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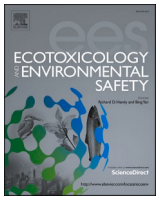

Long-term effects of particulate matter on incident cardiovascular diseases in middle-aged and elder adults: The CHARLS cohort study

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ABSTRACT

Background: Although there is evidence of long-term effects of particulate matter (PM) on cardiovascular diseases (CVD), researches about long-term effects of PM_1 on CVD are limited. We aimed to examine the long-term effects and magnitude of PM, especially PM_1, on incident CVD in China.

Methods: We included 6016 participants aged ≥ 45 years without CVD at baseline in 2011 from the China Health and Retirement Longitudinal Study. Personal PM (PM_1, $PM_{2.5}$, and PM_{10}) concentrations were estimated using geocoded residential address. Generalized linear mixed models and SHapley Additive exPlanation were utilized to calculate the impacts and contributions of PM on CVD. Sensitivity analyses were used to check the robustness.

Results: After a follow up of 4-year, 481 (7.99 %) participants developed CVD. Per 10 μg/m^3 uptick in 1-year average concentrations of PM_1, $PM_{2.5}$ and PM_{10} was associated with a 1.20 [95 % confidence interval (*CI*): 1.05–1.37], 1.13 (95 % *CI*: 1.11–1.15), and 1.10 (95 % *CI*: 1.06–1.13) fold risk of incident CVD, respectively. The 2-year average concentrations of PM_1, $PM_{2.5}$ and PM_{10} were associated with incident CVD, corresponding to a 1.03 (95 % *CI*: 0.96–1.10), 1.11 (95 % *CI*: 1.02–1.21), and 1.09 (95 % *CI*: 1.03–1.15) fold risk, respectively. The SHapley Additive exPlanation values of PM_1, $PM_{2.5}$, and PM_{10} were 0.170, 0.153, and 0.053, respectively, corresponding to the first, second, and fifth among all air pollutants. Effects of PM_1, $PM_{2.5}$ and PM_{10} on CVD remained statistically significant in two-pollutant models. The elderly, males, smokers and alcohol drinkers tended to have slightly higher effects, while the differences were not statistically significant (all *P*-values > 0.05) between subgroups.

Conclusion: Long-term exposure to PM_1, $PM_{2.5}$, and PM_{10} was associated with an increased incidence of CVD. The smaller the particle size, the more important it was for incident CVD indicating that emphasis should be placed on small size of PM.

1. Introduction

Cardiovascular diseases (CVD) are a general term for conditions that affect the heart or blood vessels (Virani et al., 2021). As a major cause of morbidity worldwide, there are 330 million patients with CVD worldwide in 2020 (Disease, 2021). Bearing the largest disease burden, CVD remains the leading cause of premature death in China, responsible for 40 % of deaths (Zheng et al., 2022). Identifying modifiable risk factors for CVD is important to provide evidence for preventive strategies to diminish the disease-related burden (Liu et al., 2021a; Zhang et al., 2022).

Due to the rapidly growing economies, excessive coal combustion and vehicle emission contributed to the severe air pollution in China, which may lead to more potential health problems (Maji et al., 2020; Zhu et al., 2022). It is properly established that ambient air pollution is associated with CVD (de Bont et al., 2022; Li et al., 2022). As one of the

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major pollutants, experimental studies indicated that ambient PM may induce systemic inflammation and oxidative reaction, leading to endothelial cell apoptosis and dysfunction, thereby entailing CVD (Bhatnagar, 2022; Hahad et al., 2023; Tumolo et al., 2022; Yu et al., 2022). Short-term exposure to particulate matter (PM) has been connected with an increased risk of CVD (Wang et al., 2020; Zhou et al., 2021). However, relatively few cohort surveys have examined the impact of PM on CVD, particularly in higher levels countries (Du et al., 2021). Moreover, as the particle size of PM gets smaller, the larger the surface area, the more toxic substances are attached, which indicates that particulate matter with an aerodynamic diameter $\leq$ 1.0 μm (PM_1) may have a greater effect on CVD (Xu et al., 2022). Yang et al. found the effect of PM_1 on CVD was greater than $PM_{2.5}$ (OR: 1.11 vs. 1.07) (Yang et al., 2019).

Epidemiological investigations have reported the impacts of PM on CVD, but due to the high correlation, it is impossible to rashly compare the magnitude of effect values to determine the importance (Kim et al., 2021). Reportedly, the SHapley Additive exPlanation (SHAP) can compare the importance of variables on outcomes regardless of multicollinearity (Martinot et al., 2022). Meanwhile, emerging studies showed that household air pollution raised the danger of incident CVD (Kazemiparkouhi et al., 2022; Pan et al., 2021). However, rare studies have reported the relationship between long-term exposure to PM and incident CVD while adjusting for household air pollution including PM, formaldehyde, carbon dioxide, carbon monoxide, total volatile organic compounds, methane, etc. (Hystad et al., 2020; Qin et al., 2023; Tian et al., 2022), particularly in developing countries (Dagenais et al., 2020; Guo et al., 2022; Zhou et al., 2022).

The aim of this study was to assess the long-term PM impacts and compare the magnitude of PM impacts on incident CVD using a generalized linear mixed model and SHAP method based on the China Health and Retirement Longitudinal Study (CHARLS). We also adjusted household air pollution including cooking and heating fuels.

2. Materials and methods

2.1. Study population

The CHARLS is a longitudinal, biennial survey with inhabitants aged $\geq$ 45 years in China. It aims at establishing qualitative communal microinformation on socioeconomic conditions to health status. The details of the CHARLS have been described elsewhere (Shi et al., 2018; Zhao et al., 2014). In short, it is based on a random four-stage stratified cluster sampling, and participants aged 45 or over are enrolled from 450 communities at 150 county-level units in 28 provinces of China (Yao et al., 2021).

In this cohort study, we used the data in 2011 as the baseline and follow-up data in 2015 to identify the outcome based on CHARLS. We included all participants between 2011 and 2015 except for individuals with missing information. Then, 540 (8.2 %) participants suffering from CVD in 2011 were further excluded. The remaining number of eligible participants was 6016 (Fig. S1).

The informed consent form was signed by each participant in this study before being investigated. The CHARLS was approved by the Ethics Committee of Peking University (IRB00001052-11015).

2.2. Air pollution estimates

In the current study, the daily data at 1-km resolution were obtained from the ChinaHighAirPollutants (CHAP) dataset (https://weijing-rs.github.io/product.html). This dataset was generated using a combination of emission inventories, atmospheric reanalysis, and remote sensing compared with ground-based observations, constructed by a spatiotemporal extremely randomized trees model (Wei et al., 2019; Wei et al., 2022a; Wei et al., 2021a; Wei et al., 2021b; Wei et al., 2022b). The accuracies (cross-validation coefficient of determination, CV-R^2 = 0.86–0.90) and predictive powers (R^2 = 0.80–0.82) of the PM modelings were higher than previously reported. Long-term exposure to PM was reflected by previous 1-and 2-year (2013, 2014) averaged daily concentrations. But due to the missing data on PM_1 concentration in 2013, we used PM_1 concentrations during 2014 and 2015 as 2-year exposure. Each individual was assigned PM [PM_1, particulate matter with an aerodynamic diameter $\leq$ 2.5 μm ($PM_{2.5}$), particulate matter with an aerodynamic diameter $\leq$ 10 μm (PM_{10})] and gas air pollutants [nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3)] based on the corresponding county-level geocoding of their home address.

2.3. Assessment of outcomes

The incidence of CVD events was defined by self-report, as the positive answer to the question of whether they had a cardiac (including coronary heart disease, heart attack, congestive heart failure, angina, and other heart problems) or stroke event diagnosed by doctors (Shi et al., 2021). We used the positive response in 2015 as our endpoint.

2.4. Covariates

Potential covariates included sex, age ($\leq$65 or >65 years old), education (highest education attained: primary school and below or junior high school and higher), marital status (married or spinsterhood), socioeconomic status, smoking status (never, ever smoker or current smoker), alcohol drinking status (never, $\leq$1 time per month or >1 time per month), type of cooking fuel (solid or clean), type of heating fuel (solid or clean), depression, and night sleeping in our study. Depression status was assessed by the 10-question scale of the Center for Epidemiologic Studies Depression. Clean energy sources were defined as liquefied petroleum gas, electricity, methane gas, and natural gas. Crop residues and coal were solid fuels. The covariates adjusted in the model were decided by the directed acyclic graph, which was generated by the DAGitty (http://www.dagitty.net/) (Fig. S2) (Luo et al., 2022).

2.5. Statistical analysis

The generalized linear mixed model was utilized to estimate the association between PM and CVD. The chi-square test, Wilcoxon rank-sum test, and *t*-test were employed for characteristics discrepancy of baseline participants, and the association between PM and gas pollutants was calculated by spearman rank correlation.

Only PM was placed in Model 1. Meanwhile, cooking and heating adjustments were performed in Model 2. In Model 3, age and gender were further controlled for analysis. Finally, education, smoking, marital, drinking, depression, socioeconomic status, and night sleeping were additionally adjusted in Model 4, which was regarded as the final model of this research.

For the event that occurred during the study, the average levels of each air pollutant were calculated for the previous 1-, and 2-year (Cramer et al., 2020). We explored potentially effective corrections by performing a stratified analysis and identified features that may be more vulnerable to PM. In the sensitivity analysis, to detect the robustness of effects, the exposed PM was considered as a dichotomous variable and the findings of single-pollutant models were compared with two-pollutant models (Wang et al., 2021). Association estimates were presented as odds ratio (OR) with the 95 % confidence intervals (95 % *CI*) per 10 μg/m^3 uptick in the concentration of PM (Cao et al., 2020).

SHAP value was utilized to assess the importance of each PM on CVD, which was based on the eXtreme Gradient Boosting method (Wang et al., 2022b; Zhou et al., 2019). The SHAP assists in distinguishing the impacts of features, by showing the extent to which features changed the prediction (Balbino et al., 2022). The SHAP method allowed us to describe the importance of different factors for the outcome (as CVD in this study) (Martinot et al., 2022). In this study, we compared the SHAP

value of each PM, which was averaged by the absolute value generated from the model containing PM (PM_1, $PM_{2.5}$, and PM_{10}), gas air pollutants (NO_2, SO_2, CO, and O_3) and confounding variables simultaneously. A positive SHAP value means that PM has a positive effect on CVD, while a negative value means a negative effect. And the larger the value, the greater the effect.

R software version 4.0.2 (The R Foundation, Boston, MA) was used for data analysis, in which a $P < 0.05$ for a two-tailed test was considered statistically significant.

3. Results

3.1. Baseline characteristics

In the study, a total of 6016 participants were enrolled. After a follow-up of 4 years, 481 (7.99 %) participants developed CVD (Table 1). Compared to participants without CVD, patients with CVD tended to be the elderly, smokers, drinkers, and with more severe depression.

The annual average concentrations of PM_1, $PM_{2.5}$, PM_{10}, SO_2, and O_3 varied with medians (interquartile range, IQR) of 37.86 (17.09) μg/m^3, 65.44 (30.99) μg/m^3, 108.06 (55.96) μg/m^3, 32.18 (24.20) μg/m^3, and 84.46 (14.50) μg/m^3, respectively (Table S1). The coefficients of spearman correlation for air pollutants were distributed from 0.08 to 0.94 (Fig. S3).

Table 1
Demographic characteristics of participants included in this study from CHARLS (n = 6016).

Variables	Total (n = 6016)	Non-CVD (n = 5535)	CVD (n = 481)	*P*-value
Age (years), median (IQR)	57 (13)	56 (13)	59 (13)	**<0.001**
Sex: *n* (%)				**0.005**
Male	3086 (51.30)	2869 (51.83)	217 (45.11)	
Female	2930 (48.70)	2666 (48.17)	264 (54.89)	
Depression, median (IQR)	16 (7)	16 (7)	17 (9)	**<0.001**
Night sleeping (h), median (IQR)	7 (2)	7 (2)	7 (3)	0.362
Smoking status: *n* (%)				**0.023**
Never	3515 (58.42)	3219 (58.16)	295 (61.46)	
Ever smoker	433 (7.20)	389 (6.90)	44 (6.47)	
Current smoker	2068 (34.40)	1927 (34.94)	141 (32.07)	
Alcohol drinking: *n* (%)				**0.002**
Never	3854 (64.06)	3506 (63.39)	343 (71.46)	
≤1 time per month	488 (8.11)	459 (8.30)	29 (6.04)	
>1 time per month	1674 (27.83)	1566 (28.31)	108 (22.50)	
Education level: *n* (%)				0.099
Primary school and below	1484 (24.67)	1345 (24.33)	132 (27.50)	
Junior high school and higher	4532 (75.33)	4183 (75.67)	348 (72.50)	
Marital status				0.105
Spinsterhood	541 (8.99)	488 (8.81)	53 (11.02)	
Married	5475 (91.01)	5047 (91.19)	428 (88.98)	
Cooking fuel				0.355
Solid	2743 (45.60)	3021 (54.58)	252 (52.39)	
Clean	3273 (54.40)	2514 (45.42)	229 (47.61)	
Heating fuel				0.060
Solid	4776 (79.39)	4377 (79.08)	399 (82.95)	
Clean	1240 (20.61)	1158 (20.92)	82 (17.05)	

Notes: CVD, cardiovascular disease; *n*, number; IQR, interquartile range. $P <$ 0.05 are indicated in bold.

3.2. Long-term effects

The long-term effects of PMs on CVD were shown in Table 2. Per 10 μg/m^3 increase in the 1-year concentration of PM_1 was associated with a 1.20 (95 % *CI*: 1.07–1.35) fold risk of incident CVD in the crude model, which remained robust with OR of 1.20 (95 % *CI*: 1.05–1.37) after adjustment for covariates in Model 4. However, no significant impact of PM_1 2-year concentrations on CVD was found.

Per 10 μg/m^3 increment in 1- and 2-year average $PM_{2.5}$ corresponded to a 1.12 (95 % *CI*: 1.10–1.13) and 1.10 (95 % *CI*: 1.05–1.15) risk of CVD in crude models. The estimates were attenuated by adjusting for cooking and heating fuels in Model 2 [1.11 (95 % *CI*: 1.06–1.17), 1.09 (95 % *CI*: 1.01–1.18)]. These associations remained robust [1.13 (95 % *CI*: 1.11–1.15), 1.11 (95 % *CI*: 1.02–1.21)] between incident CVD and $PM_{2.5}$ in Model 4.

Similar trends were observed per 10 μg/m^3 increase in 1- and 2-year average concentration of PM_{10}, with OR of 1.10 (95 % *CI*: 1.06–1.13) and 1.09 (95 % *CI*: 1.03–1.15), respectively, in Model 4.

However, we failed to observe the impact of solid fuel use on incident CVD, regardless of crude or adjusted model, with the OR of 1.33 (95 % *CI*: 0.88–2.01) and 1.06 (95 % *CI*: 0.67–1.68), respectively.

3.3. Contributions of PM on incident CVD

The PM importance ranking plot obtained by the mean absolute SHAP values were shown in Fig. 1. The mean absolute SHAP values of PM_1, $PM_{2.5}$, and PM_{10} were, respectively, 0.170, 0.153, and 0.053, corresponding to the first, second, and fifth among all air pollutants.

3.4. Sensitivity analyses

The relationship between PM_1 and CVD remained consistent after adjusting for SO_2, O_3, and CO (Table 3). Changes occurred to PM_1 when further adjusted for NO_2, but the impact kept significant with the OR of 1.32 (95 % *CI*: 1.19–1.46). Similar patterns were observed for the association between $PM_{2.5}$ and PM_{10} with incident CVD. Fig. 2 showed the significant relationships between $PM_{2.5}$ and incident CVD in demographic characteristics, health behaviors, and type of fuel subgroups. However, the differences between subgroups of age, cooking, education, gender, and heating were not statistically significant. Significantly higher impacts of $PM_{2.5}$ and PM_{10} with high-level (≥15 μg/m^3 and ≥45 μg/m^3) on CVD were observed [2.37 (95 % *CI*: 1.29–4.36) and 2.59 (95 % *CI*: 1.42–4.72)] (Table 4).

4. Discussion

A longitudinal study was performed to assess the long-term impacts of PM on incident CVD in middle-aged and elder adults. Significantly positive associations were observed between PM (PM_1, $PM_{2.5}$, and PM_{10}) and incident CVD at the 1-year lag. The effect sizes slightly decreased after adjusting for household air pollution, including fuel type of cooking and heating. The SHAP values were higher when the particle size was smaller, indicating that PM_1 was more important for incident CVD. These associations with PM attenuated but remained statistically significant after adjusting for O_3 and CO.

Notably, we look at the association between PM_1 and PM_{10} with CVD in our study as well. Some studies have suggested that oxidative stress and inflammation may be responsible, in part, for PM-related CVD impacts (Bhatnagar, 2022; Riggs et al., 2020). There are some hypotheses proposed, which has been proven by experiments (Bhatnagar, 2022; Yu et al., 2022). PM-induced inflammation can be triggered by themselves or damage-associated molecular patterns, which are generated by tissue damage induced by reactive oxygen species (Zindel and Kubes, 2020). When inflammation leads to cell damage or apoptosis, redox reactions are likewise triggered to eliminate harmful substances, thus evoking oxidative stress. When PM carrying toxic substances is inhaled, undergo

Table 2
Long term effect of particle matter (per 10 μg/m^3) on incident CVD in CHARLS.

Pollutants	OR (95 % CI)			
	Model 1[a]	Model 2[b]	Model 3[c]	Model 4[d]
1-year				
PM_1	**1.20 (1.07, 1.35)**	**1.19 (1.06, 1.34)**	**1.20 (1.06, 1.35)**	**1.20 (1.05, 1.37)**
$PM_{2.5}$	**1.12 (1.10, 1.13)**	**1.11 (1.06, 1.17)**	**1.12 (1.07, 1.18)**	**1.13 (1.11, 1.15)**
PM_{10}	**1.09 (1.06, 1.12)**	**1.09 (1.05, 1.12)**	**1.10 (1.06, 1.13)**	**1.10 (1.06, 1.13)**
2-year				
PM_1	1.01 (0.95, 1.09)	1.01 (0.95, 1.98)	1.02 (0.95, 1.10)	1.03 (0.96, 1,10)
$PM_{2.5}$	**1.10 (1.05, 1.15)**	**1.09 (1.01, 1.18)**	**1.10 (1.02, 1.18)**	**1.11 (1.02, 1.21)**
PM_{10}	**1.10 (1.05, 1.15)**	**1.08 (1.03, 1.13)**	**1.09 (1.03, 1.14)**	**1.09 (1.03, 1.15)**

Notes: $P < 0.05$ are indicated in bold.
Abbreviations: OR, odds ratio; confidence interval, CI; PM_1, particles with aerodynamic diameter ≤ 1.0 μm; $PM_{2.5}$, particles with an aerodynamic diameter ≤ 2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤ 10.0 μm.
[a] Model 1 was unadjusted.
[b] Model 2 was adjusted for cooking and heating fuel.
[c] Model 3 was adjusted for cooking, heating fuel, age and sex.
[d] Model 4 was adjusted for cooking, heating fuel, age, sex, depression, night sleeping, smoking status, alcohol drinking, education level, marital and socioeconomic status.

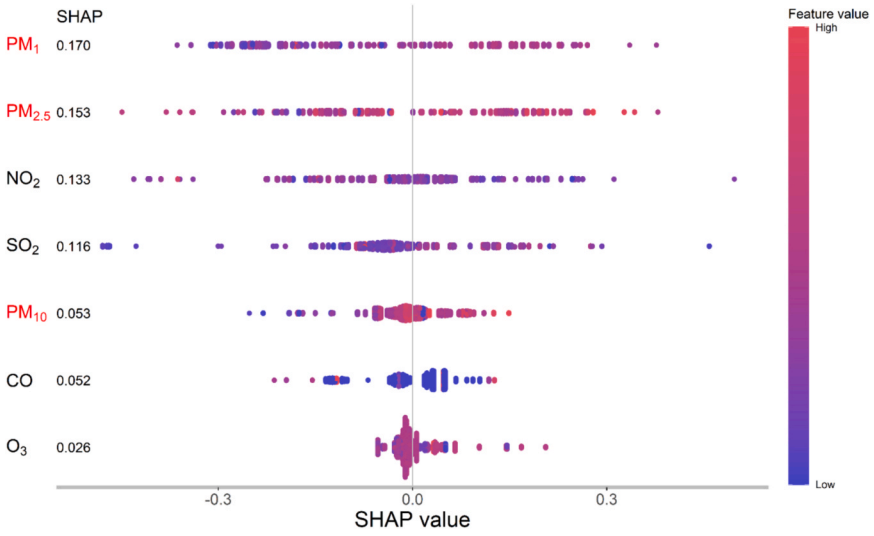

Fig. 1. Contribution of ambient PM on incident CVD ranked by SHAP value. Note: The plots showed how the value of ambient air pollutants impacted the predicted CVD. Each dot represented the prediction from the model, and the coded colors indicated the value of incident CVD. The second column in plot was the mean absolute SHAP values of each air pollutants. The model contained PM (PM_1, $PM_{2.5}$, and PM_{10}), gas air pollutants (NO_2, SO_2, CO, and O_3), cooking, heating fuel, age, sex, depression, night sleeping, smoking status, alcohol drinking, education level, marital and socioeconomic status simultaneously. Abbreviations: PM_1, particles with aerodynamic diameter ≤ 1.0 μm; $PM_{2.5}$, particles with an aerodynamic diameter ≤ 2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤ 10.0 μm; SO_2, sulfur dioxide; O_3, ozone; NO_2, nitrogen dioxide; CO, carbon monoxide; CVD: cardiovascular diseases; SHAP: SHapley Additive exPlanation.

Table 3
Odds ratio of incident CVD associated with each 10 μg/m^3 increment in concentrations of PM.

Air pollutants	OR (95 % CI)	
	1-year average	2-year average
PM_1	**1.20 (1.05, 1.37)**	1.03 (0.96, 1.10)
$PM_1 + SO_2$	**1.24 (1.12, 1.36)**	0.89 (0.79, 1.00)
$PM_1 + O_3$	**1.17 (1.15, 1.20)**	1.00 (0.93, 1.08)
$PM_1 + NO_2$	**1.32 (1.19, 1.46)**	0.92 (0.79, 1.08)
$PM_1 + CO$	**1.19 (1.10, 1.29)**	**1.15 (1.04, 1.27)**
$PM_{2.5}$	**1.13 (1.11, 1.15)**	**1.11 (1.02, 1.21)**
$PM_{2.5} + SO_2$	**1.16 (1.14, 1.18)**	**1.16 (1.03, 1.30)**
$PM_{2.5} + O_3$	**1.11 (1.05, 1.18)**	**1.13 (1.03, 1.24)**
$PM_{2.5} + NO_2$	**1.21 (1.12, 1.31)**	**1.19 (1.05, 1.35)**
$PM_{2.5} + CO$	**1.12 (1.10, 1.14)**	**1.10 (1.01, 1.20)**
PM_{10}	**1.10 (1.06, 1.13)**	**1.09 (1.05, 1.13)**
$PM_{10} + SO_2$	**1.12 (1.07, 1.16)**	**1.14 (1.06, 1.23)**
$PM_{10} + O_3$	**1.09 (1.05, 1.13)**	**1.11 (1.04, 1.17)**
$PM_{10} + NO_2$	**1.12 (1.08, 1.17)**	**1.14 (1.05, 1.23)**
$PM_{10} + CO$	**1.09 (1.03, 1.16)**	**1.09 (1.03, 1.15)**

Notes: Bolded are $P < 0.05$.
Abbreviations: PM_1, particles with aerodynamic diameter ≤ 1.0 μm; $PM_{2.5}$, particles with an aerodynamic diameter ≤ 2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤ 10.0 μm; SO_2, sulfur dioxide; O_3, ozone; NO_2, nitrogen dioxide; CO, carbon monoxide.

redox reaction to consume cellular thiols and activate lymphocytes to produce reactive oxygen (Haberzettl et al., 2018; Miller et al., 2017). To eliminate reactive oxygen, antioxidant enzymes are cellularly overexpressed, which can lead to endothelial cell apoptosis and dysfunction, thereby leading CVD (Hahad et al., 2023; Riggs et al., 2021). Moreover, the smaller particle size enables PM_1 to increase the level of inflammatory cytokine, blood clotting, and vasoconstrictor factors (Chen et al., 2015), which promote oxygen stress and the development of CVD.

As we all know, rare research assessed the link between PM_1 and CVD. We found two relevant researches, one study in Jiangsu province identified that short-term exposure to PM_1 was related to a significant increase in mortality from CVD, especially among older adults (Xu et al., 2022), and another study found that long-term exposure to PM_1 had a significant relation to CVD in Liaoning province, particularly in the elderly and males (Yang et al., 2019). This is consistent with our findings, which provide further support because of the national data used in this study.

Long-term exposure to $PM_{2.5}$ was associated with incident CVD, which is roughly in compliance with previous research (Liang et al., 2020; Wang et al., 2022a), which reported that $PM_{2.5}$ could result in an increased threat to CVD in China. Meanwhile, another study based on CHARLS find the same tendency (Mai et al., 2022). In addition, the literature found that the impacts of $PM_{2.5}$ on CVD in China varied from

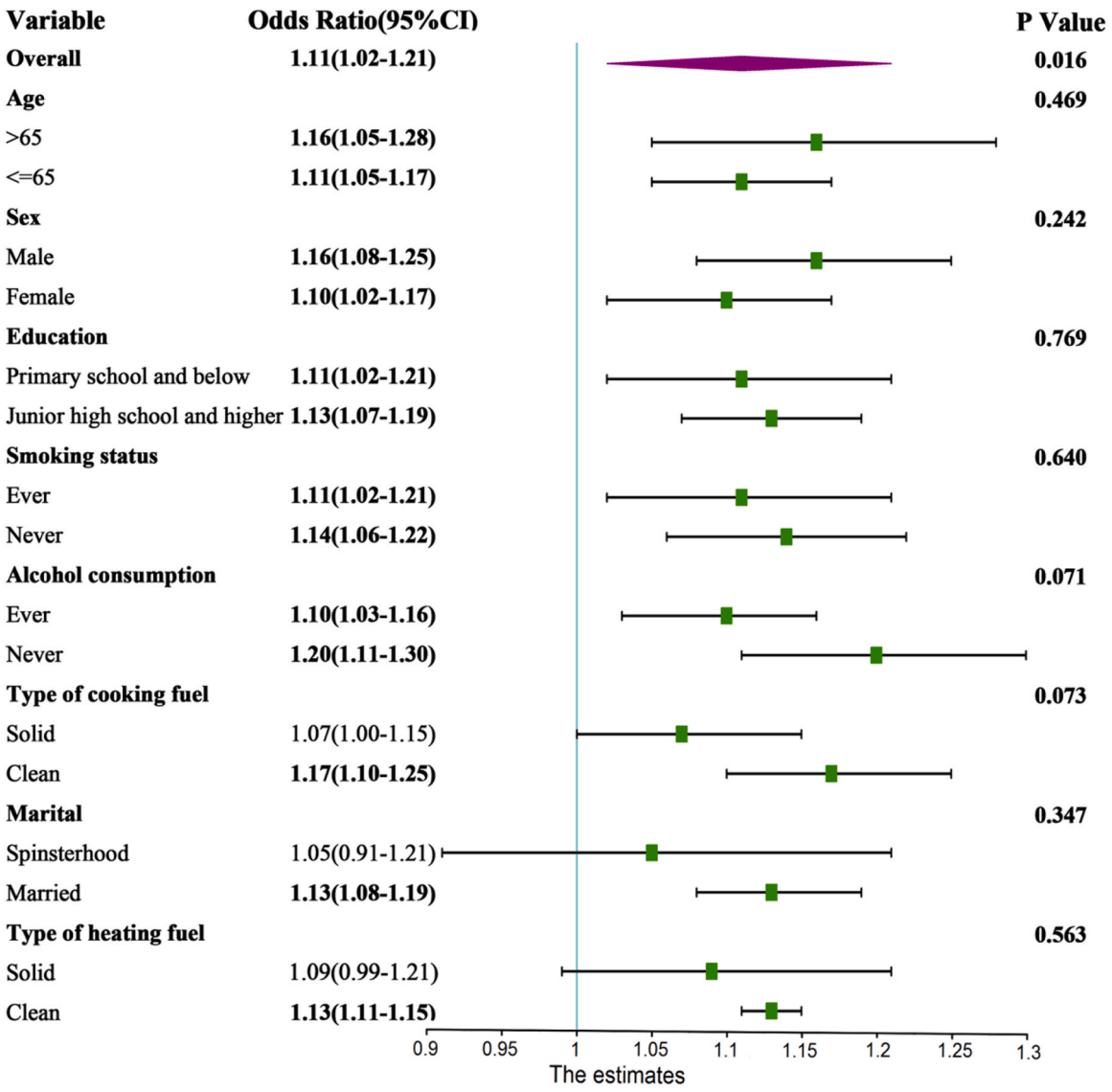

Fig. 2. Associations between annual averages of ambient $PM_{2.5}$ and risk of CVD stratified by potential effect modifications.

0.24 % to 6.11 % (Jaganathan et al., 2019). The heterogeneity of results may lie in the variation in components or period of pollutants, as well as covariates adjusted in models, like life behaviors.

Subgroup analysis showed that male participants had a higher propensity to develop PM-related CVD than females, in line with the findings reported in America (Kazemiparkouhi et al., 2022). This may be related to the pathophysiology that endothelial progenitor cells in the sex stratification respond differently to PM. A study showed that exposure to PM diminished the number of endothelial progenitor cells in males, while there was little effect on endothelial progenitor cells in females due to estrogen. (Liu et al., 2021b). The higher propensity to develop PM-related CVD of male may be also related to the more outdoor activities. This proposed mechanism may be consistent with the gender difference observed in our study. However, Heo et al. found that the prognostic impacts of $PM_{2.5}$ for CVD differed little in the gender stratification (Heo et al., 2022).

Although the exact mechanisms behind $PM_{2.5}$-CVD are unclear, plausible pathways are proposed in biology. Exposure to $PM_{2.5}$ was associated with major atherosclerotic processes (oxidative stress, inflammation, endothelial dysfunction, and thrombosis (Lederer et al., 2021). In addition, available literature indicated that $PM_{2.5}$ might perturb the autonomic nervous system resulting in an elevated threat of CVD (Zhang et al., 2020). There are scarce studies focusing on the pathogenic mechanisms of PM_1. Nevertheless, compared to $PM_{2.5}$, the surface area of PM_1 is larger and it is more likely to infiltrate into the alveoli, resulting in more harmful effects. Specifically, a study reported that 77.01 % of $PM_{2.5}$ were trusted in the upper respiratory tract, while 65.46 % of PM_1 were in the human alveoli (Goel et al., 2018).

There are several strengths. First, we assessed effects of PM_1 on CVD in middle-aged and elderly people in China. Second, we assessed the magnitude of PM_1, $PM_{2.5}$, and PM_{10} on incident CVD, indicating that the smaller the particle size, the more important it was for incident CVD. Third, we adjusted cooking and heating fuels as indicators to manipulate the impacts of household pollution (Adekoya et al., 2022). Fourth, the population in this research was focused on residents aged 45 or over, which were also the high-risk population for cardiovascular disease occurrence (Jalali et al., 2021; Yang et al., 2019).

Several limitations should be considered. First, the PM_1 concentration of 2013 was missing, we substituted two years (2014, 2015) PM_1 concentration for it. Second, people exposed to ambient air different from their home addresses for a long time may inevitably result in higher spatial misclassification. And the outcome of CVD was purely based on self-report, which might also lead to misclassification. The inclusion of only living followers into the study also influenced the effects

Table 4
Odds ratio for associated between particular matters and CVD.

Type of variable	PM	Odds ratio (95 % CI)	
		Crude model[a]	Main model[b]
Continuous (per 10 μg/m^3)	$PM_{2.5}$	**1.10 (1.05, 1.15)**	**1.09 (1.03, 1.15)**
	PM_{10}	**1.10 (1.05, 1.15)**	**1.09 (1.03, 1.15)**
Dichotomized[c]	$PM_{2.5}$ (μg/m^3)		
	< 15	Ref.	Ref.
	≥ 15	**2.13 (1.25, 3.64)**	**2.37 (1.29, 4.36)**
	PM_{10} (μg/m^3)		
	< 45	Ref.	Ref.
	≥ 45	**2.34 (1.38, 3.97)**	**2.59 (1.42, 4.72)**

Notes: $P < 0.05$ are indicated in bold.
Abbreviations: $PM_{2.5}$, particles with an aerodynamic diameter ≤ 2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤ 10.0 μm.
[a] Crude model was single pollutant model.
[b] Main model was additionally adjusted for age, sex, depression, night sleeping, smoking status, alcohol drinking, education level, marital, cooking fuel, heating fuel and socioeconomic status.
[c] The criteria for converting $PM_{2.5}$ and PM_{10} to categorical variables were the air quality standards of World Health Organization in 2021.

(Krittanawong et al., 2023). The small sample size of incident cases may attentuate the statistical power. Third, even though there were many covariates gathered to adjust for confounders, unmeasured confounders still existed, leading to bias, which made confounding facts. Fourth, the exposure of individuals to pollutants was potentially deviated because of the physicochemical transformation of the atmosphere and the uneven distribution of emission sources.

5. Conclusion

Long-term exposure to PM_1, $PM_{2.5}$, and PM_{10} may be potential risk factors for CVD. The smaller the particle size, the more important it was for incident CVD. In addition, $PM_{2.5}$ was still risky for CVD in sensitivity analyses. In general, the results contribute to the findings on the long-term impacts of PM on CVD in countries with high levels of air pollution.

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CRediT authorship contribution statement

Shiyun Lv: Writing- Reviewing & Editing, Software, Visualization. **Yadi Shi:** Data curation, Methodology, Writing- Original Draft. **Yongxi Xue:** Methodology, Software, Writing- Reviewing & Editing. **Yaoyu Hu:** Methodology, Software. **Meiling Hu:** Software, Methodology, Data curation. **Shuting Li:** Methodology, Software. **Wenhan Xie:** Methodology. **Yuan Li:** Data curation. **Yixin Ouyang:** Data curation. **Zhiwei Li:** Data curation, Software. **Mengmeng Liu:** Data curation. **Jing Wei:** Data curation, Resources. **Xiuhua Guo:** Conceptualization, Resources, Supervision. **Xiangtong Liu:** Conceptualization, Funding acquisition, Supervision, Writing- Reviewing & Editing.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2023.115181.

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