution (http://earthexplorer.usgs.gov) (Claesen et al., 2021; United States Geological 2020). Then, consistent with most previous air pollution studies ((Li et al., 2022; Qiu et al., 2021), we calculated NDVI/EVI values from January 2013 to December 2019 for each year using the images from the same days in January, April, July, and October of each year (days 001, 017, 097, 113, 193, 209, 257, 289, and 305) to represent greenness in four seasons. We then assigned EVI and NDVI to each village or community as an indicator of exposure to green spaces. We employed EVI as the measure of greenness exposure in the primary study. Similar techniques were used in a sensitivity analysis to calculate the NDVI as a substitute greenness indicator to make it easier to compare the results with past investigations.

2.5. Covariates

In this study, a DAG (Greenland et al., 1999; Shrier and Platt, 2008) was employed to select a minimally sufficient set of confounding variables (Fig. S10). DAG execution was facilitated by dagitty. net (Textor et al., 2011). Individual characteristics such as age, gender, race, genetics, and lifestyle factors, were not considered as possible confounders, because such factors do not change appreciably across short time intervals (ie, time strata). From the DAG, we adjusted for 24-h average temperature, relative humidity, and public holiday. 24-h average temperature (°C) and relative humidity (RH, %) data were obtained from the China Meteorological Administration Land Data Assimilation System (CLDAS version 2.0) (Liu et al., 2020; Xu et al., 2022).

2.6. Statistical analysis

A time-stratified case-crossover design was used to estimate the association between short-term exposure to ambient air pollution and the risk of stroke first onset. By comparing reference exposures on the days before to or after the case day, each case in this study acts as its own control. For instance, a stroke onset occurred on May 20, 2019 (Monday), and then all other Mondays in May 2019 (i.e., May 6, 13, and 27) were selected as the corresponding control days. Each case day in this design was paired with three or four control days. As a result, the impacts of seasonality, the day of the week, long-term tendencys, and individual-level time-invariant confounders may be controlled.

Spearman correlation analysis was conducted to assess the correlation between various air pollutants. We used conditional logistic regression to estimate the percent excess risk (ER%; ER% = [OR − 1] × 100%) of stroke onset and the corresponding 95% CI for each 10 $\mu g/m^3$ increase in exposure to each air pollutant. We utilized the same-day mean temperature and relative RH to control for the immediate effects and the average of the following 1–3 days of mean temperature values to examine the potential lagged effects of meteorological variables. Natural cubic splines with 3 degrees of freedom were used to control for the nonlinear effects of such meteorological variables (Sun et al., 2020). Additionally, a binary variable for public holidays was included in all models. The variance inflation factor (VIF) were calculated to diagnose the potential multicollinearity among multiple variables (Table S1).

To determine whether neighbourhood greenness affects the association between air pollution and risk of stroke first onset, an interaction term (ie $PM_{2.5}$ × EVI [low or high]) was included in our models. We used a slice plot to visualise the interaction effects (Hood et al., 2021). We further divided the EVI values of neighbourhood greenness exposure into 4 greenness quartiles, with quartile 1 being the lowest exposure, to estimate the effects of greenness. We included an interaction terms between the air pollutants and greenness quartiles to estimate the additional excess risk associated with air pollution for greenness quartiles 2, 3, and 4 relative to quartile 1, which was used as the reference (Sun et al. 2019, 2020). By including the median values of the EVI quartiles as a continuous variable in the models, we looked for a tendency related to the extra per cent excess risks (Guo et al., 2022; Sun et al., 2020).

In further analyses, we stratified patients experiencing stroke by age, sex, and region and analysed the modifying effects of greenness within these subgroups.

Two sensitivity analyses were performed: (1) one using same-day (lag 0 day) exposure data and (2) one using the NDVI as the greenness index. (3) To assess the seasonal impacts of neighbourhood greenness, EVI exposure in the season of onset was assigned to each subject, and substituted for the average annual EVI. All data analyses were performed using R (version 4.0). $P < 0.05$ was considered statistically significant.

3. Results

3.1. Data description

Over the study period, we detected 362 947 first-episode stroke cases in the 20 study counties, including 301 068 (83.0%) cases of ischaemic stroke and 58 090 (16.0%) cases of haemorrhagic stroke (Table 1). Individuals who experienced a stroke were younger (age <65 y), more likely to be men, and more likely to reside in a rural area. The characteristics of residents of neighbourhoods with low greenness were generally similar to those of residents of neighbourhoods with high greenness. Overall, the daily mean concentrations of $PM_{2.5}$, NO_2, O_3, CO, and SO_2 on case days were 65.9 $\mu g/m^3$, 38.8 $\mu g/m^3$, 107.2 $\mu g/m^3$, 1.2 mg/m^3, and 32.0 $\mu g/m^3$, respectively (Table 2). The correlations between exposure to any 2 of $PM_{2.5}$, NO_2, SO_2, and CO were substantial and positive, whereas the correlations between exposure to O_3 and that to all other air pollutants were negative (Fig. S9). Neighbourhood greenness exposure varied considerably among the 20 Shandong

Table 1
Descriptive characteristics for participants by neighbourhood greenness[a] in 20 counties of Shandong province, China, 2013–2019.

Population characteristics	Total samples	Low greenness	High greenness	*P* value
Incident (case days), n	362 947	181 539	181 408	
Control days, n	1 175 962	588 276	587 682	
Sex[b,c], n (%)				<0.001
Male	196 050 (54.0)	99 474 (54.8)	96 576 (53.2)	
Female	166 897 (46.0)	82 065 (45.2)	84 832 (46.8)	
Age[b,c], n (%)				<0.001
<65	134 740 (37.1)	68 590 (37.8)	66 150 (36.5)	
≥65	228 207 (62.9)	112 949 (62.2)	115 258 (63.5)	
Residence[b,c], n (%)				<0.001
Urban	162 524 (44.8)	110 109 (60.7)	52 415 (28.9)	
Rural	200 423 (55.2)	71 430 (39.3)	128 993 (71.1)	

[a] Low and high greenness (EVI) were defined by the median (0.339) of enhanced vegetation index within village or community.

[b] *p* values for difference were <0.001 in ischaemic stroke.

[c] *p* values for difference were <0.001 in haemorrhagic stroke.

Table 2

Distribution of exposure to ambient air pollution and meteorological conditions on the day of stroke first onset in 20 counties of Shandong province, China, 2013–2019.

				Percentile					
Parameter	Mean	SD	Min	5th	25th	50th	75th	95th	Max
$PM_{2.5}$, μg/m^3	65.9	41.2	2.2	22.7	37.9	55.4	81.4	144.9	516.0
NO_2, μg/m^3	38.8	16.7	2.4	17.1	26.3	35.8	48.5	70.4	214.2
O_3, μg/m^3	107.2	49.2	3.8	38.9	66.8	102.3	141.5	195.1	408.1
SO_2, μg/m^3	32.0	26.7	1.8	8.5	14.8	23.2	40.1	84.6	578.9
CO, mg/m^3	1.2	0.5	0.1	0.6	0.8	1.0	1.4	2.2	47.3

Abbreviations: $PM_{2.5}$ = particulate matter <2.5 μm in aerodynamic diameter; NO_2 = nitrogen dioxide; O_3 = ozone; SO_2, sulfur dioxide; CO, carbon monoxide.

Table 3

Per cent excess risk and 95% confidence interval of stroke first onset per 10 μg/m^3 increase in air pollutants at 2-day moving average ($lag_{0\text{-}1}$) in the low and high neighbourhood greenness areas measured by enhanced vegetation index (EVI) with village or community.

	Air pollution	Total samples	Low greenness	High greenness	*P* value
Total stroke	$PM_{2.5}$	0.254 (0.095,0.413)	0.275 (0.060,0.490)	0.232 (0.020,0.445)	0.767
	NO_2	1.188 (0.714,1.665)	1.765 (1.205,2.328)	0.368 (-0.252,0.991)	**0.001**
	O_3	0.294 (0.113,0.475)	0.476 (0.246,0.706)	0.085 (-0.156,0.327)	**0.011**
	CO	0.018 (0.005,0.031)	0.025 (0.009,0.041)	0.008 (-0.011,0.028)	0.191
	SO_2	0.318 (-0.080,0.717)	0.632 (0.138,1.129)	−0.177 (-0.782,0.431)	**0.035**
Ischemic stroke	$PM_{2.5}$	0.330 (0.141,0.519)	0.328 (0.088,0.568)	0.259 (0.027,0.491)	0.667
	NO_2	1.662 (1.151,2.176)	1.899 (1.288,2.514)	0.643 (-0.047,1.337)	**0.005**
	O_3	0.427 (0.226,0.627)	0.498 (0.250,0.747)	0.265 (0.000,0.530)	0.165
	CO	0.025 (0.011,0.039)	0.028 (0.010,0.045)	0.013 (-0.009,0.034)	0.276
	SO_2	0.396 (-0.019,0.813)	0.534 (-0.010,1.081)	−0.12 (-0.801,0.566)	0.128
Hemorrhagic stroke	$PM_{2.5}$	0.071 (-0.292,0.436)	0.024 (-0.478,0.529)	0.014 (-0.518,0.549)	0.978
	NO_2	0.141 (-0.814,1.105)	0.854 (-0.568,2.297)	−1.045 (-2.490,0.421)	**0.050**
	O_3	−0.257 (-0.735,0.222)	0.289 (-0.338,0.920)	−0.807 (-1.423,-0.186)	**0.007**
	CO	−0.001 (-0.032,0.030)	0.007 (-0.032,0.045)	−0.013 (-0.059,0.033)	0.505
	SO_2	0.346 (-0.393,1.091)	0.968 (-0.231,2.182)	−0.889 (-2.234,0.476)	**0.036**

Abbreviations: $PM_{2.5}$ = particulate matter <2.5 μm in aerodynamic diameter; NO_2 = nitrogen dioxide; O_3 = ozone; CO, carbon monoxide; SO_2, sulfur dioxide.
Low and high greenness(EVI) were defined by the median (0.339) of enhanced vegetation index within village or community.

counties in the present study because of factors such as climate, flora, municipal greening policies, number of farms, and degree of urbanisation. Residents of north-western Shandong were exposed to the highest level of greenness at the village or community level, followed by those in south-western Shandong, the Shandong Peninsula, and central Shandong (Figs. S1 and S2).

3.2. *Modifying effects of greenness*

The relationships of pollution with total stroke and the 2 stroke subtypes were related to greenness exposure; specifically, air pollution exposure had a greater effect on the risks of total stroke and stroke subtypes in regions with less greenness (Table 3 and Fig. S8). For instance, the ER% for total stroke associated with each 10-μg/m^3 increase in NO_2 was 1.765% (95% CI: 1.205%–2.328%) in low-EVI regions and 0.368% (95% CI: −0.252%–0.991%) in high-EVI regions, the ER% for ischaemic stroke was 1.899% (95% CI: 1.288%–2.514%) in low-EVI regions and 0.643% (95% CI: −0.047%–1.337%) in high-EVI regions, and the ER% for haemorrhagic stroke was 0.854% (95% CI: −0.568%–2.297%) in low-EVI regions and −1.045% (95% CI: −2.490%–0.421%) in high-EVI regions. The differences between the ER% for total stroke low- and high-EVI regions were statistically significant for exposure to NO_2 ($P = 0.001$), O_3 ($P = 0.011$), and SO_2 ($P = 0.035$). The difference between the ER% for ischaemic stroke in low- and high-EVI regions was statistically significant for NO_2 ($P = 0.005$). Finally, the differences between the ER% of haemorrhagic stroke in low- and high-EVI regions were statistically significant for NO_2 ($P = 0.050$), O_3 ($P = 0.007$), and SO_2 ($P = 0.036$; Table 3).

The risk of stroke due to air pollution was lower for higher greenness quartiles (Table 4). Specifically, the percent excess risk of total stroke for each-10 μg/m^3 increase in each air pollutant for greenness quartiles 2 through 4 (compared with quartile 1) was 0.478% (95% CI: −0.584%–1.553%), −0.366% (95% CI: −1.427%–0.707%), and −1.982% (95% CI: −3.025% to −0.927%), respectively, for NO_2, and −0.204% (95% CI: −0.623%–0.217%), −0.406% (95% CI: −0.824%–0.014%), and −0.546% (95% CI: −0.954%–0.137%), respectively, for O_3. Decreasing tendencies were observed in the risk estimates for total stroke for NO_2 (P for tendency <0.001), O_3 (P for tendency $= 0.006$), and SO_2 (P for tendency $= 0.036$) as well as for ischaemic stroke for NO_2 (P for tendency $= 0.003$) and haemorrhagic stroke for NO_2 (P for tendency $= 0.049$), O_3 (P for tendency $= 0.002$), and SO_2 (P for tendency $= 0.050$).

3.3. *Stratified analysis*

Living in areas with higher greenness exposure may be more protective for female patients, younger patients (age <65 years), and patients living in rural areas (Fig. 2). For instance, significant interaction effects between air pollution and greenness on the risk of total stroke were identified among women (P for $NO_2 = 0.024$, $O_3 = 0.017$, and $SO_2 = 0.037$), individuals aged <65 years (P for $PM_{2.5} = 0.050$, $NO_2 < 0.001$, $O_3 = 0.004$, $CO = 0.002$, and $SO_2 = 0.003$), and those living in rural regions (P for $NO_2 < 0.001$, and $SO_2 = 0.006$).

3.4. *Sensitivity analysis*

We conducted a series of sensitivity analyses (Supplementary Tables S3–S13). Whether we used different exposure windows (i.e., 0-day lag) or other greenness metrics (i.e., NDVI), as well as different seasonal EVI, we observed the modifying effect of greenness, suggesting that our results are robust.

4. Discussion

To the best of our knowledge, this study is the first to comprehensively examine the effects of neighbourhood greenness on the association between short-term exposure to air pollution and the risks of total stroke, ischaemic stroke, and haemorrhagic stroke by using multi-city and village- or community-level exposure data. Our results suggest

Table 4
Additional per cent excess risk in stroke first onset associated with 10 μg/m^3 increase in air pollutants at the 2-day moving average (lag$_{0-1}$) by greenness (EVI)quartiles within village or community.

	Air pollution	Q1 (lowest)	Q2	Q3	Q4 (highest)	*P* for trend
Total stroke	$PM_{2.5}$	Reference	0.168 (-0.236,0.574)	0.294 (-0.104,0.693)	−0.040 (-0.421,0.342)	0.976
	NO_2	Reference	0.478 (-0.584,1.553)	−0.366 (-1.427,0.707)	−1.982 (-3.025,-0.927)	**<0.001**
	O_3	Reference	−0.204 (-0.623,0.217)	−0.406 (-0.824,0.014)	−0.546 (-0.954,-0.137)	**0.006**
	CO	Reference	0.014 (-0.018,0.046)	0.000 (-0.032,0.033)	−0.023 (-0.056,0.010)	0.209
	SO_2	Reference	0.880 (-0.110,1.879)	0.305 (-0.701,1.321)	−1.304 (-2.311,-0.286)	**0.036**
Ischemic stroke	$PM_{2.5}$	Reference	0.045 (-0.398,0.491)	0.275 (-0.159,0.711)	−0.082 (-0.502,0.341)	0.994
	NO_2	Reference	0.452 (-0.711,1.629)	−0.332 (-1.492,0.840)	−1.794 (-2.947,-0.628)	**0.003**
	O_3	Reference	−0.100 (-0.554,0.356)	−0.231 (-0.683,0.223)	−0.316 (-0.761,0.130)	0.136
	CO	Reference	−0.002 (-0.038,0.034)	−0.012 (-0.048,0.024)	−0.020 (-0.057,0.017)	0.261
	SO_2	Reference	0.674 (-0.425,1.785)	0.192 (-0.921,1.318)	−1.072 (-2.205,0.074)	0.132
Hemorrhagic stroke	$PM_{2.5}$	Reference	0.976 (-0.037,2.000)	0.531 (-0.491,1.563)	0.476 (-0.471,1.432)	0.581
	NO_2	Reference	1.274 (-1.418,4.040)	−0.435 (-3.142,2.348)	−2.000 (-4.584,0.654)	**0.049**
	O_3	Reference	−0.901 (-2.032,0.244)	−1.321 (-2.467,-0.162)	−1.726 (-2.811,-0.628)	**0.002**
	CO	Reference	0.094 (0.014,0.174)	0.059 (-0.025,0.143)	−0.016 (-0.095,0.064)	0.742
	SO_2	Reference	1.878 (-0.455,4.265)	0.241 (-2.173,2.714)	−2.145 (-4.433,0.199)	**0.050**

Abbreviations: $PM_{2.5}$ = particulate matter <2.5 μm in aerodynamic diameter; NO_2 = nitrogen dioxide; O_3 = ozone; CO, carbon monoxide; SO_2, sulfur dioxide. Low and high greenness(EVI) was defined by the median (0.339) of enhanced vegetation index within village or community.

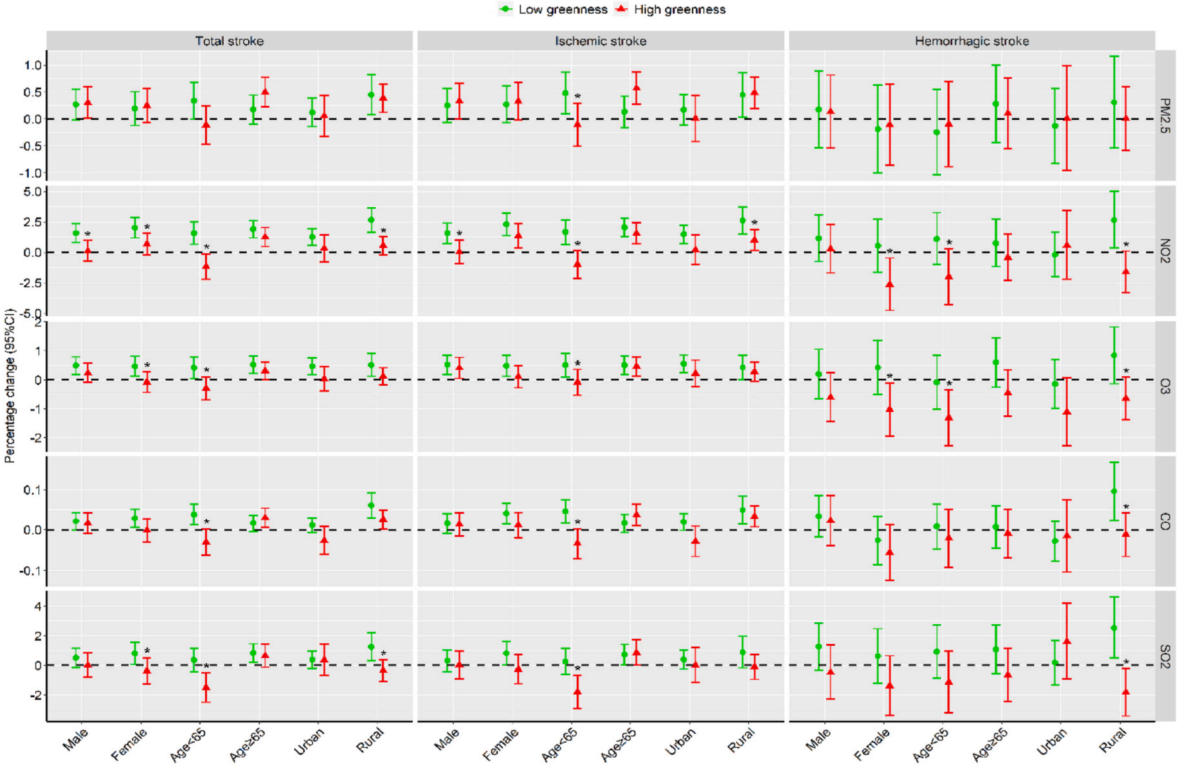

Fig. 2. Stratified analysis of the modification effects of greenness exposure on the association between short-term exposure to air pollution and the risk of stroke and its subcategories onset for gender, age, and region. Low and high greenness (EVI) were defined by the median (0.339) of enhanced vegetation index within village or community. * p-value of the interaction term <0.05.

that, in China, neighbourhood greenness considerably mitigates the stroke risks (total, ischaemic, and haemorrhagic) presented by short-term exposure to air pollutants (particularly NO_2, O_3, and SO_2). Moreover, the effect of neighbourhood greenness is more pronounced on the risk of haemorrhagic stroke as well as among women, individuals aged <65 years, and those living in rural areas.

The effect of greenness on the association between long-term air pollution and risk of stroke has been extensively studied (Avellaneda-Gomez et al., 2022; Klompmaker et al., 2021; Liao et al., 2022; Magnoni et al., 2021; Poulsen et al. 2023a, 2023b), but only a limited number of studies investigated short-term exposure to air pollution and the results remain inconsistent (Heo and Bell, 2019; Vivanco-Hidalgo et al., 2018; Yang et al., 2022). In this study, we did not observe the significant modification effect ($P_{\text{for interaction}}$>0.05) of greenness in short-term exposure to $PM_{2.5}$, CO and stroke onset. Similarly, the one study, which was conducted in Spain, evaluated the effect of greenness on the association between short-term exposure to $PM_{2.5}$ and ischaemic stroke onset. This study did not identify a significant effect of greenness (Vivanco-Hidalgo et al., 2018); however, significant associations were reported in one study in US for $PM_{2.5}$ exposure (Heo and Bell, 2019). Our study found that neighbourhood greenness alleviated the risk of stroke (ischemic and hemorrhagic) onset due to transient exposure to NO_2, O_3, and SO_2. Although no study was directly comparable, our findings were similar to some cohort studies. A cohort study conducted in Spain discovered that residential greenness in the areas surrounding where the participants lived appeared to mitigate the effect of long-term exposure to NO_2 on the incidence of ischaemic stroke (Avellaneda-Gomez et al., 2022). A US open cohort study (Klompmaker et al., 2021), which also found regions with higher levels of greenness may have weaker associations between NO_2 and cerebrovascular disease, but no significant modification effect was found for O_3. Moreover, our findings also were consistent with other studies. A longitudinal study in China found that greenness could alleviate the damage efects of SO_2 exposure on the risks of HBP among children and adolescents (Zhang et al., 2023). A study conducted in north-western Florida, United States, discovered that communities with high levels of air pollution and low levels of greenness had higher risks of stroke-related mortality (Hu et al., 2008). Our results also agree with those of another study conducted in the United States (Yitshak-Sade et al., 2019), which discovered that high greenness exposure mitigated the association between short-term exposure to air pollution and cardiovascular mortality. However, in another study conducted in the United States, higher local greenness was linked to increased mortality risks from air pollution (Kioumourtzoglou et al., 2016). Two cohort studies conducted in Denmark discovered the stronger associations between air pollution ($PM_{2.5}$, NO_2) and risk of stroke among individuals with much green space around the residence (Poulsen et al. 2023a, 2023b). In summary, the results of previous studies are inconsistent, possibly because greenness levels and the source compositions and levels of air pollution vary by region, geographic, and climate features (Feng and Astell-Burt, 2019). Therefore, further research is required to account for these differences.

Although the biological mechanisms underlying the connection between greenness exposure and stroke are not fully understood, several explanations have been proposed. First, vegetation may directly reduce air pollution through several mechanisms, such as uptake, deposition, dispersion, and modification (Diener and Mudu, 2021; Mondal and Singh, 2022). Gaseous pollutants can be absorbed by vegetation, especially by leaf stomata s (Ji et al., 2020). Plants can also aid in particulate matter deposition on the surface and leeward side of leaves (Javanmard et al., 2020; Roy et al., 2020). Plants can alter the direction and velocity of pollutants in the air (Diener and Mudu, 2021) and the inherent characteristics of PM by accelerating deposition and removing particles from the air. For example, plants can lessen the toxicity and concentration of pollution by capturing large and heavy particles, altering the solubility or loading of particles, and changing compositions (Diener and Mudu, 2021; Kelly and Fussell, 2020; Yang et al., 2018). Second, vegetation can inhibit pollution emissions indirectly. In the summer, vegetation may cool the air by providing shade and aiding in evaporation, which can minimise the amount of pollution emitted by reducing the energy production needed for cooling (Yang et al., 2005). Likewise, increased vegetation can reduce the amount of energy buildings use to cool their interiors and thus lower the resulting emissions from power plants (Nowak et al., 2018). Third, vegetation may encourage people to engage in exercise and social interaction, which can improve their mental health and immunological function, reducing their vulnerability to air pollution (James et al., 2015; van den Berg et al., 2010).

We discovered that greenness modified the risk of haemorrhagic stroke onset due to short-term exposure to air pollution to a greater extent than it modified that of ischaemic stroke onset. Although we cannot directly compare this finding with those of other studies, we propose a possible explanations:the mechanism underlying the effect of short-term exposure to air pollution on haemorrhagic stroke compared may differ from that underlying the increased risk of ischaemic stroke; unlike ischaemic stroke, haemorrhagic stroke is caused mainly by an acute and rapid increase in blood pressure or vascular endothelial activation, which leads to cerebral vascular rupture (An et al., 2017; Verhoeven et al., 2021) and triggers cerebral haemorrhage. Greenness can not only directly reduce the effects of air pollution on hypertension by reducing air pollution levels but also reduce the risk of hypertension by improving immune regulation, encouraging exercise, reducing stress, and promoting metabolism, all of which may offset the effects of air pollution (Jiang et al., 2021; Labib et al., 2020; Liu et al., 2021; Yang et al., 2021).

Similar to some previous studies (Sun et al. 2019, 2020), in several occasions, we found that the association between air pollutants and stroke became negative in the high greenness regions, which may seem counterintuitive. In high green regions, greenness may attenuate the effects of air pollution on stroke, which in turn may have some ineffective or even negative outcomes. In addition, this also may be related to factors such as sample size, air pollutant concentrations, meteorological factors, economic level and geographic location. More studies need to be included in the future to provide explanations.

The results of our stratified analyses suggest that the effects of greenness on different populations and regions vary. For example, a stronger effect of greenness was observed in individuals aged <65 years. This supports our original assumption that greenness is more beneficial to younger people because they are more active and have fewer functional limitations than older people have and thus spend more time outdoors being exposed to green spaces (Yang et al., 2021). Additionally, the protective effects of greenness might be stronger for women because of differences from men in their characteristics, physiological structures, and various lifestyles factors, such as proclivity for drinking, smoking, and physical activity (Li et al., 2022). We patients living in rural areas may benefit more from the protective effect of greenness. One reason for this may be that Chinese cities, which tend to be more developed, have poorer air quality and more air pollution than do rural areas (Hu et al., 2017). As the economy develops, energy production (eg coal firing) and industrial waste increase in urban areas, along with traffic-related air pollution caused by rapid increases in motor vehicle ownership and use. Additionally, rural areas have a greater density and variety of vegetation (Ji et al., 2020), which may help to reduce air pollution.

This study has several strengths. First, this study has a sufficiently large sample size and used population-based registry data, which are more robust than the admissions data from selected hospitals, which were used in previous studies. Second, time of stroke symptom onset, rather than the date of diagnosis, was used in the analysis, which may not cause a temporal mismatch between air pollution exposure and stroke onset and thus a true assessment of the effects of exposure. Third, by using a time-stratified case-crossover design, we could investigate associations on the individual level and consider potential confounders, such as long-term tendencies, time-invariant personal factors or traits, and time-varying weather conditions. Finally, we assessed greenness exposure in residential neighbourhoods by performing our analyses at the village or community level. This aspect of our analysis is especially valuable for urban planners because, although they may not be able to change individual-level greenness exposure, they can increase village- and community-level greenness through effective resource allocation and evidence-based planning.

This study also has several limitations. First, similar to other researchers, we were unable to directly measures air pollution exposure. Instead, we calculated village- or community-level environmental exposure by extracting data from a verified gridded data set. Second, although case-crossover studies enable valid control of time-invariant confounders (eg age or sex), unmeasured confounders (eg smoking, alcohol consumption, education level, or concomitant diseases) may have affected the results. Future research must focus on susceptible populations to enable more precise development and implementation of preventive measures. Third, we used the EVI and NDVI to measure the greenness of neighbourhoods, but these measure only the quantity but not the quality of green space. More informative greenness assessments are required in future research. Finally, because our study region was a single province, our findings may not be generalisable to other regions or socioeconomic contexts. Future studies can overcome this limitation by conducting research in various geographic settings on populations with diverse socioeconomic status.

5. Conclusions

In conclusion, neighbourhood greenness mitigates the association between short-term exposure to air pollution and the risk of stroke onset in Shandong, China. Our research demonstrates that creating green spaces in areas with high levels of air pollution may be a preventive public health strategy. Our findings highlight the importance of allocating and planning green areas as a public health intervention. According to our stratified research, people who live in rural regions are more likely to benefit from greenness. Because air pollution is more severe in urban areas, the health risks are greater there than in other areas. Therefore, more effective planning and allocation of green spaces in cities may enhance the purifying effects of vegetation on air pollution and thus reduce the pollution load and sewage costs of cities.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2023.114262.

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