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# Effects of $PM_{2.5}$ components on hypertension and diabetes: Assessing the mitigating influence of green spaces

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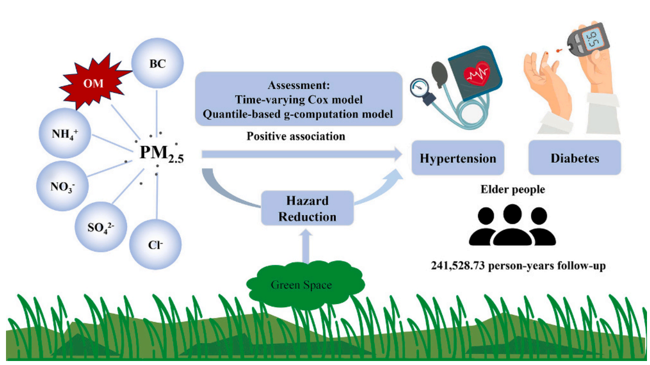
## HIGHLIGHTS

- An 8-year cohort study assessed the effects of $PM_{2.5}$ components on chronic disease.
- Exposure to $PM_{2.5}$ component is linked to risk, while green spaces offer protection.
- A one IQR increase in all $PM_{2.5}$ components increased chronic disease risk by 50.3 %.
- Green spaces mitigated the adverse health impacts of $PM_{2.5}$ components exposure.

## GRAPHICAL ABSTRACT

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A R T I C L E I N F O

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$PM_{2.5}$ components
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Diabetes
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Joint association

A B S T R A C T

*Background:* Particulate matter with diameters ≤2.5 μm ($PM_{2.5}$) is a significant air pollutant associated with hypertension and diabetes. However, the specific contributions of its components and their joint exposure with green spaces remain poorly understood, especially in developing regions.

*Objectives:* This study aims to investigate the individual and joint impacts of $PM_{2.5}$ and its components on the middle-aged and older adults, identify primary risk factors, and assess disease risks associated with simultaneous exposure to green spaces.

*Method:* We conducted a prospective cohort study in Tianjin from 2014 to 2021, involving individuals aged ≥45 years. Satellite-based machine learning models quantified $PM_{2.5}$ components, including black carbon (BC), organic matter (OM), sulfate ($SO_4^{2-}$), nitrate ($NO_3^-$), ammonium ($NH_4^+$), and chloride ($Cl^-$). Residential greenness was assessed using the Normalized Difference Vegetation Index (NDVI). A time-varying Cox proportional hazards model analyzed associations between $PM_{2.5}$ components and the incidence of hypertension and diabetes. The quantile g-computation model evaluated joint exposure effects and relative contributions of the components. Pollutants and NDVI were dichotomized using median values and combined to create a joint exposure model, aimed at exploring the potential effects of NDVI. Stratified analyses were performed to identify vulnerable subpopulations.

*Results:* Over 241,528.73 person-years of follow-up, there were 15,747 (38.34 %) new cases of hypertension and 8945 (13.59 %) new cases of diabetes. Each standard deviation (SD) increase in OM was associated with increased incidence of hypertension (hazard ratio: 1.609; 95 % confidence interval: 1.583, 1.636) and diabetes (1.484; 1.453, 1.515). Joint exposure to components is linked to higher incidence of hypertension and diabetes, with OM identified as the primary contributor. The joint exposure model indicated elevated population risk in areas with low NDVI and high $PM_{2.5}$ concentrations, particularly affecting males and individuals younger than 60 years.

*Conclusions:* Long-term exposure to higher levels of $PM_{2.5}$ components is significantly associated with increased hypertension and diabetes, with OM potentially being the primary contributor. Joint exposure to green space may mitigate these risks. These findings highlight how $PM_{2.5}$ sources impact health, informing more effective governance measures.

## 1. Introduction

Hypertension and diabetes are globally prevalent chronic non-communicable diseases, posing significant public health challenges (Yan et al., 2022). The prevalence of these conditions is rising due to China's accelerated aging process (Man et al., 2021). Studies indicate that hypertension and diabetes affect 16.9 % to 50 % of the middle-aged and older Chinese population (Li et al., 2015; Wang et al., 2017). Therefore, it is essential to address the risk of diabetes and hypertension in Chinese adults over 45 years old.

Ambient air pollution, particularly particulate matter (PM) with diameters ≤2.5 μm ($PM_{2.5}$), is a significant environmental risk factor for hypertension and diabetes (Chen et al., 2014; Sørensen et al., 2022; Yusuf et al., 2020). $PM_{2.5}$ consists of various components, including black carbon (BC), organic matter (OM), ammonium ($NH_4^+$), nitrate ($NO_3^-$), sulfate ($SO_4^{2-}$), chlorine ($Cl^-$), soil particles (SOIL), sea salt (SS), and others (Harrison and Yin, 2000). Different $PM_{2.5}$ compositions impact human health differently (Achilleos et al., 2017; Wei et al., 2022). Studies indicate that carbonaceous aerosols from agricultural biomass burning and forest fires, ultrafine particles from vehicle exhaust, and fine particles contributing to severe haze exhibit high toxicity (Sinharay et al., 2018; Yang et al., 2016). Furthermore, accumulating evidence indicates that residing in neighborhoods with greater green space encourages physical activity, supports mental well-being, enhances microbial diversity, reduces exposure to harmful environmental factors, and ultimately improves overall health and extends life expectancy (Yang et al., 2021a; Yang et al., 2021b).

An increasing number of studies are investigating the effects of $PM_{2.5}$ and its components on chronic disease. Research from the China Multi-Ethnic Cohort (CMEC) indicates that exposure to $PM_{2.5}$ and its components significantly increases the risk of dyslipidemia, with $NO_3^-$ being the most influential component. Prospective cohort studies have shown that long-term exposure to $PM_{2.5}$ and its components increases the risk of cardiovascular mortality (Liang et al., 2022; Pan et al., 2023; Sun et al., 2024). Numerous studies also associate exposure to $PM_{2.5}$ and its components with higher risks of prevalent diabetes and hypertension (Li et al., 2023; Zhang et al., 2018). However, the relationship between exposure to specific sources of fine particulate matter and the incidence of hypertension and diabetes remains unclear. (Okokon et al., 2021; Puett et al., 2011). Moreover, individuals living in greener urban areas are less likely to develop cardiovascular diseases and diabetes (Chen et al., 2020; Clark et al., 2017). Increasing evidence suggests that urban green spaces provide protective effects against traditional cardiometabolic risk factors, including hypertension (Lai et al., 2023; Zhao et al., 2022), diabetes (Ccami-Bernal et al., 2023), and dyslipidemia (Fernández Núñez et al., 2022). However, studies examining the association between $PM_{2.5}$ components and chronic diseases have not identified which components are most harmful to humans, nor have they explored the role of joint exposure to these components and green spaces.

Hence, the 8-year cohort follow-up was conducted in the Tianjin region of China, an area with high levels of $PM_{2.5}$ pollutants. The objective was to investigate the relationship between joint exposure to $PM_{2.5}$ components and the development of hypertension and diabetes in middle-aged and older adults. Both single and multiple contamination models were employed to assess the risks posed by these components to humans and to identify the primary contributor, explore potential joint exposure effects between green space and $PM_{2.5}$ components on disease onset, and explore sensitive populations for hypertension and diabetes. Gaining insights into the harmful effects of $PM_{2.5}$ components from various sources, along with exploring the significant role of green spaces, is crucial for alleviating the disease burden associated with chronic illnesses.

## 2. Materials and methods

### 2.1. Study setting and population

This prospective 8-year cohort study was conducted in the Tianjin Binhai New Area (BNA). In brief, Tianjin is situated within the Beijing-Tianjin-Hebei (BTH) region and serves as a significant industrial city in northern China. The BNA lies on the eastern coast of Tianjin, encompassing a total area of 2270 $km^2$ with a population of 2.97 million. Further geographic details can be found in published articles (Lin et al., 2020).

The program, initiated in 2014, included approximately 223,000 residents for regular free medical examinations. This study included participants who received annual check-ups at 37 community hospitals in Tianjin BNA, between January 1, 2014, and December 31, 2021, and were aged 45 years or older. After excluding participants with missing addresses, incomplete basic information, and those undergoing multiple checkups within a year, the baseline population totaled 112,394. Annual follow-up medical examinations were conducted from January 1, 2015, to December 31, 2021. The population inclusion and exclusion criteria are illustrated in Fig. 1. Ultimately, 71,784 individuals completed the final follow-up, with all participants surviving. Among them, 41,070 were included in the hypertension analysis, and 65,824 were available for diabetes analysis. Demographic characteristics and lifestyle information were collected through face-to-face surveys conducted by trained professionals. The collected data included sex, age, weight, height, body mass index (BMI), smoking status (never, former, and current smoker), drinking status (never, < twice a week, ≥ twice a week but < daily, and daily), and frequency of exercise (never, < once a week, ≥ once a week but < daily, and daily). In addition, dietary status was investigated and categorized into sugar addicts (yes vs. no) and salt addicts (yes vs. no). Additionally, systolic blood pressure (SBP) and diastolic blood pressure (DBP), along with fasting blood glucose (FBG), were measured by trained physicians.

### 2.2. Definition of outcomes

According to the International Classification of Diseases, Tenth Revision (ICD-10), two chronic non-communicable diseases, hypertension (ICD 10: I10-15) and diabetes mellitus (ICD-10: E10-14), were chosen for coding and defining outcomes. New cases were initially diagnosed in community hospitals and subsequently confirmed at higher-level hospitals. The date of new-onset diabetes diagnosis was defined as follows: (1) the date of diagnosis by a medical practitioner or the date of self-reported physician's diagnosis; (2) the date of initiation of glucose-lowering medication or insulin therapy within 12 months prior to the physical examination; and (3) the date of the medical recommendation of the diabetes diet and physical activity program. For new-onset hypertension, the date of new-onset hypertension diagnosis was based on: (1) the date of self-reported diagnosis by hospital medical staff or physicians; and (2) the initiation date of the patient's first antihypertensive medication. Since type 2 diabetes mellitus ($T_2DM$) accounts for approximately 90 % of diabetes in adults, and this study focused on individuals ≥45 years, it is reasonable to assume that the majority of diabetes cases in this study were $T_2DM$ (Alberti and Zimmet, 1998).

### 2.3. Exposure assessment

The $PM_{2.5}$ pollution data from 2014 to 2021 were generated from the Moderate Resolution Imaging Spectroradiometer (MODIS) Multi-Angle Implementation of Atmospheric Correction (MAIAC) AOD product at a 1-km resolution (Lyapustin et al., 2018), supplemented by ground-based measurements of surface $PM_{2.5}$ and ample auxiliary variables, utilizing a space-time extra-trees model (Wei et al., 2021). The sources and variations of $PM_{2.5}$ components are highly complex. To address this, we employed robust deep learning models with advanced data-mining capabilities, i.e., deep forest model, to identify $PM_{2.5}$ components. We

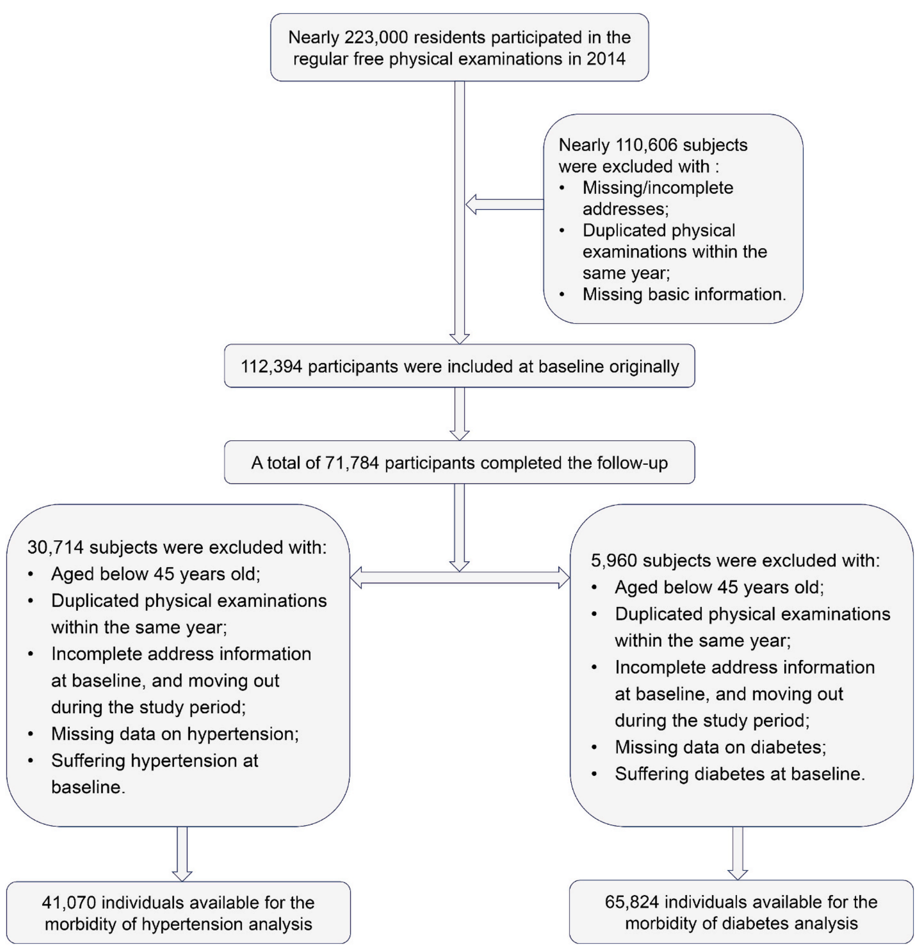


**Fig. 1.** The flow chart of the participant's selection.

incorporated the spatiotemporal heterogeneity of air pollutants into the model to enhance its predictive accuracy and integrated high-density observational networks, satellite-derived $PM_{2.5}$ inversion data, and atmospheric reanalysis products for simulations. Finally, we estimated the daily chemical composition of $PM_{2.5}$ in China at a spatial resolution of 1 km using the four-dimensional spatiotemporal deep forest (4D-STDF) model, significantly enhancing data precision (Wei et al., 2023a). Cross-validation results confirmed the reliability of the estimates, showing cross-validation coefficients of determination ($CV\text{-}R^2$) ranging from 0.66 to 0.82 compared to ground-based observations (Wei et al., 2023a).

The Normalized Difference Vegetation Index (NDVI) was utilized to evaluate the extent of green space surrounding participants' addresses. NDVI values range from −1 to 1, with higher values indicating a greater concentration of vegetation near the addresses. Remote sensing images in the visible and near-infrared bands were acquired from the MODIS sensors aboard Terra and Aqua, polar-orbiting satellites of the U.S. Earth Observing System (EOS). These images were processed using radiometric calibration, atmospheric correction, and orthometric correction (PRC parameters) as described by the following equation: NDVI = (NIR-RED) / (NIR + RED), where NIR denotes the near-infrared band and RED denotes the red band (Dadvand et al., 2015). Mean NDVI values were calculated at 16-day intervals within a 500-meter buffer zone surrounding participants' residential locations. The annual mean NDVI was then computed for each year from 2014 to 2021. In this study, negative values were categorized as zero, as they typically represent water bodies (Helbich et al., 2020; Martinez and Labib, 2023; Reid et al., 2018).

Annual means of $PM_{2.5}$ components and NDVI were quantified for each subject from 2014 to 2021 to facilitate the assessment of covariates over time. Long-term exposure for each subject was determined based on the annual average of air pollution at the time of their diagnosis of a chronic non-communicable disease or at the end of follow-up (Huang et al., 2023).

### 2.4. Statistical analysis

Characteristics of the study population at baseline are presented as numbers (%) for categorical variables and as means ± standard deviations (SD) for continuous variables. The follow-up period for both cohorts started on January 1, 2014, and ended on December 31, 2021, or the date of the disease new-onset. Correlations between $PM_{2.5}$ components and NDVI were assessed using the Spearman rank test. Results are presented with hazard ratios (HR) and 95 % confidence intervals (95 % CI).

Time-varying Cox proportional hazards model serves as the primary analytical approach. Calendar years served as the time scale in the model (Griffin et al., 2012; Liang et al., 2020), with $PM_{2.5}$ components, NDVI, BMI, exercise, smoking status, and alcohol frequency included as time-dependent variables. Given the wide concentration variations among the components, results were reported based on one standard deviation (SD) increase in each pollutant or NDVI. Moreover, the effects of quartile exposures were estimated by categorizing pollutants and NDVI into quartiles based on their concentrations, with the first quartile serving as the reference group. To explore the exposure-response relationship between $PM_{2.5}$ components and NDVI and chronic non-communicable disease, we plotted exposure-response curves using a restricted cubic spline (RCS) function (Yan et al., 2022). In this model, we adjusted for the same covariates as in the main model and used the median pollutant concentration as the reference point. Optimal knot values for the curve were selected based on the Akaike information criterion (AIC) and the smoothness of the curve.

Quantile g-computation was also employed to investigate the relationship between joint exposure to $PM_{2.5}$ components and chronic non-communicable diseases, as well as to evaluate the relative contribution of each component. More broadly, g-computation serves as an effective framework for estimating the combined effects of exposure mixtures, particularly when these exposures change over time (Keil et al., 2014). This approach is commonly used in studies examining the effects of joint exposure to pollutants on health (Huang et al., 2023; Wen et al., 2023). Unlike conventional multi-pollutant models for weighted quantile sum (WQS) regression, this approach integrates its estimator and g calculations into an edge-structured model. This model can accommodate joint exposure nonlinearities, overcome unidirectional assumptions, is less affected by strong correlations among exposure substances, and facilitates the use of Cox proportional hazards modeling for event time analysis (Keil et al., 2020). The $PM_{2.5}$ component was incorporated into the multi-pollutant analytical model, with adjustments made for the same confounders as in the primary analysis.

In order to explore the joint effect between NDVI and $PM_{2.5}$ components, we divided $PM_{2.5}$, $PM_{2.5}$ components, and NDVI into two groups according to the median (high: >median and low: ≤median), resulting in four categorical variables: 1. High NDVI and Low pollutants; 2. Low NDVI and Low pollutants; 3. High NDVI and High pollutants; and 4. Low NDVI and High pollutants. Subsequently, we designated the first subgroup as the reference group and adjusted for the same covariates used in the main model. To explore susceptible populations, we performed stratified analyses for age (<60 years old vs. ≥60 years old), sex (male vs. female), and BMI (<24 $kg/m^2$ vs. ≥24 $kg/m^2$), and used multiplicative interactions to examine the effects of the various components on the at-risk population. Additionally, a series of sensitivity analyses were conducted to illustrate the stability of our results. First, we performed sensitivity analyses using multiple models for the above analysis, Crude model, adjusted for only pollutants or NDVI; Model 1, with additional adjustments for age, sex, and BMI; and Model 2 with additional adjustments for exercise level, smoking status, and alcohol frequency. Secondly, residual analyses were employed to investigate the independent effects of components on the results. This approach enabled us to estimate the effect of elevated constituents while controlling for other inorganic chemical components of $PM_{2.5}$ (Mostofsky et al., 2012). Third, in both cohorts, we added sugar addicts and salt addicts as covariates to the main model based on dietary risk factors for chronic non-communicable diseases. Fourth, the association between pollutants and NDVI and diabetes in the hypertension population was explored by us. Ultimately, we concluded the cohort study in 2019 to eliminate potential interference from COVID-19 and account for the steady decline in air pollution over recent years.

All statistical analyses were conducted in R v4.3.0 (R Development Core Team). A two-tailed $P$-value <0.05 was considered statistically significant.

## 3. Results

For the hypertension cohort, there were 41,070 participants, with 15,747 new cases and 241,528.73 person-years of follow-up. The average age at baseline was 64.19 ± 7.85 years, with 55.20 % of participants being female. For the diabetes cohort, there were 65,824 participants, with 8945 new cases and 479,971.09 person-years of follow-up. Subjects were, on average, 64.64 ± 7.84 years old at baseline, with 55.88 % being female. Table 1 presents baseline information. Fig. S1 illustrates the annual trends in mean exposure concentrations of $PM_{2.5}$ components and NDVI among participants from 2014 to 2021, showing a general decline in $PM_{2.5}$ and its components and a steady increase in NDVI over time. Table S1 describes the exposure levels of $PM_{2.5}$ components and NDVI for participants during the study period (2014–2021). The SD of $PM_{2.5}$ and its components ranged from 0.464 μg/$m^3$ to 15.034 μg/$m^3$, while the SD of NDVI was 0.045. Fig. S2 presents the Spearman correlation coefficients for annual mean concentrations of $PM_{2.5}$, its components, and NDVI during the follow-up period. The $PM_{2.5}$ components showed strong positive correlations with one another but were significantly negatively correlated with NDVI.

In the time-varying Cox model, consistent and positive associations were identified between $PM_{2.5}$ components and the incidence of chronic non-communicable diseases, while NDVI was negatively correlated

**Table 1**
Baseline characteristics of study population in hypertension and diabetes cohorts.

| Characteristics | Hypertension cohort ($n$ = 41,070) | Diabetes cohort ($n$ = 65,824) |
|---|---|---|
| Age (years) | 64.19 ± 7.85 | 64.64 ± 7.84 |
| Sex (%) | | |
| Male | 18,401 (44.80) | 29,041 (44.12) |
| Female | 22,669 (55.20) | 36,783 (55.88) |
| BMI (kg/m$^2$) | 24.42 ± 3.03 | 24.82 ± 3.16 |
| Exercise frequency | | |
| Never | 11,234 (27.35) | 15,832 (24.05) |
| Occasionally | 2346 (5.71) | 3517 (5.34) |
| Every week | 8495 (20.68) | 15,957 (24.24) |
| Every day | 18,995 (46.26) | 30,518 (46.37) |
| Smoking status (%) | | |
| Never | 32,222 (78.45) | 50,896 (77.32) |
| Former | 1240 (3.02) | 2363 (3.59) |
| Current | 7608 (18.53) | 12,565 (19.09) |
| Alcohol frequency (%) | | |
| Never | 35,339 (86.04) | 55,943 (84.99) |
| Occasionally | 2744 (6.68) | 4527 (6.88) |
| Frequently | 936 (2.28) | 1746 (2.65) |
| Every day | 2051 (5.0) | 3608 (5.48) |
| FBG (mmol/L) | 5.66 ± 1.40 | 5.44 ± 1.07 |
| SBP (mmHg) | 122.78 ± 11.87 | 126.95 ± 12.88 |
| DBP (mmHg) | 76.37 ± 6.57 | 78.09 ± 7.12 |
| New onsets (%) | 15,747 (38.34) | 8945 (13.59) |

**Abbreviation**: BMI, body mass index; FBG, fasting blood glucose; SBP, systolic blood pressure; DBP, diastolic blood pressure.

(Table 2). For example, each SD increase in OM was associated with a higher incidence of diabetes (HR: 1.484; 95 % CI: 1.453, 1.515) and hypertension (1.609; 1.583, 1.636). Similar significant effects were observed for other components. Each SD increase in NDVI was associated with a reduction in the incidence of diabetes (HR: 0.900; 95 % CI: 0.881, 0.919) and hypertension (0.866; 0.852, 0.880). Compared with the first exposure quartile, the HRs of diabetes incidence associated with the second to fourth exposure quartiles of OM were 1.399 (95 % CI: 1.297, 1.509), 2.538(95 % CI: 2.370, 2.717), and 2.929 (95 % CI: 2.738, 3.132), respectively. The same trend occurred in the hypertension cohort.

Fig. S3 illustrated the exposure-response relationship between $PM_{2.5}$ components and NDVI and chronic non-communicable diseases. We observed a positive, non-linear relationship between $PM_{2.5}$ components and chronic non-communicable diseases. In contrast, NDVI showed a negative correlation.

Table 3 demonstrated that joint exposure to six components had a relatively greater effect on the human body. The HRs for joint exposure to six components with hypertension and diabetes were 1.503 (95 % CI: 1.479, 1.527), and 1.456(95 % CI: 1.426, 1.487), respectively. OM was the primary detrimental factor, consistent across both the diabetes and hypertension cohorts (Fig. S4). In the joint exposure model of $PM_{2.5}$ components and NDVI, using the first group as the reference, the effect values for the second through fourth groups showed a gradual increase. This suggests that higher pollutant concentrations remain a primary risk factor for the increase in the incidence of chronic diseases, while increased green space may partially mitigate the adverse effects of pollutants (Figs. 2, 3).

The age-stratified results indicated that the $PM_{2.5}$ components had a more pronounced effect on the under-60 age group in both the hypertension and diabetes cohorts, whereas NDVI exhibited a more significant protective effect on the under-60 age group. $PM_{2.5}$ components were found to be more significant for individuals with a BMI $\geq$ 24 kg/m$^2$ only in the hypertensive cohort. NDVI was better able to protect the female population from hypertension (Fig. 4, Table S2). Additionally, we conducted a sensitivity analysis. Initially, we assessed the stability of our main model results using various models, which confirmed robustness (Table S3). Additionally, introducing residuals as independent variables yielded results indicating that the effects of BC, OM, and $NH_4^+$ were comparable to those observed in the main study, albeit with a slight reduction in effect size (Table S4). Similar effect sizes to the main model were observed after adjustment for dietary risk factors, and the effect sizes increased (Table S5). In the hypertensive population, associations consistent with the main analysis were obtained (Table S6). Our results remain robust after accounting for the exclusion of COVID-19 and air pollution trends, although the effect sizes are slightly reduced (Table S7).

**Table 2**
The associations of each standard deviation increase in $PM_{2.5}$, $PM_{2.5}$ components, and NDVI with hypertension and diabetes using a time-varying Cox model with adjustment.

| | HR (95 % CI) | | | | |
|---|---|---|---|---|---|
| | SD | Q1 | Q2 | Q3 | Q4 |
| Hypertension | | | | | |
| $PM_{2.5}$ | 1.550 (1.526, 1.575) | Reference | 1.740 (1.637, 1.849) | 3.472 (3.287, 3.669) | 3.659 (3.464, 3.866) |
| BC | 1.398 (1.377, 1.418) | Reference | 1.478 (1.396, 1.565) | 2.792 (2.652, 2.940) | 2.894 (2.749, 3.047) |
| OM | 1.609 (1.583, 1.636) | Reference | 1.815 (1.707, 1.931) | 3.700 (3.498, 3.914) | 3.878 (3.667, 4.101) |
| $NH_4^+$ | 1.594 (1.568, 1.621) | Reference | 1.704 (1.604, 1.810) | 3.455 (3.271, 3.650) | 3.612 (3.420, 3.815) |
| $NO_3^-$ | 1.465 (1.441, 1.488) | Reference | 1.588 (1.497, 1.685) | 3.190 (3.025, 3.365) | 3.302 (3.131, 3.482) |
| $SO_4^{2-}$ | 1.531 (1.508, 1.554) | Reference | 1.369 (1.290, 1.454) | 3.029 (2.874, 3.194) | 3.333 (3.164, 3.512) |
| $Cl^-$ | 1.311 (1.292, 1.331) | Reference | 2.122 (2.006, 2.245) | 3.041 (2.883, 3.207) | 2.921 (2.768, 3.082) |
| NDVI | 0.866 (0.852, 0.880) | Reference | 0.860 (0.826, 0.896) | 0.671 (0.642, 0.702) | 0.664 (0.636, 0.695) |
| Diabetes | | | | | |
| $PM_{2.5}$ | 1.459 (1.430, 1.489) | Reference | 1.330 (1.234, 1.434) | 2.429 (2.271, 2.598) | 2.818 (2.637, 3.011) |
| BC | 1.352 (1.326, 1.377) | Reference | 1.153 (1.074, 1.239) | 1.924 (1.804, 2.053) | 2.341 (2.199, 2.492) |
| OM | 1.484 (1.453, 1.515) | Reference | 1.399 (1.297, 1.509) | 2.538 (2.370, 2.717) | 2.929 (2.738, 3.132) |
| $NH_4^+$ | 1.478 (1.448, 1.509) | Reference | 1.296 (1.203, 1.397) | 2.361 (2.207, 2.525) | 2.762 (2.586, 2.950) |
| $NO_3^-$ | 1.421 (1.392, 1.450) | Reference | 1.372 (1.275, 1.476) | 2.224 (2.080, 2.378) | 2.655 (2.487, 2.834) |
| $SO_4^{2-}$ | 1.429 (1.402, 1.457) | Reference | 1.077 (1.000, 1.161) | 2.142 (2.007, 2.286) | 2.560 (2.403, 2.728) |
| $Cl^-$ | 1.332 (1.307, 1.357) | Reference | 1.586 (1.476, 1.704) | 2.199 (2.055, 2.354) | 2.673 (2.501, 2.856) |
| NDVI | 0.900 (0.881, 0.919) | Reference | 0.935 (0.884, 0.988) | 0.803 (0.758, 0.851) | 0.743 (0.700, 0.788) |

**Abbreviation**: SD: standard deviation; Q: quartile; HR: hazard ratios; $PM_{2.5}$: fine particulate matter; BC: black carbon; OM: organic matter; $NH_4^+$: ammonium salt; $NO_3^-$: nitrate; $SO_4^{2-}$: sulfate; $Cl^-$: chloride; NDVI: Normalized Difference Vegetation Index.
Adjusted for age, gender, BMI, exercise frequency, smoking status, and alcohol frequency.

**Table 3**
Adjusted hazard ratios (HRs) and 95 % confidence intervals (CIs) of hypertension and diabetes incidence associated with $PM_{2.5}$ components in a multi-pollutant model.

| Disease | $PM_{2.5}$ components | Proportion | HR (95%CI) | *p* |
|---|---|---|---|---|
| Hypertension | BC | −0.127 | 1.503 (1.479, 1.527) | <0.001 |
| | OM | 0.375 | | |
| | $NH_4^+$ | 0.285 | | |
| | $NO_3^-$ | 0.190 | | |
| | $SO_4^{2-}$ | 0.150 | | |
| | $Cl^-$ | −0.873 | | |
| Diabetes | BC | 0.027 | 1.456 (1.426, 1.487) | <0.001 |
| | OM | 0.566 | | |
| | $NH_4^+$ | 0.128 | | |
| | $NO_3^-$ | 0.085 | | |
| | $SO_4^{2-}$ | 0.194 | | |
| | $Cl^-$ | −1.000 | | |

**Abbreviation**: $PM_{2.5}$: fine particulate matter; BC: black carbon; OM: organic matter; $NH_4^+$: ammonium salt; $NO_3^-$: nitrate; $SO_4^{2-}$: sulfate; $Cl^-$: chloride.
Adjusted for age, gender, BMI, exercise frequency, smoking status, and alcohol frequency.

## 4. Discussion

In this population-based cohort study, which included 241,528.73 and 479,971.09 person-years of follow-up, we found that $PM_{2.5}$ and its components exhibited a stable positive correlation with the incidence of hypertension and diabetes, whereas NDVI showed a negative correlation. Among these, OM emerged as the major harmful $PM_{2.5}$ component, and joint exposure with green spaces significantly reduced the risk associated with $PM_{2.5}$ and its components. Notably, individuals under 60 years old, BMI $\geq$24 kg/m$^2$, and men appear more susceptible to the elevated risk of disease associated with $PM_{2.5}$ and its components.

As atmospheric pollution has become a major threat to human health, more studies have focused on the relationship between $PM_{2.5}$ and hypertension and diabetes. Previous cohort studies have shown that for each 10 μg/m$^3$ increase in $PM_{2.5}$ concentration, hazard ratios ranged from 1.04 to 1.20 for hypertension (Chen et al., 2014; Chen et al., 2023), and exhibited similar effects for diabetes (Chen et al., 2013; Yan et al., 2022). However, we observed higher effect values, likely due to the study population comprising middle-aged and older adults living in a region with elevated pollution levels. $PM_{2.5}$ consists of complex components from various sources, each posing distinct health risks. Effective control of $PM_{2.5}$ pollution at its source could yield substantial socio-economic benefits (Sun et al., 2024).

BC primarily originates from the combustion of solid fuels, shipping emissions, and industrial activities, with higher concentrations in densely populated areas (Wei et al., 2023b). OM can be secondary formed by the oxidation of volatile organic compounds (VOCs) and reactions that convert VOCs into low-vapor-pressure compounds, which condense on existing particles. OM can also be directly emitted from biogenic sources and combustion processes (Hao et al., 2023; Li et al., 2017). In eastern China, $SO_4^{2-}$ has the highest share in the inorganic constituents of $PM_{2.5}$, especially in areas with high temperatures and strong radiation from coal power plants (Li et al., 2017). $NO_3^-$ mainly comes from transportation and industrial emissions of nitrogen oxides, while $NH_4^+$ is derived from agricultural emissions of ammonia ($NH_3$) (An et al., 2019). $Cl^-$ is mainly concentrated in heavy industrial zones (Wei et al., 2023a).

Research into the influence of $PM_{2.5}$ components on hypertension incidence remains limited, with no consensus reached. Previous studies have shown that long-term exposure to $PM_{2.5}$ and its components leads to a significant increase in cardiovascular disease (CVD) morbidity and mortality (Bell et al., 2014; Chung et al., 2015; Kazemiparkouhi et al., 2022). Hypertension is the primary risk factor for CVD, and research on hypertension can help reduce the incidence of CVD (Roth et al., 2020). Previous cohort studies in China have demonstrated that long-term exposure to $PM_{2.5}$ and its components is associated with an increased incidence of hypertension (Fu et al., 2024; Wu et al., 2023). However, some studies have not found an association between OM and hypertension, possibly due to differences in concentration (Liu et al., 2021). Our study found that OM had the highest HR for hypertension. Differences in study results may be attributed to variations in $PM_{2.5}$ component concentration, outcome definitions, and populations in different regions and time periods (Arnett et al., 2016). Previous studies have demonstrated the protective effect of NDVI on hypertension (Yang et al., 2019; Zeng et al., 2024). However, most of these studies have focused solely on the impact of green space on hypertension.

Although research on the association between $PM_{2.5}$ and diabetes is growing, studies specifically examining $PM_{2.5}$ components and diabetes remain limited. Many studies in developing countries have observed similar trends to ours but have often relied on single models for their assessments, leading to inconsistent results. A study from the CHARLS cohort found a positive association between $PM_{2.5}$ and some of its components and diabetes, but no such difference was found for $SO_4^{2-}$ (Zhou et al., 2022). Similarly, research from the Jinchang cohort revealed that long-term exposure to $PM_{2.5}$ and its components was positively correlated with the incidence of diabetes, with BC contributing the most to the overall effect (Wang et al., 2024). Exposure to $PM_{2.5}$ and its components leads to increased diabetes mortality, according to a Danish cohort study (So et al., 2023). Another cross-sectional study in southwest China showed that long-term exposure to $PM_{2.5}$ and its components was positively associated with diabetes, with the highest effect sizes for OM (Li et al., 2023). However, the study could not explore the relationship between $PM_{2.5}$ and its components and the incidence of diabetes. We observed higher effect values compared to previous studies, possibly because our study area had higher pollution levels and our study population consisted predominantly of middle-aged and older adults. Previous cohort studies have shown that the degree of greenery around a home is negatively associated with the risk of dying from diabetes (Bereziartua et al., 2022; Rodriguez-Loureiro et al., 2022).

The relationship between $PM_{2.5}$ components and diabetes and hypertension remains incompletely understood. BC exposure has been linked to increased levels of TNF-α, inflammation, and impaired vasodilation, which are known to elevate blood pressure (Lei et al., 2019). Additionally, BC can contribute to the development of diabetes by inducing impaired β-cell function and insulin resistance (Apostolopoulou et al., 2018; Bourdon et al., 2012). Previous studies have indicated that exposure to OM is associated with endothelial dysfunction and may increase the risk of hypertension by raising sympathetic tone (McGraw et al., 2021). Exposure to OM was positively associated with inflammation and biomarkers of platelet activation, suggesting that OM exposure induces systemic inflammation (Li et al., 2023). Exposure to $SO_4^{2-}$, $NH_4^+$, and $NO_3^-$ activates the hypothalamic-pituitary-adrenal (HPA) axis, and the normal function of the HPA axis and the resulting glucocorticoids play an important role in the development of hypertension and diabetes (Arnett et al., 2016). $SO_4^{2-}$ creates an acidic environment that promotes the solubility and bioavailability of metals in $PM_{2.5}$. This process can lead to the generation of reactive oxygen species, which may increase the risk of diabetes by promoting insulin resistance (Houstis et al., 2006), and hypertension by causing oxidative stress in different organs (Griendling et al., 2021). Although green spaces do not contribute to $PM_{2.5}$ emissions or directly reduce $PM_{2.5}$ concentrations, they can have an indirect effect by adsorbing and blocking $PM_{2.5}$ particles (Jeanjean et al., 2016). Green spaces can filter air pollutants through two possible mechanisms: one involves biological interactions within the plant itself, and the other operates through aerodynamic effects (Ji et al., 2020).

In previous studies, exposure-response curves for $PM_{2.5}$ and its components and hypertension or diabetes were similarly found to be nonlinear (Fu et al., 2024; Wu et al., 2023). It is critical to recognize the effects of area selection, individual precautions in high-concentration

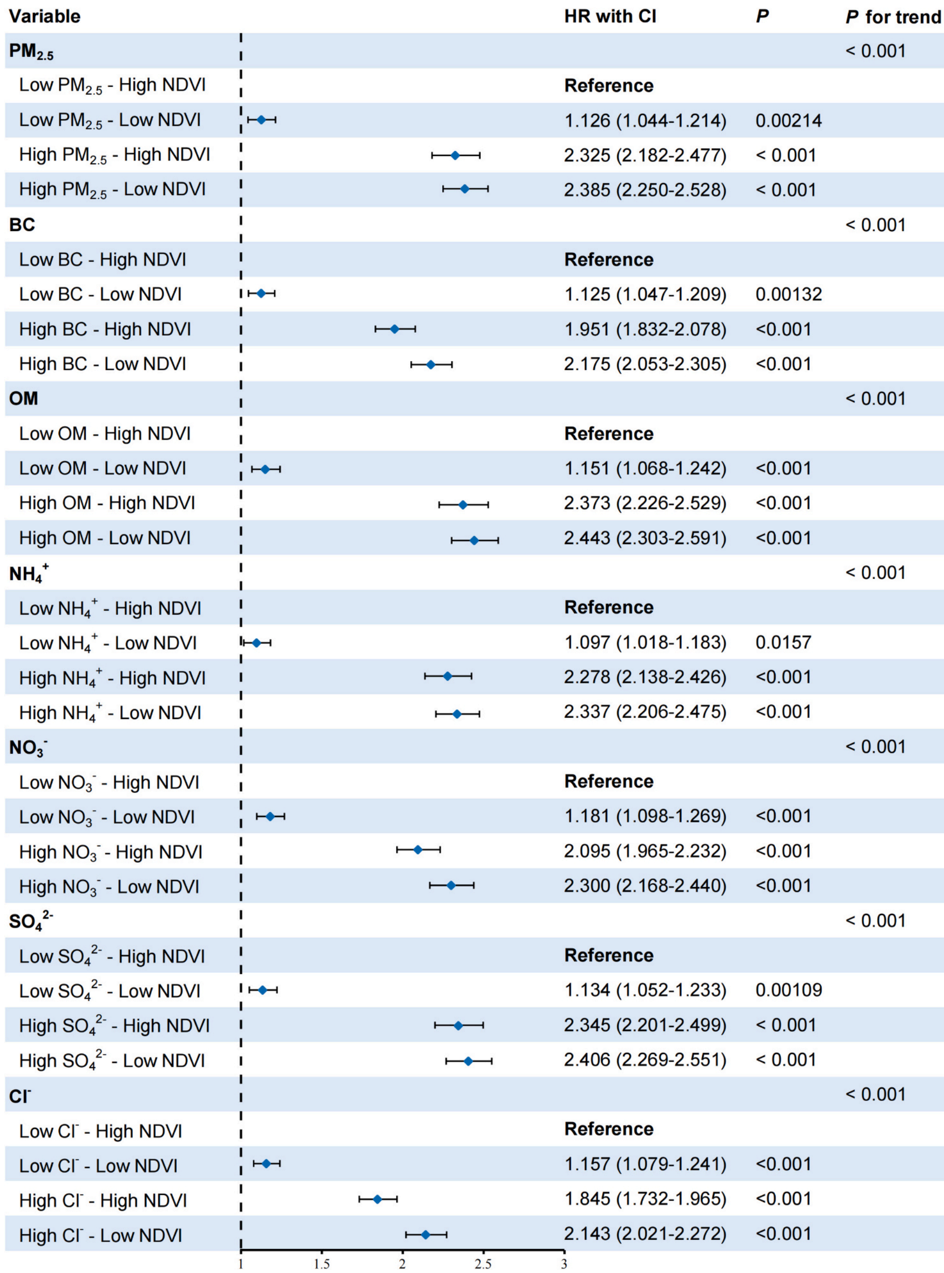


**Fig. 2.** The joint associations of NDVI and exposure to $PM_{2.5}$ and its components on diabetes. Pollutants and NDVI were divided into high and low concentration groups (denoted as High and Low in the figure) based on their medians. Subsequently, four groups were formed by pairing pollutants and NDVI in pairs following the initial grouping. Comparing these groups with low pollutant concentration and high NDVI as the reference, it was observed that the other combinations exhibited a more pronounced hazardous effect, indicating that NDVI offers a degree of protective effect when exposed to pollutants and NDVI concurrently.

**Abbreviation**: HR: hazard ratios; $PM_{2.5}$: fine particulate matter; BC: black carbon; OM: organic matter; $NH_4^+$: ammonium salt; $NO_3^-$: nitrate; $SO_4^{2-}$: sulfate; $Cl^-$: chloride.

Adjusted for age, gender, BMI, exercise frequency, smoking status, and alcohol frequency.

environments, and differences in the size of population samples exposed to different constituent concentrations. Stratification and interaction analyses were applied to identify sensitive subgroups. $PM_{2.5}$ and its components had a slightly stronger effect on males compared to females in both hypertension and diabetes. Previous studies have also reached similar conclusions to ours (Lv et al., 2023). This difference is attributed to males generally having unhealthier lifestyles, including smoking and alcohol abuse, which may lead to greater exposure to $PM_{2.5}$ components. Additionally, males were more likely to work outdoors and drive, further increasing their exposure to $PM_{2.5}$ and its components (Liu et al., 2021). The effects of $PM_{2.5}$ and its components on both diabetes and hypertension were more pronounced in individuals younger than 60 years old. Previous studies have reported similar findings (Shan et al., 2020). Older adults are less responsive to stimulation of the sympathetic and autonomic nervous systems than younger adults. Additionally, younger individuals are more susceptible to chronic disease risk factors such as environmental stress and unhealthy lifestyles. The effect of BMI on the two diseases was inconsistent. Individuals with a BMI $\geq 24$ kg/m$^2$ had a higher risk of developing hypertension (Chen et al., 2014). While the opposite was true for those with diabetes, the differences between the groups were not statistically significant.

Our study has several key strengths: First, it is based on an 8-year prospective cohort, providing a robust foundation for exploring the relationships between $PM_{2.5}$, its components, NDVI, and their joint effects

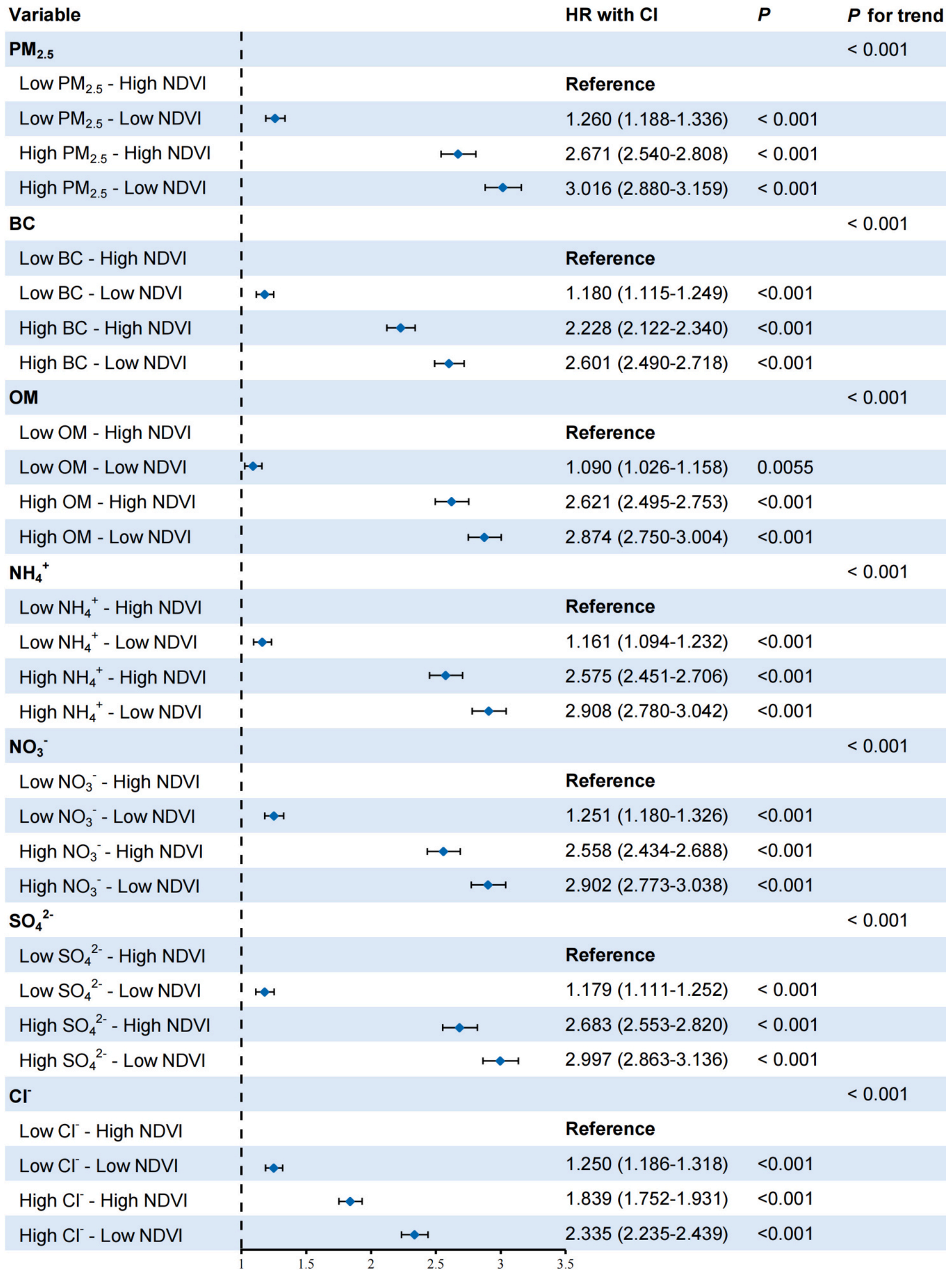


**Fig. 3.** The joint associations of NDVI and exposure to $PM_{2.5}$ and its components on hypertension. Pollutants and NDVI were divided into high and low concentration groups (denoted as High and Low in the figure) based on their medians. Subsequently, four groups were formed by pairing pollutants and NDVI in pairs following the initial grouping. Comparing these groups with low pollutant concentration and high NDVI as the reference, it was observed that the other combinations exhibited a more pronounced hazardous effect, indicating that NDVI offers a degree of protective effect when exposed to pollutants and NDVI concurrently.
**Abbreviation**: HR: hazard ratios; $PM_{2.5}$: fine particulate matter; BC: black carbon; OM: organic matter; $NH_4^+$: ammonium salt; $NO_3^-$: nitrate; $SO_4^{2-}$: sulfate; $Cl^-$: chloride.
Adjusted for age, gender, BMI, exercise frequency, smoking status, and alcohol frequency.

on the prevalence of chronic non-communicable diseases among middle-aged and older adults in Tianjin, China. Second, we used the quantile g-computation model to identify OM as the most impactful component on diabetes and hypertension incidence and found that NDVI can mitigate the hazardous effects of $PM_{2.5}$ and its components through joint exposure. Finally, we screened for sensitive populations, providing valuable insights into improving the protective measures for these vulnerable groups.

Despite its strengths, our study has several limitations. First of all, the decreasing pollution levels over the study period in China, coupled with improvements in medical care and heightened awareness of protective measures, may have introduced bias into our effect estimates. However, we used a time-varying Cox model to account for these changes as much as possible, addressing the reduction in pollution concentration alongside the improvements in treatment. Secondly, diagnostic reports of time of onset can produce recall bias; however, this bias was mitigated by the annual follow-up of subjects, ensuring that recall was only required for the past year. Finally, we did not adjust for temperature and humidity in the model because of the scale of the study area.

## 5. Conclusions

In conclusion, our study demonstrates a consistent positive association between $PM_{2.5}$ and its components with hypertension and diabetes.

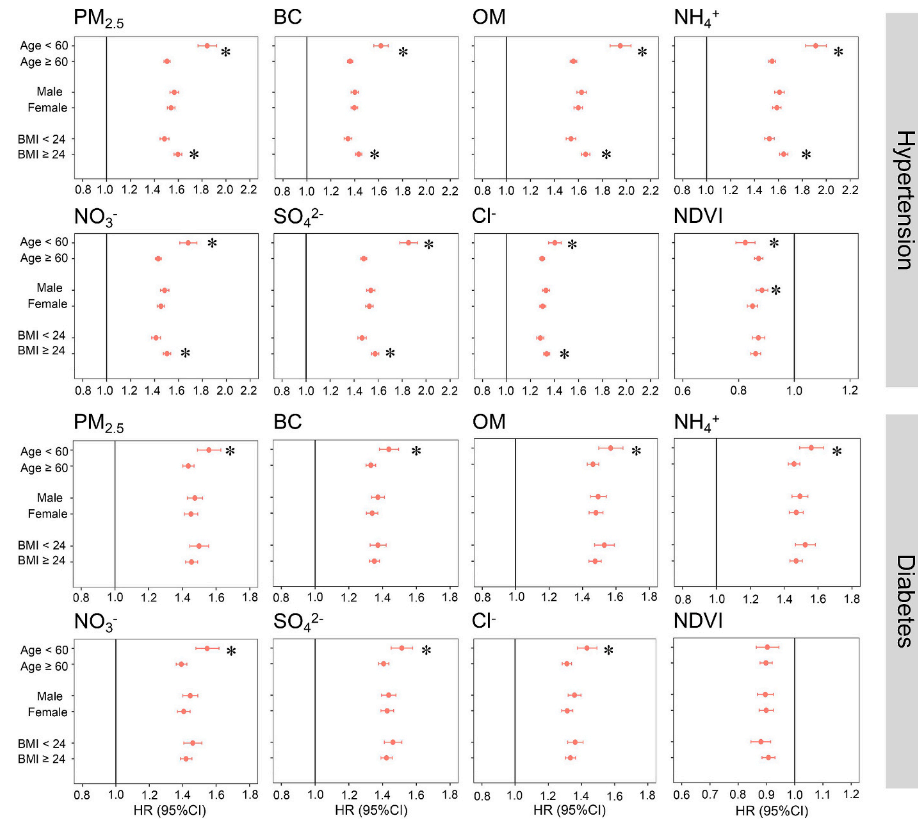


**Fig. 4.** Association of per standard deviation increase in $PM_{2.5}$ and $PM_{2.5}$ components with incidence hypertension and diabetes, stratified by age, gender, and BMI. Sensitive populations were investigated using stratified analyses and multiplicative interaction assessments. The results revealed heightened susceptibility among individuals <60 years old to $PM_{2.5}$ and its components, evident in both hypertensive and diabetic cohorts. Furthermore, within the hypertensive cohort, individuals with a BMI $\geq$24 kg/m$^2$ exhibited greater susceptibility, potentially exacerbating hypertension onset.
**Abbreviation**: HR: hazard ratios; $PM_{2.5}$: fine particulate matter; BC: black carbon; OM: organic matter; $NH_4^+$: ammonium salt; $NO_3^-$: nitrate; $SO_4^{2-}$: sulfate; Cl-: chloride.
Adjusted for age, gender, BMI, exercise frequency, smoking status, and alcohol frequency.
*Interaction is statistically significant ($P < 0.05$).

Among these components, OM was identified as having the greatest impact, highlighting the importance of targeted control measures for better health and economic efficiency, especially for middle-aged and older adults. Furthermore, increasing green spaces and reducing $PM_{2.5}$ pollution were found to offer additional protective benefits. These findings provide valuable insights into how various $PM_{2.5}$ components affect chronic non-communicable diseases, contributing to the government's more effective public health strategies.

## CRediT authorship contribution statement

**Hongyue Sun:** Writing – original draft, Methodology, Formal analysis, Data curation. **Chengjie Pan:** Writing – original draft, Visualization, Methodology, Formal analysis. **Mengfan Yan:** Methodology, Data curation. **Zhongli Wang:** Methodology. **Jiayu He:** Methodology. **Honglu Zhang:** Software, Methodology. **Ze Yang:** Methodology. **Zinuo Wang:** Methodology. **Yiqing Wang:** Data curation, Conceptualization. **Hongyan Liu:** Supervision, Methodology. **Xueli Yang:** Supervision, Methodology. **Fang Hou:** Methodology. **Jing Wei:** Resources, Data curation. **Pei Yu:** Resources, Project administration, Funding acquisition, Data curation. **Xi Chen:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Nai-Jun Tang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.


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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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Dr. Chen and Dr. Yu had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Designed the study: Chen, Yu, Tang.

Acquisition, analysis, or interpretation of data: Sun, Pan, Wang, Wei.

Drafting of the manuscript: Sun, Pan.

Critical revision of the manuscript for important intellectual content: All authors.

Statistical analysis: Sun, Pan.
Obtained funding: Tang, Yu, Chen.
Administrative, technical, or material support: Chen, Tang, Yu.
Supervision: Chen, Yu, Tang.

## Appendix A. Supplementary data

Concentration parameters of pollutants and NDVI; results for the constituent residual model; results of stratified analysis; sensitivity analysis findings; inclusion and exclusion criteria for participants; correlation among pollutants; results of RCS models graphs depicting pollutant weights. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.178219.

## Data availability

Data will be made available on request.

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