Interaction between plant-based dietary pattern and air pollution on cognitive function: a prospective cohort analysis of Chinese older adults

Anna Zhu,[a,b] Hui Chen,[c] Jie Shen,[c] Xiaoxi Wang,[d] Zhihui Li,[e] Ai Zhao,[e] Xiaoming Shi,[f] Lijing Yan,[g] Yi Zeng,[h,i] Changzheng Yuan,[c,j] and John S. Ji[e,]**

[a]Division of Clinical Epidemiology and Aging Research, German Cancer Research Center (DKFZ), Heidelberg, Germany
[b]Medical Faculty Heidelberg, Heidelberg University, Heidelberg, Germany
[c]School of Public Health, Zhejiang University School of Medicine, Zhejiang, China
[d]China Academy for Rural Development, Zhejiang University, Hangzhou, China
[e]Vanke School of Public Health, Tsinghua University, Beijing, China
[f]National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China
[g]Global Health Research Center, Duke Kunshan University, Kunshan, China
[h]Center for the Study of Aging and Human Development, Duke Medical School, Durham, NC, USA
[i]Center for Healthy Aging and Development Studies, National School of Development, Peking University, Beijing, China
[j]Department of Nutrition, Harvard T.H. Chan School of Public Health, Boston, Massachusetts, US

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Summary

Background Air pollution is a risk factor for poor cognitive function, while a plant-based dietary pattern is associated with better cognitive function. We aimed to explore their interaction with cognitive function among older adults.

Methods We used a prospective cohort of old individuals, including 6525 participants of the Chinese Longitudinal Healthy Longevity Survey (CLHLS), aged 65-110 years and with normal cognition at baseline. Air pollution measurement was derived using satellite-derived annual average fine particulate matter ($PM_{2.5}$) concentrations based on residential locations. Plant-based diet index (PDI) was calculated using survey responses to assess the dietary pattern. Repeated measures of the Mini-Mental State Examination (MMSE) were utilized to assess cognitive function. We applied the Cox proportional hazard regression to explore the associations and further stratified the analysis by PDI.

Findings During a median of 5·6-year follow-up, 1537 (23·6%) out of 6525 participants with normal cognition at baseline developed poor cognitive function (MMSE <18). Living in areas with the highest quintile of cumulative $PM_{2.5}$ was associated with a 46% increase in the risk of developing poor cognitive function (hazard ratio (HR): 1·46, 95% confidence interval (CI): 1·20, 1·77), compared to those living in areas with the lowest quintile. We observed a significant interaction between cumulative $PM_{2.5}$ and PDI (p-interaction: 0·04), with the corresponding associations of cumulative $PM_{2.5}$ being more pronounced among participants with lower PDI (HR: 1·68, 95% CI: 1·26, 2·24) than those with higher PDI (HR: 1·28, 95% CI: 0·98, 1·68).

Interpretation Plant-based dietary pattern may attenuate detrimental impacts of $PM_{2.5}$ on cognitive function among older adults. Adherence to the plant-based dietary pattern could be used to prevent adverse neurological effects caused by air pollution, especially in developing regions.

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Keywords: Cognitive function; Air pollution; Plant-based dietary pattern; Healthy longevity

Background

Incidences of dementia are growing worldwide because of increased life expectancy, with 50 million dementia cases and counting. The case number is projected to increase to 152 million by 2050. A recent 2020 *Lancet Commission on dementia prevention, intervention, and care* identified air pollution as one of 12 modifiable risk factors that could prevent or delay dementia.[1] Estimates on

*Co-corresponding Authors: John S. Ji, Vanke School of Public Health, Tsinghua University, Changzheng Yuan, School of Public Health, Zhejiang University School of Medicine.
E-mail addresses: chy478@zju.edu.cn (C. Yuan), johnji@tsinghua.edu.cn (J.S. Ji).

Research in context

Evidence before this study

We searched PubMed, Web of Science, and Google Scholar for the studies on air pollution, plant-based dietary patterns, and cognitive function, published in English up to September 1st, 2021. We used a combination of search terms, including "air pollution", "fine particulate matter", "$PM_{2.5}$", "plant-based dietary pattern", "cognition", and "cognitive function". We found consistent evidence on higher levels of air pollution and worse cognitive function from numerous observational studies in different places such as North America, Europe, and Asia. Adherence to the plant-based dietary pattern was associated with better cognitive function, observed in most observational studies. There was only one published abstract of a doctoral dissertation on Mediterranean-like diet, air pollution, and cognitive function. This cross-sectional study of women aged 54-55 years old from Germany reported that those with a lower Mediterranean diet score were more vulnerable to cognitive decline induced by air pollution, although the interaction between air pollution and the Mediterranean diet was not significant.

Added value of this study

To the best of our knowledge, this is the first epidemiological study exploring the interaction between air pollution and plant-based dietary pattern on cognitive function among older adults with normal cognition. Our study found that the effects of long-term exposure to $PM_{2.5}$ on the risks of developing poor cognitive function were stronger among older adults with lower adherence to the plant-based dietary pattern, compared to those with higher adherence.

Implications of all the available evidence

Our findings suggest higher adherence to the plant-based dietary pattern may be beneficial to poor cognitive function induced by long-term $PM_{2.5}$ exposure. Promoting the plant-based dietary pattern may be a strategy to reduce the effects of $PM_{2.5}$ on neurological health.

the contribution of air pollution on dementia are rapidly emerging, although it is not yet formally recognized as a risk factor outcome pair in the Global Burden of Disease Study, or the new WHO Air Quality Guideline 2021. However, estimates suggest about 2·1 million incident dementia cases could be attributable to ambient exposure to fine particulate matter ($PM_{2.5}$) pollution in 2015.[2] Air pollutants could directly elicit inflammatory changes and oxidative stress in the brain and increase the risk of cardiometabolic diseases, ultimately increasing the risks of dementia and cognitive decline.[3]

Plant foods, such as vegetables and fruits, often rich in nutrients including polyphenols, flavonoids, antioxidant vitamins, could reduce inflammation and oxidative stress in the central nervous system.[4-7] Evolving evidence showed that the plant-based dietary pattern might be associated with better neurological health.[8,9] The Singapore Chinese Health Study of 16,948 men and women reported that plant-based dietary patterns in middle life were associated with lower risks of cognitive impairment in late life.[10] Another cohort of 12,062 participants from Taiwan found that vegetarians had a 38% lower risk of dementia compared with non-vegetarians.[11] Nutritional solution or intervention for air pollution induced cardiopulmonary was introduced in several studies. These findings suggested plant-based food with higher antioxidants could reduce oxidative stress and inflammation in cardiovascular disease and other chronic inflammatory diseases induced by air pollution.[12-14] Currently, no studies have looked at the plant-based dietary pattern and the association between air pollution and cognitive decline.

Given the positive association between plant-based dietary patterns and cognitive function and the opposite association of air pollution and cognitive function, it is plausible to hypothesize that it may modify the association between air pollution and cognitive function. Our study aimed to test this hypothesis and add additional dimensions to food, air pollution, and dementia.

Methods

Study population

Initiated in 1998, the CLHLS aimed to study determinants of healthy longevity. The CLHLS has a nationally representative sample, with participants recruited from 22 provinces in China. The CLHLS applied a multistage, stratified cluster sampling in 631 randomly selected cities and counties where the Han Chinese are the largest majority. These sample sites represent about 85% of the Chinese population. A more detailed description of the sampling design can be found elsewhere.[15]

Our study used the 2008 wave of the CLHLS. We excluded participants who were younger than 65 years old since age group of 65 and over had a vast majority of dementia cases, had missing values in the dietary pattern (less than 2%) and covariates, and with poor cognitive function at baseline (Mini-Mental State Examination (MMSE) <18). In total, 6525 participants were included in the analysis. More details on participant inclusion and exclusion can be found in Figure S1.

$PM_{2.5}$ exposure assessment

Based on participants' residential addresses, we calculated the ground-level concentrations of $PM_{2.5}$ from the Atmospheric Composition Analysis Group. It combined

the remote sensing from National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer, Multiangle Imaging SpectroRadiometer, and Sea-viewing Wide Field-of-view Sensor satellite instruments, vertical profiles derived from the GEOS-Chem chemical transport model, and calibration to ground-based observations of $PM_{2.5}$ using geographically weighted regression.[16] We calculated annual $PM_{2.5}$ from 1998 to 2014, at 1 km² spatial resolution, which was the longest and the highest resolution exposure dataset available in China.[17] Additionally, our estimations were highly consistent with cross-validated concentrations from monitors (R^2=0·81) and another exposure dataset (R^2=0·81) in China.[16,17]

We calculated two exposure measures to reflect long-term exposure for each participant. We averaged the estimated $PM_{2.5}$ concentrations from recruitment to a diagnosis of poor cognitive function (MMSE <18), death, loss to follow-up, or the end of follow-up (September 2014) to indicate cumulative exposure. We also averaged the estimated exposures for three years prior to a diagnosis of poor cognitive function, death, loss to follow-up, or the end of follow-up (September 2014) to indicate 3-year average exposure, which suggested recent accumulated exposure levels.

Cognitive function assessment

We used the Mini-Mental State Examination (MMSE) to measure cognitive function, adapted to the Chinese language. The MMSE in the CLHLS has been validated for reliability in prior findings.[18,19] The reliability of the MMSE scale is high (Cronbach's a=0·96).[20] MMSE assesses cognitive function in five dimensions, including orientation, registration, attention and calculation, recall, and language.[21] We scored each question as zero (wrong or unable to answer) or one (correct),[22] and the score ranged from 0 to 30. Higher scores indicated better cognitive function.[23] We defined MMSE scores to ≥18 as normal cognitive function and <18 as poor cognitive function. This cut-off point was typically used in other prior research studies.[19,23,24] We also used the MMSE score as a continuous variable in a secondary analysis.

Dietary assessment

We evaluated the plant-based dietary pattern by constructing the plant-based diet index (PDI), an adapted approach used by Satija et al.[25] We included 16 food groups for the assessment, using dietary data collected by a simplified food frequency questionnaire. The included food groups covered the most common food consumed in the daily diet in China. The plant food included whole/refined grain, vegetable oil, fresh fruit, fresh vegetable, legume, garlic, nut, tea, salt-preserved vegetable, and sugar. The animal food included animal fat, dairy product, egg, fish, and meat.

We scored the PDI according to intake frequency. Although servings or quintiles of intake are commonly used, using a non-quantitative food frequency questionnaire to assess dietary patterns has been demonstrated to be reliable and valid in some studies.[26-28] In addition, previous studies also showed that frequency of intake is more important than portion size to distinguish between high and low consumption of fruits and vegetables.[29] The CLHLS recorded the intake frequency as "almost everyday" or "≥1 time/week" or "≥1 time/month" or "occasionally" or "rarely or never" for most food groups, including legume, garlic, nut, tea, salt-preserved vegetables, sugar, eggs, fish, meat, and dairy products. The CLHLS recorded the intake frequency of fruits and fresh vegetables as "almost everyday" or "quite often" or "occasionally" or "rarely or never". We scored 5 for the most frequent consumption, and 1 for the least frequent consumption of plant food (positive scores). We scored 1 for the most frequent consumption, and 5 for the least frequent consumption of animal food (reverse scores). We scored 5 for the consumption of whole grain, vegetable oil, and refined grain, and scored 1 for the consumption of animal fat. More details on constructing and scoring PDI can be found in Table S1. PDI score ranges from 16 to 80 theoretically. Higher PDI scores indicated more frequent consumption of plant food. We first ranked the PDI scores of all participants and then divided them into two half according the median level. Those with lower half scores were defined as lower PDI. Those with higher half scores were defined as higher PDI.

Covariates

We assessed demographic characteristics, socioeconomic status, health behaviour, and health status. The covariates included age (years), sex (male or female), urban/rural residence, education (with or without formal education), main occupation before age 60 (professional work like professional and technical personnel, government, and management or non-professional work like agriculture, fishing, service, industry, and housework), financial status (financial independence or dependence), regular exercise (yes or no), and geographic regions (Central China, Eastern China, Northeastern China, Northern China, Northwestern China, Southern China, Southwestern China). We calculated the social and leisure activity index by taking into consideration seven activities: gardening, personal outdoor activities (like square dancing and Tai Chi), raising poultry or pets, reading, playing cards or *mah-jong*, listening to the radio or watching TV, and participating in organized social activities.[30] Each activity was scored as zero (no) or one (yes), and the index ranged from zero to seven. We defined never smokers as those who neither smoked in the past nor at the time of the interview, former smokers as those who smoked in the past but

not at the time of the interview, and current smokers as those who smoked at the time of interview. We defined never, former, and current drinkers using a similar evaluation.

Statistical analysis

We summarized the baseline characteristics using descriptive statistics. We used the Cox proportional hazard regression to calculate the hazard ratios (HRs) and 95% confidence intervals (CIs) for the association between long-term $PM_{2.5}$ exposure and risks of developing poor cognitive function (MMSE <18) during the follow-up. We stratified the analysis by PDI scores and individual food groups. We plotted the stratified analysis to see whether the associations differed by PDI. We also plotted three knots cubic splines to explore non-linearity between $PM_{2.5}$ exposure and risks of developing poor cognitive function. Wald test was used to assess whether the observed relationships were linear or nonlinear. We further stratified the associations of $PM_{2.5}$ exposure, PDI, and cognitive function by sex. The regression models were multivariable-adjusted for age, sex, urban/rural residence, education, main occupation before age 60, financial status, social and leisure activity, smoking and drinking status, regular exercise, and geographic regions. We conducted extra sensitivity analysis to explore the potential bias. Given the relatively old age among our participants, there may be bias caused by competing risk from death. Therefore, we applied the competing risk model as a sensitivity analysis. In addition, we conducted another sensitivity analysis to have the regression models additionally adjusted for intake of vitamin A/C/E supplements, body mass index (BMI), and health status of five cardiometabolic diseases (hypertension, diabetes, heart disease, cerebrovascular disease, and dyslipidemia). Cardiometabolic diseases were the risk factors of poor cognitive function.[31] We also updated the regressional models by adjusting for baseline MMSE score. Furthermore, we applied MMSE scores as a continuous variable in the generalized estimating equation model to look at changes in the score as an outcome variable. Since education could significantly influence MMSE score, we applied education-specific cut-off points to categorize MMSE score.[10] Specifically, we used the MMSE score of 18, 20, and 24 as the cut-off points for the participants without formal education, primary school education (1-6 years), and secondary school or higher education (>6 years), respectively. Lastly, we examined the associations between $PM_{2.5}$ exposure, PDI, and changes in cognitive function by using ordinary logistic regression. All statistical analysis was conducted by using R software (version: 3·6·2, R Core Team, R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was defined by $p<0.05$ in two-sided testing.

Ethical approval

The study protocol was approved by the Institutional Review Board, Duke University (Pro00062871), and the Biomedical Ethics Committee, Peking University (IRB00001052-13074). Paper-based informed consent was signed and collected from all participants.

Role of the funding sources

The funders of the study had no role in study design; collection, analysis, and interpretation of data; or manuscript drafting. The corresponding author had full access to the data and had full responsibility for the final submission of the manuscript.

Results

Table 1 presented the baseline characteristics of 6525 CLHLS participants with normal cognitive function at baseline. Their mean age was 81 (standard deviation (SD): 10·8) years old, 50·8% were females, 17·2% were urban residents, and 48·0% had formal education. About 21·8% and 20·7% were current smokers and drinkers. Mean BMI was 20·9 (SD: 3·5) kg/m^2. Cumulative $PM_{2.5}$ during the follow-up period ranged from 9 to 106 $\mu g/m^3$, and the mean value was 49·3 $\mu g/m^3$. The mean PDI was 49·6. PDI score was slightly higher among the participants living in the areas with a higher level of $PM_{2.5}$. There were no distinguished changes in participants' characteristics during the follow-up surveys (see Table S2).

Table 2, Figure 1, and Figure 2 showed the risks of developing poor cognitive function under long-term $PM_{2.5}$ exposure. During a median of 5·6-year follow-up, 1537 (23·6%) participants with normal cognition at baseline developed poor cognitive function. Living in the areas with the highest quintile of cumulative $PM_{2.5}$ (range: 62-106 $\mu g/m^3$) was associated with a 46% increase in the risk of developing poor cognitive function (HR_{Q5vsQ1} for cumulative $PM_{2.5}$: 1·46, 95% CI: 1·20, 1·77), compared to those living in the areas with the lowest quintile (range: 9-38 $\mu g/m^3$). Per 10 $\mu g/m^3$ increase in cumulative $PM_{2.5}$ was related to a 10% increase in the risk of developing poor cognitive function (HR for cumulative $PM_{2.5}$: 1·10, 95% CI: 1·04, 1·15). Their associations were non-linear (Figure 2, $p<0.001$). We also observed a significant interaction between cumulative $PM_{2.5}$ and PDI (p-value of interaction: 0·04), with the corresponding associations of cumulative $PM_{2.5}$ being much more pronounced among participants with lower PDI (HR_{Q5vsQ1}=1·68, 95% CI: 1·26, 2·24), compared to those with higher PDI (HR_{Q5vsQ1}=1·28, 95% CI: 0·98, 1·68). Similar associations and the significant modification by the plant-based dietary pattern were also observed for 3-year average $PM_{2.5}$. The results of the main analysis were consistent with the results of sensitivity analysis by adjusting for

Characteristics	Total	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5	p-value
N	6525	1305	1305	1305	1305	1305	
Cumulative $PM_{2.5}$ ($\mu g/m^3$)*	49·3 (13·8)	31·0 (6·4)	41·2 (1·9)	48·8 (2·4)	56·8 (2·9)	69·0 (7·0)	<0·001
PDI score*	49·6 (6·1)	47·3 (6·9)	47·8 (6·0)	50·4 (5·5)	51·5 (5·3)	51·3 (5·1)	<0·001
PDI score (range)	25-70	25-67	26-64	32-70	28-68	35-66	
Age, years*	80·8 (10·8)	81.4 (10·1)	81·9 (10·0)	79·6 (9·6)	80·1 (9·8)	80·8 (10·7)	<0·001
Sex, females	3317 (50·8)	656 (50·2)	681 (52·2)	640 (49·0)	655 (50·2)	685 (52·5)	0·338
Urban residence	1125 (17·2)	117 (9·0)	124 (9·5)	302 (23·1)	271 (20·8)	311 (23·8)	<0.001
With formal education	3132 (48·0)	573 (43·9)	679 (52·0)	689 (52·8)	629 (48·2)	562 (43·1)	<0·001
With professional work	578 (8·9)	107 (8·2)	91 (7·0)	112 (8·6)	122 (9·3)	146 (11·2)	0·003
Financial independence	2296 (35·2)	376 (28·8)	360 (27·6)	503 (38·5)	535 (41·0)	522 (40·0)	<0·001
Social and leisure activity index*	2.7 (1·4)	2.8 (1·5)	2.7 (1·4)	2.8 (1·4)	2.7 (1·5)	2.6 (1·5)	0·027
With regular exercise	2318 (35·5)	464 (35·6)	477 (36·6)	497 (38·1)	400 (30·7)	480 (36·8)	0·001
Smoking status							<0·001
Never smoker	4070 (62·4)	877 (67·2)	882 (67·6)	721 (55·2)	807 (61·8)	783 (60·0)	
Former smoker	1031 (15·8)	203 (15·6)	165 (12·6)	245 (18·8)	190 (14·6)	228 (17·5)	
Current smoker	1424 (21·8)	225 (17·2)	258 (19·8)	339 (26·0)	308 (23·6)	294 (22·5)	
Alcohol consumption							0·001
Never drinker	4293 (65·8)	872 (66·8)	880 (67·4)	824 (63·2)	835 (64·0)	882 (67·6)	
Former drinker	878 (13·5)	207 (15·9)	159 (12·2)	188 (14·4)	167 (12·8)	157 (12·0)	
Current drinker	1354 (20·7)	226 (17·3)	266 (20·4)	293 (22·4)	303 (23·2)	266 (20·4)	
Geographic region							<0·001
Central China	1007 (15·4)	27 (2·1)	136 (10·4)	163 (12·5)	332 (25·4)	349 (26·7)	
East China	2442 (37·4)	323 (24·8)	128 (9·8)	428 (32·8)	827 (63·4)	736 (56·4)	
Northeast China	459 (7·0)	112 (8.6)	64 (4·9)	239 (18·3)	44 (3·4)	0 (0)	
North China	290 (4·4)	21 (1·6)	26 (2·0)	30 (2·3)	6 (0·5)	207 (15·9)	
Northwest China	74 (1·1)	31 (2·4)	8 (0·6)	2 (0·2)	26 (2·0)	7 (0·5)	
South China	1467 (22.5)	662 (50·7)	688 (52·7)	117 (9·0)	0 (0)	0 (0)	
Southwest China	786 (12·0)	129 (9·9)	255 (19·5)	326 (25·0)	70 (5·4)	6 (0·5)	
Body mass index (kg/m^2)*	20·9 (3·5)	19.8 (3·1)	20·2 (3·2)	21.5 (3·5)	21·3 (3·7)	21·9 (3·7)	<0·001
Daily intake of vitamin A/C/E supplements	389 (6.0)	50 (3·8)	50 (3·8)	77 (5·9)	96 (7.4)	116 (8·9)	<0·001
Hypertension**	1445 (22·1)	246 (18·9)	234 (17.9)	257 (19·7)	314 (24·1)	394 (30·2)	<0·001
Diabetes**	189 (2·9)	24 (1·8)	28 (2·1)	37 (2·8)	42 (3·2)	58 (4·4)	<0·001
Heart diseases**	623 (9·5)	82 (6·3)	64 (4·9)	143 (11·0)	152 (11·6)	182 (13·9)	<0·001
Cerebrovascular disease**	344 (5·3)	53 (4·1)	37 (2·8)	77 (5·9)	71 (5·4)	106 (8·1)	<0·001
Dyslipidemia**	114 (1·7)	16 (1·2)	14 (1·1)	19 (1·5)	24 (1·8)	41 (3·1)	<0·001

***Table 1*: Baseline characteristics of participants by quintiles of cumulative $PM_{2.5}$.**

Number (%) were reported.

Abbreviations: PDI: plant-based diet index; $PM_{2.5}$: fine particulate matter.

* mean (standard deviation) was reported.

** Cases of hypertension, diabetes, heart diseases, cerebrovascular disease, and dyslipidemia were self-reported.

	N of MMSE<18	N of risk	Cumulative $PM_{2.5}$		3-year average $PM_{2.5}$	
			Range ($\mu g/m^3$)	HR (95% CI)	Rang ($\mu g/m^3$)	HR (95% CI)
All participants						
$PM_{2.5}$ by quintiles						
Quintile 1	248	1305	9-38	Ref	10-38	Ref
Quintile 2	376	1305	38-44	1·25 (1·07, 1·47)	38-44	1·81 (1·54, 2·13)
Quintile 3	276	1305	44-52	1·29 (1·07, 1·56)	44-52	1·81 (1·48, 2·22)
Quintile 4	259	1305	52-62	1·44 (1·18, 1·75)	52-61	1·96 (1·59, 2·42)
Quintile 5	378	1305	62-106	1·46 (1·20, 1·77)	61-109	2·35 (1·91, 2·88)
Per 10 $\mu g/m^3$ increase in $PM_{2.5}$	1537	6525	..	1·10 (1·04, 1·15)	..	1·19 (1·14, 1·25)
Stratified by PDI						
Lower PDI						
$PM_{2.5}$ by quintiles						
Quintile 1	200	803	9-38	Ref	10-38	Ref
Quintile 2	236	796	38-44	1·31 (1·08, 1·59)	38-44	1·95 (1·59, 2·38)
Quintile 3	140	583	44-52	1·51 (1·15, 1·97)	44-52	2·41 (1·81, 3·21)
Quintile 4	113	524	52-62	1·51 (1·12, 2·03)	52-61	2·25 (1·63, 3·10)
Quintile 5	172	557	62-106	1·68 (1·26, 2·24)	61-108	2·94 (2·17, 3·99)
Per 10 $\mu g/m^3$ increase in $PM_{2.5}$	861	3263	..	1·13 (1·05, 1·21)	..	1·26 (1·17, 1·35)
Higher PDI						
By quintiles						
Quintile 1	105	502	10-38	Ref	10-38	Ref
Quintile 2	112	509	38-44	1·11 (0·84, 1·46)	38-44	1·58 (1·19, 2·10)
Quintile 3	127	722	44-52	1·07 (0·81, 1·41)	44-52	1·36 (1·02, 1·82)
Quintile 4	155	781	52-62	1·37 (1·05, 1·79)	52-61	1·73 (1·29, 2.31)
Quintile 5	177	748	62-105	1·28 (0·98, 1·68)	61-107	1·97 (1·48, 2·62)
Per 10 $\mu g/m^3$ increase in $PM_{2.5}$	676	3262	..	1·07 (1·01, 1·14)	..	1·15 (1·07, 1·22)

***Table 2*: The association between long-term $PM_{2.5}$ exposure and risks of developing poor cognitive function, stratified by plant-based dietary index.**

The regression models were multivariable-adjusted for age (years), sex (male or female), urban/rural residence, education (with or without formal education), occupation before age 60 (professional or non-professional work), financial status (financial independence or dependence), social and leisure activity, smoking and drinking status (never, former or current smokers/drinkers), regular exercise (yes or no), and geographic regions (Central China, Eastern China, Northeastern China, Northern China, Northwestern China, Southern China, Southwestern China).

Abbreviations: MMSE: Mini-Mental State Examination; PDI: plant-based diet index; $PM_{2.5}$: fine particulate matter

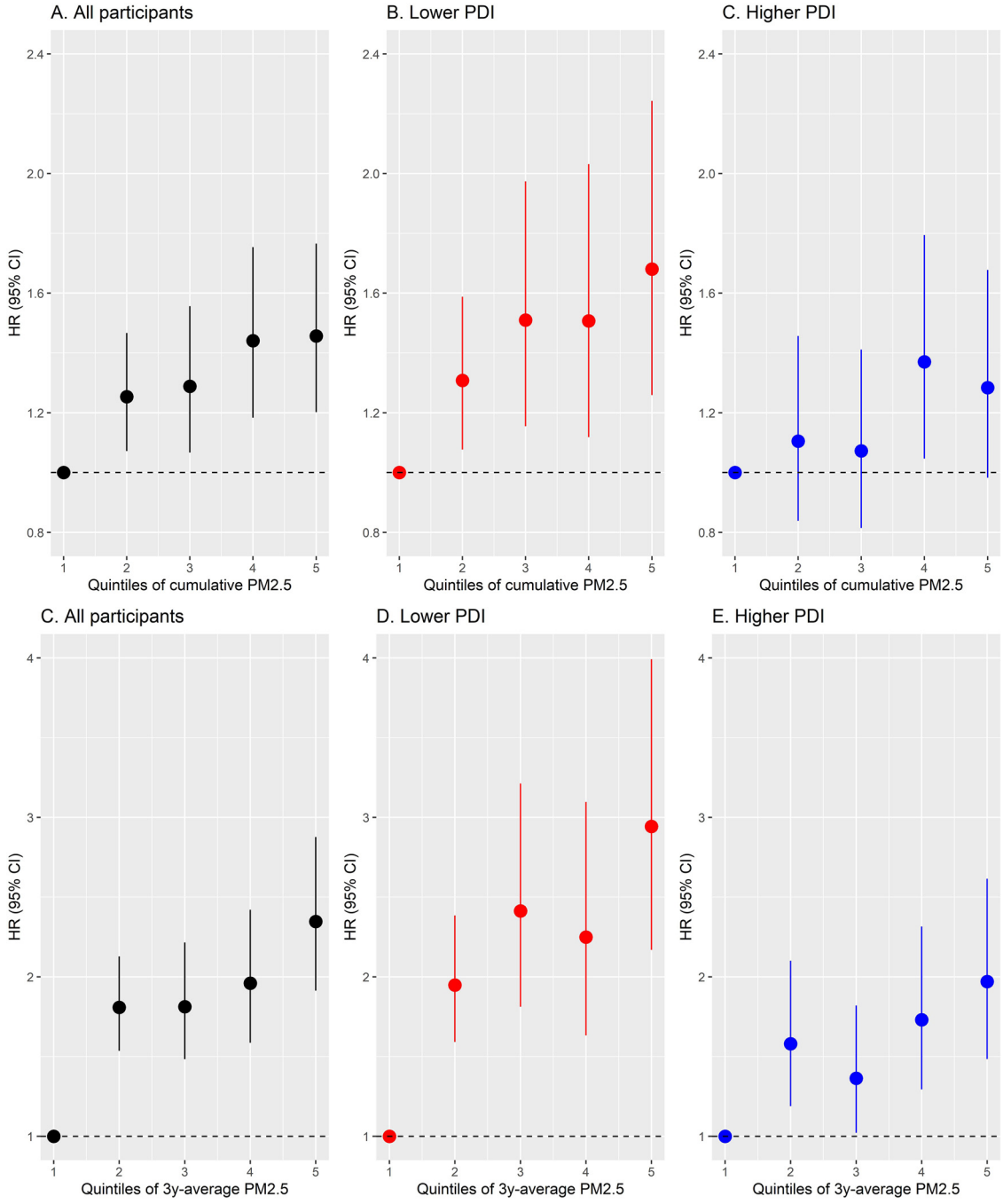

Figure 1. Hazard ratios (95% CI) of developing poor cognitive function by quintiles of long-term $PM_{2.5}$ exposure, stratified by plant-based diet index.

extra covariates (see Table S3), adjusting for baseline MMSE score (see Table S4), using competing risk models (see Table S5), using the MMSE score as a continuous variable (see Table S6), using education-specific cut-off points for MMSE score (see Table S7). The inverse associations between $PM_{2.5}$ exposure and changes in MMSE scores during the follow-up survey were also consistent with main results (see Table S8). We further stratified the associations of $PM_{2.5}$, PDI, and cognitive function by sex (see Figure S2). Among the participants with lower PDI, the effect estimates of $PM_{2.5}$ on the risks of developing

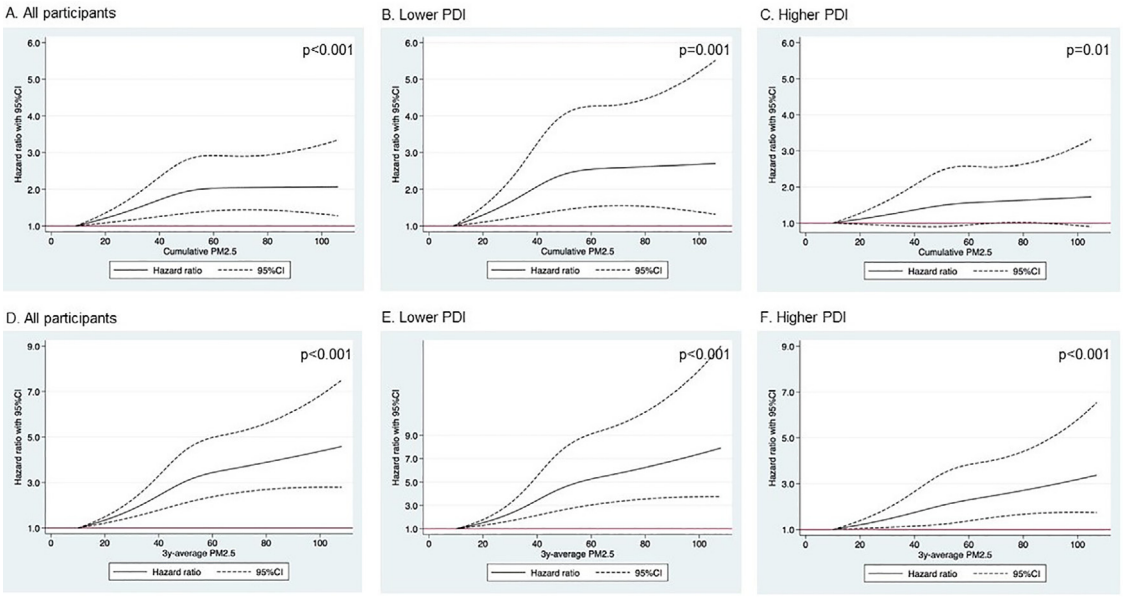

Figure 2. Cubic splines for long-term PM2.5 exposure and risks of developing poor cognitive function, stratified by plant-based diet index.

poor cognitive function were slightly higher among males than females.

Figure 3 reported the risks of developing poor cognitive function by per 10-$\mu g/m^3$ increase in cumulative $PM_{2.5}$ exposure, stratified by individual food group. The risk estimates of cumulative $PM_{2.5}$ exposure on developing poor cognitive function were lower among the participants with daily intake of fresh fruit, fresh vegetable, legume, garlic, tea, salted preserved vegetable, sugar, egg, dairy product, and less frequent (<1 time/per day) intake of meat and fish. Similar results were also found for 3-year average $PM_{2.5}$ exposure (see Figure S3).

Discussion

In this prospective cohort study of 6525 Chinese older adults with normal cognitive function at baseline, we found living in the areas with the highest quintiles of cumulative $PM_{2.5}$ was associated with a 46% increase in the risk of developing poor cognitive function. The associations were significantly modified by the plant-based dietary pattern. The association of cumulative $PM_{2.5}$ with cognitive function was attenuated with a 28% increased risk and marginally significant among those with higher PDI, in contrast with a 68% increase in the risk of developing a poor cognitive function outcome among those with lower PDI. Our findings indicated that higher adherence to the plant-based dietary pattern might be beneficial to poor cognitive function induced by long-term $PM_{2.5}$ exposure.

There is scarce evidence on whether the association between long-term $PM_{2.5}$ exposure and cognitive function differed by the plant-based dietary pattern. To the best of our knowledge, there was only one published abstract from a doctoral dissertation on a relevant topic from Germany. The author reported that women with a low Mediterranean diet score were more vulnerable to cognitive decline induced by air pollution, although the interaction between air pollution and the Mediterranean diet was not significant.[32] Emerging evidence showed that plant-based dietary pattern was beneficial to other health outcomes associated with $PM_{2.5}$ exposure. A prospective cohort of 548,845 participants with a follow-up of 17 years in the United States found that those with a higher Mediterranean diet score had significantly lower cardiovascular mortality rates associated with $PM_{2.5}$ and nitrogen dioxide (NO_2) exposures.[14] The Northeast Cohort Study of China reported that pregnant women who had a higher intake of animal food had higher risks of gestational diabetes mellitus associated with NO_2 and carbon monoxide (CO) exposures.[33] A study of 501 children from Portugal showed that the association between $PM_{2.5}$ and asthma was stronger among those having a pro-inflammatory diet, in contrast with those having an anti-inflammatory diet with more fresh vegetables and fruits, suggesting that inflammatory characteristics of diet may modify the association.[34] Potential benefits of the plant-based dietary pattern on various health outcomes induced by air pollution were also reported in other contexts.[35,36]

Rich antioxidants and anti-inflammatory nutrients from the plant-based dietary pattern may help explain how it could modify the association between long-term $PM_{2.5}$ exposure and cognitive function. First, the nutrients like unsaturated fatty acids from vegetable oil were related to lower risks of $PM_{2.5}$ associated

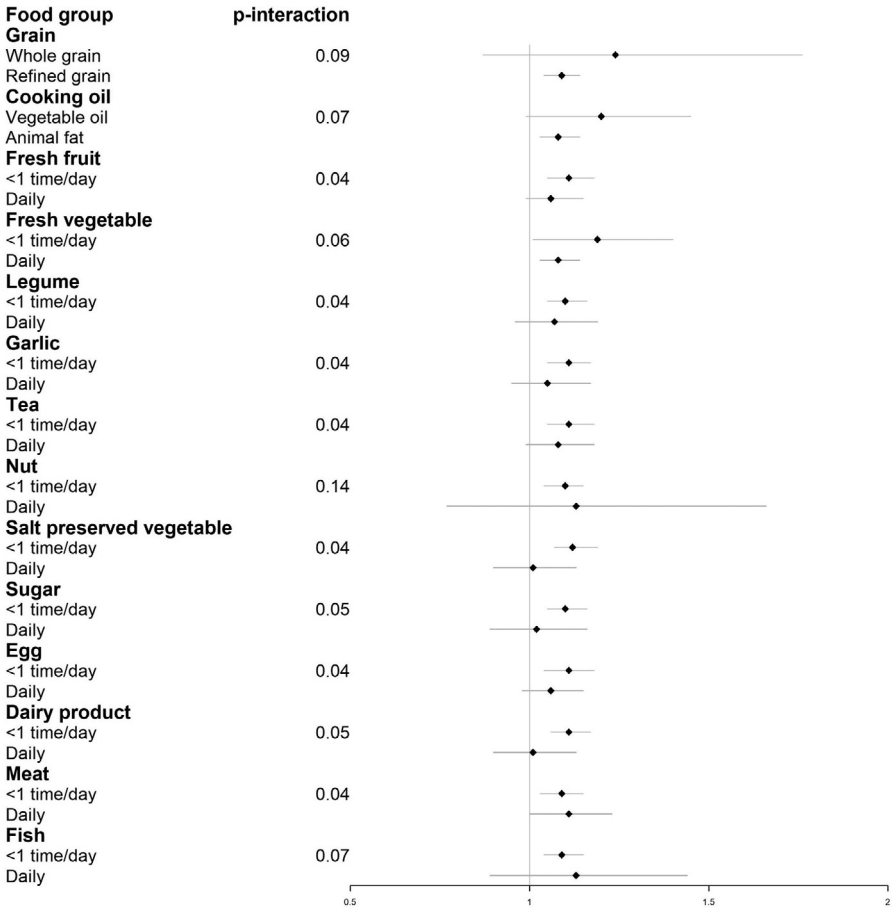

Figure 3. Hazard ratios (95% CI) of developing poor cognitive function by per 10-μg/m^3 increase in cumulative $PM_{2.5}$ exposure, stratified by individual food group.

cardiometabolic diseases,[14,37] through suppressing arrhythmias, modulating autonomic function, and its anti-thrombotic, anti-inflammatory, and vasodilatory effects.[13] While cardiometabolic diseases were risk factors of poor cognitive function.[38] Additionally, vegetables and fruits have rich nutrients, including polyphenols, antioxidant vitamins, and dietary fiber, which could reduce inflammation and oxidative stress induced by ambient pollutant exposures in the central nervous system,[4-7,39,40] ultimately influencing the pathogenesis of neurodegenerative disorder.[41,42] Although many studies showed antioxidant and anti-inflammatory effects of specific foods or nutrients like n-3 fatty acids, antioxidant vitamins, their effects on cognitive function among the non-demented population were controversial in practice.[7,43-45] There is still a lack of mechanistic evidence in the perspective of the plant-based dietary pattern.

The plant-based dietary pattern maybe not only beneficial to air pollution associated health outcomes, but also decrease air pollution produced by agriculture, and relevant disease burden. The global simulation showed that agriculture, largely due to animal farming, is the largest contributing sector to $PM_{2.5}$ in eastern United States, Russia, East Asia, and Europe.[46,47] For instance, food-related $PM_{2.5}$ pollution caused 15,900 annual deaths in the United States. About 80% of these deaths could be attributable to animal-based food.[48] A 50% decrease in agricultural ammonia emissions would reduce annual $PM_{2.5}$ concentration levels by 11%, 8%, and 5% in Europe, North America, and East Asia respectively.[47] Promoting the plant-based dietary pattern at the population level may be a cost-effective strategy for decreasing the relevant burden of diseases induced by air pollution.

In our study, inverse associations between $PM_{2.5}$ exposure and risks of developing poor cognitive function were stronger among males than females. Sex differences may be due to sex-linked biological differences or gender differences in activity patterns, coexposures, or accuracy of measurement.[49] However, the current evidence on sex differences in the air pollution effects is not consistent. For example, a Korean study reported women had a higher risk of cognitive decline associated

with $PM_{2.5}$ exposure than men.[50] However, no sex difference was reported in another cohort of older adults in the United States.[51]

The strengths of our study included using a national-representative sample of older adults with relatively large sample size, reliable $PM_{2.5}$ exposure, and considering a wide range of confounding variables for adjustment. Our study setting covers diverse geographic regions (22 provinces) in China with average annual $PM_{2.5}$ levels ranging from 9 to 106 $\mu g/m^3$. $PM_{2.5}$ concentrations are generally higher in the northern than southern areas, which could be partly explained by a higher density of coal consumption and heavy industries and favorable atmospheric conditions for accumulation, formation, and processing of aerosols in the northern areas.[52] The wide distribution of both PDI and $PM_{2.5}$ allows us to have heterogeneity which aids the robustness of our findings. Our study also provided evidence from East Asia to a western-centric nutrition research paradigm. Lastly, to our knowledge, our study was the first one of its kind and the novel findings may provide new perspectives against poor cognitive function induced by $PM_{2.5}$ exposure.

Our study also had several limitations. First, residual confounding may not be ruled out. With the mean age of 81 years old at the time of the interview, our participants were mainly born between the 1900s and 1940s, when China experienced societal instability, disrupted economic activities, and war. It requires careful consideration when generalizing our findings to the general population of older adults, and to other populations. Some demographic characteristics cannot be fully controlled for in the study. The status of cardiometabolic diseases was self-reported and unverified by the clinical diagnosis in the CLHLS. The prevalence was underreported, but it shall not bias our results since they were not the key covariates. Second, we used intake frequency to score the diets, rather than using the servings or quintiles of intake per day. We do not have information on portion sizes, which did not allow us to adjust for total energy intake. But the frequency of intake may be more important than portion size to distinguish between high and low consumption of fruits and vegetables.[29] A further complication is that our food questionnaire may not be standardized enough to be comparable with other nutrition studies and face challenges translating into nutrition recommendations. Diet questionnaires are notoriously difficult to be made generalizable across cultures and populations. But several studies have demonstrated the reliability and validity of using non-quantitative food frequency questionnaires to assess dietary patterns.[26-28] Thirdly, we used MMSE rather in lieu of clinical diagnoses, but the adapted Chinese version used in our study was demonstrated reliable and valid in prior research.[18,19] Additionally, there may be survival bias and competing risks from death given the relatively advanced age of participants (mean age: 81 years old). But our sensitivity analysis by using competing risk models showed consistent results, which supported the robustness of the main analysis.

Conclusions

We found that the effects of long-term $PM_{2.5}$ exposure on developing poor cognitive function were lower among the participants with higher PDI. Our findings suggested that higher adherence to the plant-based dietary pattern may benefit poor cognitive function induced by long-term $PM_{2.5}$ exposure. Promoting the plant-based dietary pattern may be a strategy to reduce the effects of $PM_{2.5}$ on neurological health.

Declaration of interests

The authors declared no competing interests.

Contributors

JSJ and CY conceived and designed the study design. A Zhu conducted statistical analysis and drafted the manuscript. A Zhu, HC, JS, XW, ZL, A Zhao, XS, LY, YZ, CY, and JSJ helped interpret data. All authors contributed to the interpretation of findings, provided revisions to the manuscript, and approved the final manuscript.

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Data sharing statements

CLHLS data is available through the request portal at the Center for Healthy Aging and Development Studies, Peking University.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.lanwpc.2021.100372.

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