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The associations of outdoor and indoor air pollution with cognitive function among older adults in China

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Background Air pollution exposure has been associated with cognitive decline, but evidence remains limited regarding outdoor and household air pollution, different cognitive domains, and urban-rural differences. This study examined the longitudinal associations of outdoor particulate matter and household solid fuel use with cognitive function among older Chinese adults.

Methods We used nationally representative data from 8,806 participants aged ≥60 years in the China Health and Retirement Longitudinal Study from 2013 to 2020. Outdoor air pollution was assessed using annual mean PM1, PM2.5, and PM10 concentrations, and household air pollution was assessed by solid fuel use for cooking and heating. Cognitive function included global cognition, memory, and mental status. Linear mixed-effects models were used to examine the associations of air pollution exposure with subsequent cognitive function. Stratified analyses were conducted by urban-rural residence.

Results Higher outdoor particulate matter exposure was generally associated with poorer subsequent global cognition and memory. PM2.5 exposure in 2013 was inversely associated with global cognition in both 2015 and 2018. Solid fuel use for cooking in 2013 was associated with lower global cognition (β=−0.57; 95% confidence interval (CI)=−0.93, −0.22), memory (β=−0.53; 95% CI=−0.77, −0.31), and mental status (β=−0.23; 95% CI=−0.40, −0.06) in 2018, while solid fuel use for heating was associated with lower global cognition (β=−0.42; 95% CI=−0.79, −0.05) and memory (β=−0.67; 95% CI=−0.92, −0.41). In stratified analyses, inverse associations appeared more evident among rural participants.

Conclusions Outdoor particulate matter exposure and household solid fuel use were associated with poorer subsequent cognitive function among older adults in China, particularly global cognition and memory. These findings suggest that ambient and household air pollution may be relevant to cognitive ageing.

Keywords PM2.5; PM10; memory; mental status; solid fuel use

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Cognitive impairment and associated dementia have emerged as significant health and societal challenges on a global scale, attributed to the rapid aging of the population and population growth [1]. The number of people living with dementia is currently estimated to be around 50 million and is expected to increase to 150 million by 2050 [2]. By 2030, the projected economic burden is expected to rise to approximately 2 trillion USD, and by 2050 it is forecasted to reach a staggering 9.12 trillion USD [3,4]. China's elderly population is on the rise, driven by the impact of the one-child pol-

icy and remarkable advancements in life expectancy over the last forty years. The percentage of elderly individuals (≥60 years old) in the Chinese population is projected to increase from 10.2% in 2000 to 25.1% in 2030, and the number of people with dementia will reach 10 million by 2050 [5]. This is expected to lead to a loss of independence in daily activities, reduced quality of life in old age, and an increased burden on individuals, families, and healthcare systems. Therefore, a more comprehensive understanding of the relevant risk factors or protective factors affecting cognitive function is necessary to form a crucial basis for public health decisions regarding the control and prevention of dementia in the future.

As indicated by the 2020 Lancet Commission on dementia prevention, ambient air pollution is identified as an emerging modifiable risk factor for cognitive decline in later life [2]. This conclusion is further supported by the improvement of cognitive ability observed following the implementation of strict clean air policies [6]. It's important to note that the number of individuals with dementia is growing at a faster rate in low-income and middle-income countries (LMICs) than in high-income countries (HICs). This is primarily due to the quicker aging of the population and the presence of poorer environmental conditions [7]. In recent years, several epidemiological studies have reported associations between exposure to air pollution and cognitive performance. Multiple prospective cohort studies have found a positive correlation between exposure to high concentrations of particulate matter (including coarse particles PM10, fine particles PM1 and PM2.5), tropospheric ozone (O3) pollution, nitrogen dioxide (NO2), and cognitive impairment [8,9]. A retrospective cohort study in Taiwan from 2001–2010 found that long-term exposure to high levels of O3 and PM2.5 increased the risk of cognitive impairment in individuals aged 65 and above [10]. Besides, a study in Europe found that exposure to NO2 and PM2.5 was associated with an increased risk of dementia [11]. In a cross-sectional study in Mexico, the National Survey of Health and Nutrition found a positive association between exposure to PM2.5 and cognitive decline in older adults [12]. Similarly, a cross-sectional study in France involving 104,733 participants aged 45 years or older discovered that even at low levels of exposure, outdoor air pollution was significantly linked to poorer cognitive performance [3]. Additionally, two large cohort studies in Canada, which included two million individuals aged between 55–85 years, revealed that living closer to main roads and long-term exposure to PM2.5 and NO2 were associated with a 7% higher risk of cognitive decline [13,14].

Although many studies have reported associations between outdoor air pollution exposure and an increased risk of cognitive impairment, evidence on the relationship between indoor air pollution and cognitive function remains limited [15,16]. Moreover, existing studies have generally examined outdoor or indoor air pollution separately and have often assessed cognitive function using a single global measure. Such approaches may not adequately capture different dimensions of cognitive function, particularly mental status and memory. Consequently, the associations of outdoor and indoor air pollution with specific cognitive domains remain insufficiently understood. Additionally, previous studies have predominantly relied on cross-sectional designs, leaving limited longitudinal evidence on the associations between air pollution exposure and cognitive function. Consequently, the associations of outdoor and indoor air pollutants with different dimensions of cognitive function over varying exposure periods remain unclear. Although the relationship between air pollution and cognitive function has been widely examined in developed countries [11,17], the generalisability of these findings to developing settings remains uncertain. China, which has experienced substantial ambient air pollution and widespread household solid fuel use, still lacks sufficient high-quality evidence on the associations of both outdoor and indoor air pollution with cognitive ageing [18]. Moreover, substantial urban-rural disparities in socioeconomic development, environmental conditions, healthcare access, and household energy use may modify these associations. However, existing studies have mainly focused on urban populations or areas with relatively high levels of ambient pollution exposure, providing limited evidence for rural older adults [3,4].

To address this knowledge gap, we conducted a longitudinal study to examine the associations of outdoor air pollution, including PM1, PM2.5, and PM10, and indoor air pollution, indicated by the use of solid fuels for cooking and heating, with cognitive function among older adults in China. Using nationally representative longitudinal data, we further compared the associations of dif-

ferent air pollutants with multiple dimensions of cognitive function. In addition, we examined whether these associations differed between rural villages and urban communities. This study aimed to address two main research questions:

1. Are outdoor and indoor air pollution associated with poor cognitive function among Chinese older adults, and do these associations differ across specific cognitive domains?
2. Do the associations of air pollution with cognitive function differ between urban and rural older adults?

A growing body of evidence has examined the association between outdoor air pollution and cognitive function in middle-aged and older adults [19,20]. From a biological perspective, exposure to ambient air pollutants may affect cognitive function through several interrelated pathways, including oxidative stress, systemic inflammation, neuroinflammation, vascular injury, and neurodegenerative processes [21]. Particulate matter may reach the central nervous system directly or indirectly through respiratory and circulatory pathways, thereby contributing to oxidative damage and inflammatory responses in the brain [22]. Airborne particles may also be involved in amyloid-β deposition and altered amyloid precursor processing, which are biological processes implicated in cognitive impairment and dementia related pathology [23].

However, the potential influence of air pollution on cognitive function should not be understood solely as a biological process. Bioecological systems theory emphasises that individual health develops through dynamic interactions between people and their surrounding environmental contexts [24]. For older adults, residential environments, household conditions, neighbourhood characteristics, and broader social contexts may jointly shape both exposure to environmental hazards and vulnerability to their health effects. Within this framework, outdoor air pollution can be conceptualised as a contextual environmental exposure embedded in older adults' daily living environments, while education, income, lifestyle, and urban-rural residence may influence both exposure intensity and cognitive resilience. Thus, the biological effects of particulate matter may operate within a socially patterned environmental context.

Although many studies have examined the association between outdoor air pollution exposure and cognitive function, existing findings remain inconsistent. For example, a UK Biobank cohort study of 86,759 middle-aged and older adults with a mean follow-up of 2.8 years found no significant association between PM1 or PM10 exposure and cognitive performance [25]. Similarly, a community-based prospective cohort study of older adults reported no significant association between PM2.5 exposure and cognitive function [26]. In contrast, a longitudinal study of 7,928 middle-aged and older Chinese adults found that PM1 exposure within a 90-day window and PM10 exposure within a 60-day window were significantly associated with poor cognitive performance [27]. These inconsistent findings suggest that the association between outdoor air pollution and cognitive function remains to be further clarified, particularly across different particulate matter indicators, cognitive domains, and population contexts.

In addition, previous studies have often focused on individual pollutants, such as PM2.5, PM10, or PM1, and have frequently used overall cognitive scores as the primary outcome [28,29]. Relatively fewer studies have compared different particulate matter indicators in relation to specific cognitive domains among older adults. Moreover, emerging evidence suggests that vulnerability to air pollution-related cognitive impairment may differ across population subgroups [19,30]. Urban-rural differences in environmental exposure, socioeconomic conditions, household energy use, and living environments may therefore contribute to heterogeneous associations between outdoor air pollution and cognitive function. Based on the integrated biological and bioecological framework and prior empirical evidence, we proposed the following hypotheses:

Hypothesis 1: Outdoor air pollution exposure is associated with lower subsequent cognitive function among older Chinese adults.

Hypothesis 2: The associations between outdoor air pollution and subsequent cognitive function are different in urban and rural areas.

Indoor air pollution is also an important environmental health concern, particularly in low- and middle-income countries. Globally, approximately three billion people, or 41% of households, use solid fuels such as wood, dung, crop residues, charcoal, and coal for cooking and heating [31]. This issue is especially relevant in China, where a substantial number of people still lack access to clean cooking and heating fuels and continue to rely on traditional biomass or coal for household energy needs [15]. Indoor solid fuel use may affect cognitive function through mechanisms similar to those of outdoor particulate pollution. Combustion of solid fuels produces fine and coarse particles, carbonaceous components, and other toxic substances that may contribute to systemic inflammation, oxidative stress, vascular dysfunction, and neuroinflammatory responses [32]. These biological processes may be particularly relevant for older adults, who may have greater biological susceptibility due to aging-related changes in vascular, immune, and neurological systems [33]. At the same time, household air pollution is strongly embedded within the social and material conditions of daily life. From a bioecological perspective, cooking and heating fuels are not merely individual household choices but are shaped by socioeconomic resources, housing conditions, energy infrastructure, cultural practices, and urban-rural context. Older adults may spend considerable time indoors, and household fuel use may therefore represent an important proximal environmental exposure within their microsystem. The potential cognitive consequences of indoor air pollution should thus be interpreted as arising from the interaction between household environmental exposures, biological vulnerability, and broader social context.

Recent studies have examined the association between polluting cooking fuel use and cognitive function in LMICs. Evidence from Mexico showed that adults aged 50 years and older who were exposed to household air pollution from polluting cooking fuels had poorer cognitive performance [34,35]. Similarly, a comparative analysis of adults aged 50 years and older in Mexico, India, and China found that polluting cooking fuel use was consistently associated with poorer cognitive function across all three countries [36]. However, evidence on the association between polluting heating fuel use and cognitive function remains limited. Existing studies on indoor air pollution from solid fuel use have often relied on cross-sectional designs or have assessed only one dimension of cognitive function. Therefore, longitudinal evidence is needed to clarify whether solid fuels used for cooking and heating are associated with subsequent cognitive function across different cognitive domains among older adults in China.

The integrated conceptual framework also supports examining potential urban-rural difference in the associations between indoor air pollution and cognitive function. Rural older adults may experience higher reliance on solid fuels, different housing and ventilation conditions, fewer healthcare resources, and different patterns of socioeconomic disadvantage compared with urban older adults. These contextual differences may influence both the level of indoor air pollution exposure and susceptibility to its cognitive effects. Therefore, examining urban-rural differences may help clarify how environmental exposures and social context jointly shape cognitive health in later life. We therefore proposed the following hypotheses:

Hypothesis 3: Indoor air pollution exposure is associated with lower subsequent cognitive function among older Chinese adults.

Hypothesis 4: The associations between outdoor air pollution and subsequent cognitive function are different in urban and rural areas.

METHODS

Study sample

This study used data from the 2013, 2015, 2018 and 2020 waves of the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative longitudinal survey of middle-aged and older adults in China [37]. The surveys were carried out by the China Centre for Economic

Research of Peking University, using a probability-proportional-to-size sampling technique covering 450 villages and 150 counties in 28 provinces. Data was collected through face-to-face interviews. The CHARLS was approved by the Ethical Review Committee at Peking University (approval number IRB00001052-11015). In the present analysis, 8,806 respondents aged 60 years or older were included in the linear mixed-effects model analyses (**Figure 1**).

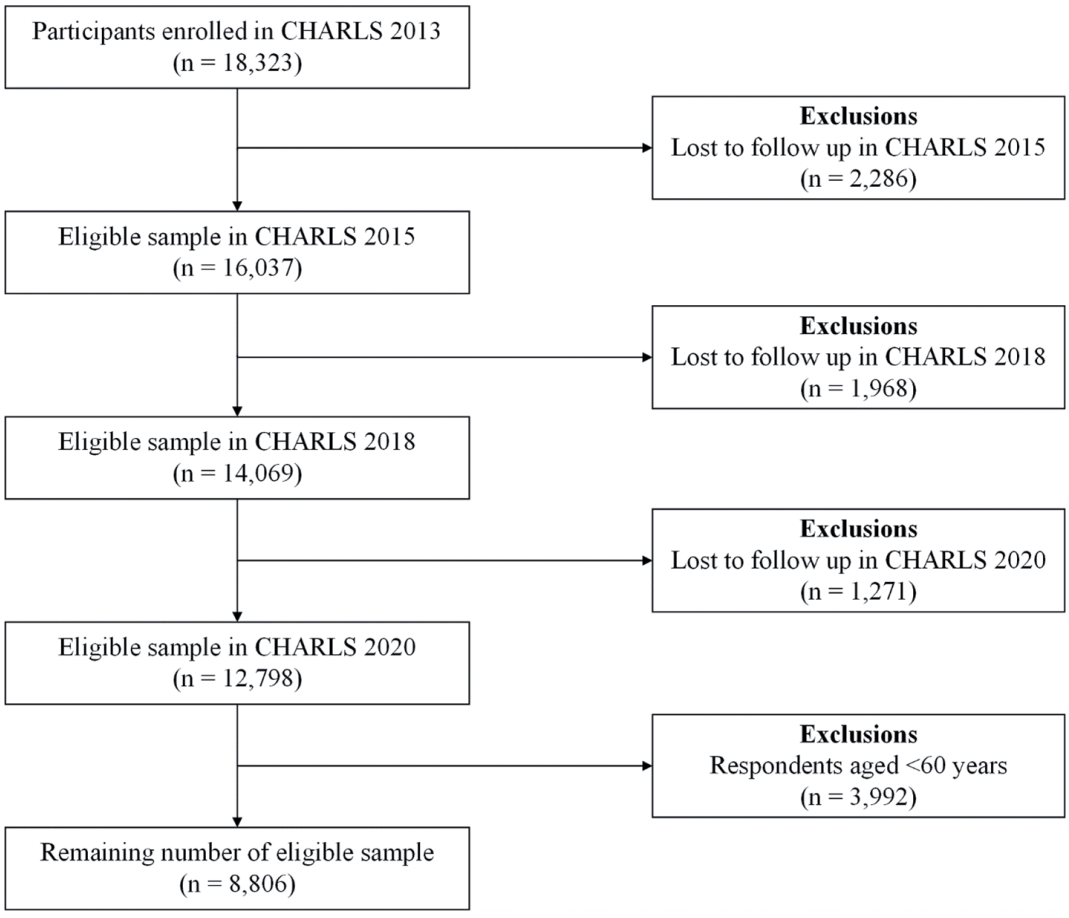


Figure 1. Flowchart of participant selection.

Measures

Cognitive function

In line with the USA Health and Retirement Study, CHARLS used components of the Telephone Interview of Cognitive Status (TICS) battery to access cognitive function [38]. This battery is a telephone version of the Mini-Mental State Examination and measures two dimensions of cognitive function: memory and mental status. Memory was assessed by immediate and delayed word recall. Immediate recall involved immediately repeating 10 Chinese nouns, and delayed recall involved repeating the same list of words four minutes later. The memory score ranges from 0–20. Mental status was assessed based on time orientation, picture drawing, and numeric ability, with a score range of 0 to 11. Time orientation was assessed by asking respondents to name the year, month, and day, as well as the season and day of the week. Picture drawing involved redrawing a previously shown picture accurately, while numeric ability was assessed by requiring respondents to subtract 7 from 100 consecutively for five times. The total cognitive function scores were calculated by combining the memory and mental status scores and range from 0 to 31. Higher scores indicate better cognitive function.

Outdoor air pollution

Annual ambient concentrations of PM1, PM2.5, and PM10 with complete spatial coverage were obtained from the China High Air Pollutants (CHAP) data set. Exposure data were estimated at a 1 km resolution using the Space-Time Extra-Trees (STET) model, satellite remote sensing techniques, and ground-based measurements. These methods provided highly accurate and stable estimates of ground-level air pollutants (cross-validation R^2: 0.83 for PM1, 0.92 for PM2.5, and 0.90 for PM10; root mean square error: 9.25 μg/m^3 for PM1, 12.67 μg/m^3 for PM2.5, and 24.34 μg/m^3 for PM10) [39–41]. The respondents' residential addresses were geocoded into latitude and longitude data using the application programming interface provided by Gaode Map, a leading commercial-use mapping and navigation service provider in China. We then matched the respondents' residential addresses with the concentrations of PM1, PM2.5, and PM10 based on latitude and longitude.

Indoor air pollution

In this study, indoor air pollution is defined as pollution caused by cooking and heating. By utilising a structured questionnaire, we collected information from participants regarding the primary cooking and heating fuel sources used in their households. We then categorised the cooking fuels into clean fuels (such as natural gas, marsh gas, liquefied petroleum gas, and electric) and solid fuels (including coal, crop residue, and wood burning). Similarly, we classified heating fuels into clean fuels (such as solar, natural gas, electric, and liquefied petroleum gas) and solid fuels (including coal, crop residue, and wood burning).

Control variables

In the baseline survey, we took into account factors such as sociodemographic characteristics, health behaviours, and health outcomes. The sociodemographic characteristics included age, gender (male, female), residency (rural, urban), education level (below primary school, primary school, middle school, high school and above), marital status (divorced/widowed/single, married/partnered), work status (agricultural work, non-agricultural work, retired, never worked), and annual household expenditures. For health behaviours, we considered smoking (no, yes) and alcohol consumption (no, yes). As for health outcomes, we included hypertension (no, yes), diabetes (no, yes), and instrumental activities of daily living (IADLs). In this study, IADLs impairment was defined as having difficulty in one or more of five IADL items.

Data analysis

Participant characteristics were summarised as means and standard deviations (SDs) for continuous variables and as frequencies and percentages for categorical variables. Differences in baseline characteristics were compared using *t* tests for continuous variables and χ^2 tests for categorical variables. Linear mixed-effects models were used to examine the associations of air pollution exposure with subsequent cognitive function:

$$Cognitive\ function_{ij} = \beta_0 + \beta_1 X_{ij} + \beta_2 Time_{ij} + \beta_3 (X_{ij} \times Time_{ij}) + \delta_{ij} + b_i + \varepsilon_{ij}$$

Where $Cognitive\ function_{ij}$ indicates the cognitive function of individual i at time j, X_{ij} represents air pollution exposure, including PM1, PM2.5, PM10, cooking and heating fuels use. $Time_{ij}$ denotes the exposure-outcome interval, $X_{ij} \times Time_{ij}$ represents the interaction between air pollution exposure and exposure-outcome interval, δ_{ij} denotes a set of control variables and baseline cognitive function. The b_i represents the participants specific random intercept, and ε_{ij} is the random error.

To explore potential urban-rural heterogeneity, stratified analyses were further conducted among rural and urban participants separately. Results are presented as standardised regression coefficients (β) with 95% confidence intervals (CIs). All statistical analyses were conducted using R, version 4.5.2 (R Foundation for Statistical Computing, Vienna, Austria).

Sensitivity analysis

In the primary analysis, the models were adjusted for age, gender, education level, residency, work status, marital status, smoking, alcohol consumption, IADLs, per capita expenditure, hypertension, and diabetes. To assess the robustness of the findings, we additionally adjusted for stroke and depression. We also conducted inverse probability weighting analyses to evaluated the potential influence of survivor bias and attrition bias. Furthermore, to examine whether the results were influenced by potential measurement limitations of brief cognitive assessments among very old adults, we performed a restriction-based sensitivity analysis among participants aged 60–79 years at baseline, excluding those aged ≥80 years.

RESULTS

Basic characteristics of the respondents

Participants who took part in the study in 2013 were aged 60 years and older, with an average age of 68.54 years (standard deviation (SD) = 7.09). Of the total participants, 4,408 (50.1%) were men, 6,925 (78.7%) were living with a partner, 3,260 (38.2%) worked in agriculture, 5,276 (59.9%) lived in rural areas, 5,133 (58.3%) had an education level below primary school, and 6,192 (71.1%) reported no difficulty with IADLs. Furthermore, respondents living in urban areas had higher scores on global cognition, memory, and mental status than those living in rural areas (**Table 1**).

Table 1. Sample characteristics at baseline

Variables	Overall (n = 8806)	Urban (n = 3530)	Rural (n = 5276)	*P*-value
Cognitive scores, mean (SD)				
Global cognition	14.79 (5.02)	16.11 (4.84)	13.81 (4.92)	<0.001
Memory	6.44 (3.38)	7.14 (3.45)	5.97 (3.25)	<0.001
Mental status	7.90 (2.74)	8.62 (2.45)	7.37 (2.81)	<0.001
Age, mean (SD)	68.54 (7.09)	68.73 (7.24)	68.41 (6.98)	0.041
Per capital household consumption, median (IQR)	6,093.53 (3,588.13, 10,635.49)	8,145.08 (4,757.19, 14,285.07)	5,113.16 (3,029.56, 8588.13)	<0.001
Gender				
Female	4,398 (49.9)	1,795 (50.8)	2,603 (49.3)	0.171
Male	4,408 (50.1)	1,735 (49.2)	2,673 (50.7)	
Marital status				
Married/ partnered	6,925 (78.7)	2,800 (79.5)	4,125 (78.2)	0.161
Divorced/ widowed/ single	1,870 (21.3)	722 (20.5)	1,148 (21.8)	
Education level				
Below primary school	5,133 (58.3)	1,598 (45.3)	3,535 (67.0)	<0.001
Primary school	2,000 (22.7)	829 (23.5)	1,171 (22.2)	
Middle school	1,060 (12.0)	618 (17.5)	442 (8.4)	
High school and above	613 (7.0)	485 (13.7)	128 (2.4)	
Work status				
Agricultural work	3,260 (38.2)	621 (18.6)	2,639 (50.7)	<0.001
Non-agricultural work	1,019 (11.9)	464 (13.9)	555 (10.7)	
Unemployed	163 (1.9)	102 (3.1)	61 (1.1)	
Retired	4,102 (48.0)	2,147 (64.4)	1,955 (37.5)	
Smoking				
No	5,516 (81.5)	2,289 (83.1)	3,227 (80.5)	0.007
Yes	1,248 (18.5)	465 (16.9)	783 (19.5)	
Alcohol consumption				
No	5,977 (68.6)	2,388 (68.9)	3,589 (68.5)	0.727
Yes	2,732 (31.4)	1,080 (31.1)	1,652 (31.5)	
IADLs				
No difficulty	6,192 (71.1)	2,589 (74.7)	3,603 (68.7)	<0.001
Some difficulty	2,521 (28.9)	879 (25.3)	1,642 (31.3)	
Hypertension				
No	5,411 (63.9)	1,993 (59.8)	3,418 (66.7)	<0.001
Yes	3,051 (36.1)	1,341 (40.2)	1,710 (33.3)	

Table 1. Continued

Variables	Overall (n = 8806)	Urban (n = 3530)	Rural (n = 5276)	*P*-value
Diabetes				
No	7,619 (90.8)	2,876 (87.0)	4,743 (93.3)	<0.001
Yes	771 (9.2)	429 (13.0)	342 (6.7)	
Outdoor air pollution, mean (SD)				
PM1	44.78 (0.30)	44.69 (0.28)	44.82 (0.30)	0.001
PM2.5	75.29 (0.20)	75.23 (0.19)	75.31 (0.20)	0.001
PM10	111.29 (1.70)	110.79 (1.59)	111.50 (1.70)	0.001
Indoor air pollution				
Cooking use solid fuels				
No	4,243 (49.2)	2,515 (73.5)	1,728 (33.2)	<0.001
Yes	4,387 (50.8)	908 (26.5)	3,479 (66.8)	
Heating use solid fuels				
No	2,732 (37.7)	1,792 (63.5)	940 (21.3)	<0.001
Yes	4,507 (62.3)	1,031 (36.5)	3,476 (78.7)	

SD – standard deviation, IQR – interquartile range

Outdoor air pollution, indoor air pollution, and cognitive function

The global cognition scores showed a general decline from 2013 to 2018, followed by an improvement from 2018 to 2020. Overall, individuals living in urban areas exhibited better cognitive performance compared to those in rural areas from 2013 to 2020 (**Figure 2**).

Annual mean concentrations of PM1, PM2.5, and PM10 declined substantially from 2013 to 2018. The overall mean concentration of PM1 decreased from 44.69 μg/m^3 in 2013 to 25.93 μg/m^3 in 2018, while PM2.5 decreased from 75.23 μg/m^3 to 41.93 μg/m^3 and PM10 decreased from 110.80 μg/m^3 to 68.12 μg/m^3. However, despite these improvements, nearly all participants continued to live in areas where annual mean concentrations of PM2.5 and PM10 exceeded the WHO air quality guideline levels of 5 μg/m^3 and 15 μg/m^3, respectively. For indoor air pollution, the proportion of participants using solid fuels for cooking declined from 50.83% in 2013 to 38.78% in 2018, while the proportion using clean fuels for heating increased from 37.74% to 95.70% (Tables S1 and S2 in the **Online Supplementary Document**).

The associations of outdoor and indoor air pollution exposure with cognitive function

In the cross-wave analyses, higher exposure to PM1, PM2.5, and PM10 in 2013 was significantly associated with lower global cognition and memory scores in 2015 and 2018, whereas no significant associations were observed for mental status. In the multivariable-adjusted model, PM2.5 exposure in 2013 was inversely associated with global cognition in both 2015 (β = −6.34; 95%

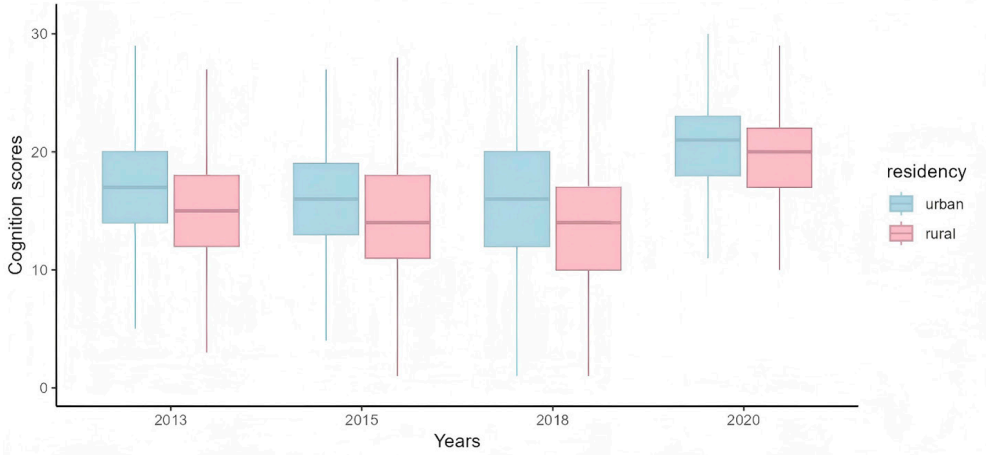


Figure 2. Distributions of global cognition scores during 2013–2020 by residency.

CI = −10.64, −2.89) and 2018 (β = −7.88; 95% CI = −13.07, −2.69). Similar inverse associations were observed for PM1 exposure in 2013, with lower global cognition in 2015 (β = −3.97; 95% CI = −6.85, −1.09) and 2018 (β = −5.06; 95% CI = −8.52, −1.59) (Table 2).

Table 2. The associations of outdoor and indoor air pollution exposure with cognition during 2013–2020*

Pollutants	Cognition (2015)			Cognition (2018)			Cognition (2020)		
Outdoor air pollution (2013)	**β (95% CI)**	**SE**	***P*-value**	**β (95% CI)**	**SE**	***P*-value**	**β (95% CI)**	**SE**	***P*-value**
PM1	−3.97 (−6.85, −1.09)	1.46	0.007	−5.06 (−8.52, −1.59)	1.77	0.004	−1.05 (−4.15, 2.06)	1.58	0.507
PM2.5	−6.34 (−10.64, −2.89)	2.19	0.004	−7.88 (−13.07, −2.69)	2.64	0.003	−2.02 (−6.67, 2.63)	2.37	0.394
PM10	−0.70 (−1.21, −0.19)	0.26	0.007	−0.89 (−1.50, −0.28)	0.31	0.004	−0.19 (−0.73, 0.36)	0.28	0.507
Indoor air pollution (2013)									
Cooking from solid fuels use (ref: no)	0.06 (−0.24, 0.37)	0.15	0.680	−0.57 (−0.93, −0.22)	0.18	0.001	−0.18 (−0.50, 0.14)	0.16	0.263
Heating from solid fuels use (ref: no)	−0.10 (−0.42, 0.23)	0.17	0.552	−0.42 (−0.79, −0.05)	0.19	0.025	−0.06 (−0.39, 0.28)	0.17	0.749
Outdoor air pollution (2015)									
PM1	-	-	-	−2.90 (−5.04, −0.76)	1.09	0.008	−0.82 (−2.79, 1.14)	1.00	0.411
PM2.5	-	-	-	−1.87 (−3.23, −0.50)	0.69	0.007	−0.52 (−1.77, 0.734)	0.64	0.415
PM10	-	-	-	−0.62 (−1.08, −0.16)	0.23	0.008	−0.18 (−0.59, 0.24)	0.21	0.411
Indoor air pollution (2015)									
Cooking from solid fuels use (ref: no)	-	-	-	−0.65 (−0.96, −0.34)	0.16	<0.001	−0.31 (−0.59, −0.02)	0.14	0.033
Heating from solid fuels use (ref: no)	-	-	-	0.76 (0.26, 1.26)	0.25	0.003	0.16 (−0.32, 0.63)	0.24	0.524
Outdoor air pollution (2018)									
PM1	-	-	-	-	-	-	−4.92 (−25.10, 15.26)	10.30	0.632
PM2.5	-	-	-	-	-	-	−1.14 (−4.04, 1.76)	1.48	0.440
PM10	-	-	-	-	-	-	−0.31 (−1.57, 0.95)	0.64	0.633
Indoor air pollution (2018)									
Cooking from solid fuels use (ref: no)	-	-	-	-	-	-	−0.005 (−0.31, 0.29)	0.15	0.973
Heating from solid fuels use (ref: no)	-	-	-	-	-	-	0.15 (−0.42, 0.73)	0.29	0.611

CI – confidence interval, IADLs – instrumental activities of daily living, SE – standard error
*The model was adjusted for age, gender, education level, residency, work status, marital status, smoking, alcohol consumption, IADLs, per capita expenditure, hypertension, diabetes, and baseline cognition].

Exposure to outdoor air pollution in 2015 showed similar adverse associations with subsequent global cognition and memory in 2018. Higher PM1, PM2.5, and PM10 exposure in 2015 was associated with poorer global cognition in 2018. Comparable patterns were observed for memory, with inverse associations for PM1 (β = −2.93; 95% CI = −4.17, −1.68), PM2.5 (β = −1.89; 95% CI = −2.66, −1.12), and PM10 (β = −0.61; 95% CI = −0.87, −0.35) in relation to memory performance in 2018. No statistically significant associations were observed between PM1, PM2.5, and PM10 exposure and subsequent mental status (Tables S3 and S4 in the Online Supplementary Document).

For indoor air pollution, solid fuel use for cooking and heating also showed adverse associations with subsequent cognition and memory, whereas no consistent association was observed for mental status. Solid fuel use for cooking in 2013 was associated with lower global cognition (β = −0.57; 95% CI = −0.93, −0.22), memory (β = −0.53; 95% CI = −0.77, −0.31), and mental status (β = −0.23; 95% CI = −0.40, −0.06) in 2018, while solid fuel use for heating was associated with lower global cognition (β = −0.42; 95% CI = −0.79, −0.05) and memory (β = −0.67; 95% CI = −0.92, −0.41). No statistically significant associations were observed between solid fuel use for heating and subsequent mental status.

In addition, solid fuel use for cooking in 2015 was associated with lower global cognition, memory, and mental status in both 2018 (global cognition: β=−0.65; 95% CI=−0.96, −0.34; mental status: β=−0.21; 95% CI=−0.36, −0.06) and 2020 (global cognition: β=−0.31; 95% CI=−0.59, −0.02; mental status: β=−0.25; 95% CI=−0.39, −0.12).

Associations of outdoor and indoor air pollution exposure with cognitive function in rural and urban communities

Overall, stratified estimates suggested more apparent inverse associations among rural participants, particularly for global cognition and memory. For global cognition, inverse associations between outdoor particulate matter exposure and subsequent cognition scores were observed mainly among rural participants (**Table 3**). Among rural participants, higher outdoor particulate matter exposure in 2013 was associated with lower global cognition scores in 2015 and 2018. The most pronounced association was observed for PM2.5, with higher exposure in 2013 associated with lower global cognition in both 2015 (β=−7.17; 95% CI=−11.82, −2.52) and 2018 (β=−9.97; 95% CI=−15.88, −4.07). Similar negative associations were observed for PM1 and PM10. Outdoor particulate matter exposure in 2015 was also associated with lower global cognition in 2018 (PM1: β=−2.91; 95% CI=−5.27, −0.56; PM2.5: β=−1.87; 95% CI=−3.39, −0.36; PM10: β=−0.61; 95% CI=−1.11, −0.10) among rural participants, whereas corresponding associations among urban participants were not statistically significant. However, the exposure-by-residence interaction tests were not statistically significant (Table S5 in the **Online Supplementary Document**).

The residence-stratified findings for memory were generally consistent with those observed for global cognition (Table S6 in the **Online Supplementary Document**). Among rural participants, outdoor particulate matter exposure in 2013 was associated with lower memory scores in both 2015 and 2018. For example, higher PM2.5 exposure in 2013 was associated with lower memory scores in 2015 (β=−4.91; 95% CI=−7.85, −1.98) and 2018 (β=−8.03; 95% CI=−11.38, −4.69). Outdoor particulate matter exposure in 2015 was also associated with lower memory scores in 2018 among rural participants (PM1: β=−3.11; 95% CI=−4.48, −1.74; PM2.5: β=−1.95; 95% CI=−2.82, −1.07; PM10: β=−0.67; 95% CI=−0.95, −0.37), and these associations persisted to 2020 for PM1, PM2.5, and PM10. Solid fuels use for cooking and heating in 2013 was associated with poor memory in 2018 among both rural and urban respondents.

For mental status, outdoor particulate matter exposure in 2013 was associated with lower mental status scores in 2015 among rural participants, whereas corresponding associations among urban participants were not statistically significant (Table S7 in the **Online Supplementary Document**). These associations were not consistently observed in later follow-up waves. Regarding indoor air pollution, cooking with solid fuels in 2015 was associated with lower mental status scores in 2020 among both rural and urban participants. Heating with solid fuels in 2015 was associated with lower mental status scores in 2018 among rural participants only (β=−0.42; 95% CI=−0.79, −0.06).

Sensitivity analysis

After additional adjustment for stroke and depression, the associations between air pollution exposure and subsequent cognitive function remained generally consistent with those observed in the primary analysis (Table S8 in the **Online Supplementary Document**). We further conducted inverse probability weighting sensitivity analyses to evaluate the potential influence of survivor bias and attrition bias. The weighted linear mixed-effects models yielded broadly similar results, suggesting that the observed associations were unlikely to be fully explained by selective attrition (Table S9 in the **Online Supplementary Document**). In addition, in the restriction-based sensitivity analysis limited to participants aged 60–79 years at baseline, the associations between air pollution exposure and subsequent cognitive function were also generally consistent with the primary findings. These results indicate that our main conclusions were not primarily driven by the inclusion of participants aged ≥80 years, among whom brief cognitive assessments may be more susceptible to measurement error (Table S10 in the **Online Supplementary Document**).

Table 3. The associations of outdoor and indoor air pollution exposure with cognition in rural and urban communities*

Pollutants	Cognition (2015)				Cognition (2018)				Cognition (2020)			
	Rural 95% CI	***P*-value**	**Urban 95% CI**	***P*-value**	**Rural 95% CI**	***P*-value**	**Urban 95% CI**	***P*-value**	**Rural 95% CI**	***P*-value**	**Urban 95% CI**	***P*-value**
Outdoor air pollution (2013)												
PM1	−4.78 (−7.88, −1.68)	0.002	0.10 (−4.95, 5.16)	0.967	−6.65 (−10.59, −2.72)	0.001	−0.80 (−6.57, 4.96)	0.78	−0.90 (−4.33, 2.53)	0.606	−0.02 (−5.20, 5.15)	0.992
PM2.5	−7.17 (−11.82, −2.52)	0.002	0.15 (−7.43, 7.74)	0.967	−9.97 (−15.88, −4.07)	0.001	−1.21 (−9.86, 7.44)	0.78	−1.35 (−6.50, 3.79)	0.606	−0.03 (−7.81, 7.73)	0.992
PM10	−0.85 (−1.40, −0.30)	0.002	−0.004 (−0.90, 0.89)	0.992	−1.14 (−1.83, -0.44)	0.001	−0.15 (−1.17, 0.86)	0.76	−0.09 (−0.70, 0.50)	0.751	−0.04 (−0.96, 0.87)	0.918
Indoor air pollution (2013)												
Cooking from solid fuels use (ref: no)	0.30 (−0.01, 0.63)	0.06	−0.08 (−0.51, 0.34)	0.71	−0.49 (−0.86, −0.11)	0.01	−0.30 (−0.79, 0.19)	0.24	−0.12 (−0.45, 0.20)	0.459	−0.35 (−0.81, 0.11)	0.133
Heating from solid fuels use (ref: no)	−0.26 (−0.66, 0.13)	0.192	−0.17 (−0.57, 0.23)	0.408	−0.20 (−0.67, 0.26)	0.384	−0.15 (−0.61, 0.29)	0.5	0.06 (−0.34, 0.47)	0.753	−0.28 (−0.71, 0.14)	0.198
Outdoor air pollution (2015)												
PM1	-	-	-	-	−2.91 (−5.27, −0.56)	0.015	−1.53 (−5.44, 2.37)	0.44	−1.13 (−3.21, 0.95)	0.286	0.61 (−3.22, 4.46)	0.751
PM2.5	-	-	-	-	−1.87 (−3.39, −0.36)	0.015	−0.98 (−3.50, 1.52)	0.44	−0.72 (−2.07, 0.61)	0.286	0.39 (−2.07, 2.86)	0.751
PM10	-	-	-	-	−0.61 (−1.11, −0.10)	0.018	−0.33 (−1.18, 0.52)	0.45	−0.21 (−0.66, 0.22)	0.336	0.10 (−0.72, 0.92)	0.811
Indoor air pollution (2015)												
Cooking from solid fuels use (ref: no)	-	-	-	-	−0.37 (−0.69, −0.05)	0.022	−0.63 (−1.07, −0.18)	0.01	−0.22 (−0.50, 0.06)	0.122	−0.26 (−0.68, 0.15)	0.218
Heating from solid fuels use (ref: no)	-	-	-	-	0.06 (−0.67, 0.81)	0.855	0.86 (0.34, 1.39)	0	0.12 (−0.53, 0.77)	0.716	0.08 (−0.43, 0.61)	0.743
Outdoor air pollution (2018)												
PM1	-	-	-	-	-	-	-	-	−6.14 (−27.87, 15.57)	0.578	0.52 (−36.12, 37.16)	0.977
PM2.5	-	-	-	-	-	-	-	-	−0.87 (−3.98, 2.22)	0.578	0.07 (−5.16, 5.31)	0.977
PM10	-	-	-	-	-	-	-	-	−0.31 (−1.67, 1.04)	0.648	−0.05 (−2.35, 2.24)	0.962
Indoor air pollution (2018)												
Cooking from solid fuels use (ref: no)	-	-	-	-	-	-	-	-	0.03 (−0.27, 0.34)	0.831	−0.12 (−0.65, 0.41)	0.651
Heating from solid fuels use (ref: no)	-	-	-	-	-	-	-	-	0.42 (−0.32, 1.17)	0.269	0.04 (−0.65, 0.75)	0.892

*The model was adjusted for age, gender, education level, work status, marital status, smoking, alcohol consumption, IADLs, per capita expenditure, hypertension, diabetes, and baseline cognition.

DISCUSSION

This study examined the longitudinal associations of outdoor and indoor air pollution with subsequent cognitive function among older adults in China from 2013 to 2020. We found that higher exposure to outdoor particulate matter, including PM1, PM2.5, and PM10, was generally associated with lower subsequent global cognition and memory scores, whereas associations with mental status were less consistent. Household solid fuel use for cooking and heating was also associated with poorer subsequent cognitive performance, particularly global cognition and memory. In residence-stratified analyses, inverse associations appeared more evident among rural participants. These findings add to the growing evidence on the relationship between air pollution exposure and cognitive ageing in China and highlight the importance of considering both outdoor and household air pollution in older populations.

Our findings suggest that higher exposure to outdoor particulate matter was associated with poorer cognitive function among older adults. The associations were more consistent for global cognition and memory than for mental status, indicating that different cognitive domains may vary in their sensitivity to air pollution exposure. This pattern is broadly consistent with previous epidemiological studies linking long-term exposure to ambient PM2.5 and PM10 with accelerated cognitive ageing and poorer memory performance [28]. Several biological pathways may explain these associations. Particulate matter may affect the central nervous system through systemic inflammation, oxidative stress, vascular dysfunction, disruption of the blood-brain barrier, and neuroinflammatory responses [42,43]. Indirect vascular pathways may also be involved, including endothelial dysfunction, cerebral ischemia, and changes in circulating inflammatory or coagulation-related proteins [19]. The stronger and more consistent associations observed for memory may be particularly relevant in the context of ageing. Memory function is vulnerable to cumulative vascular, inflammatory, and neurodegenerative processes, which may be exacerbated by long-term exposure to particulate matter [44]. In our analyses, outdoor air pollution exposure in earlier waves was associated with poorer memory performance in later waves, suggesting that cumulative or delayed associations may be important.

For indoor air pollution, we found that household solid fuel use for cooking and heating was associated with poorer subsequent cognitive function, particularly global cognition and memory. Solid fuel use for cooking showed relatively consistent associations with several cognitive outcomes, including mental status in some follow-up periods. These findings are in line with previous studies suggesting that household air pollution from solid fuel combustion may be related to poorer cognitive performance among older adults [35]. Potential mechanisms include exposure to fine particulate matter, carbon monoxide, nitrogen oxides, volatile organic compounds, and other combustion-related pollutants, which may contribute to systemic inflammation, cerebrovascular injury, oxidative stress, and neurodegenerative processes [45]. However, household fuel choice is embedded in broader socioeconomic and residential contexts. Solid fuel use may reflect not only exposure to household air pollution but also differences in income, education, rural residence, housing quality, kitchen structure, ventilation conditions, access to clean household energy, and healthcare resources. Although our models adjusted for several relevant demographic, socioeconomic, behavioural, and health-related factors, these covariates may not fully capture household-level deprivation or environmental conditions. Information on housing quality, ventilation, cooking or heating duration, household crowding, and healthcare access was not available. Therefore, residual confounding by unmeasured contextual factors remains plausible. The observed associations between solid fuel use and cognitive function may partly reflect broader social and environmental disadvantage rather than the independent effect of household air pollution alone.

In residence-stratified analyses, the inverse associations between outdoor particulate matter and subsequent cognitive function were more apparent among rural participants, especially for global cognition and memory. Among rural older adults, higher PM1, PM2.5, and PM10 exposure was associated with lower global cognition and memory scores across several exposure-out-

come periods. In contrast, corresponding associations among urban participants were generally weaker and often not statistically significant. These patterns may reflect differences in exposure sources, household energy use, socioeconomic resources, healthcare access, and vulnerability between rural and urban populations [46]. In rural households, solid fuels are often burned in poorly ventilated cooking or heating spaces and with inefficient combustion devices. This process can generate high concentrations of household air pollutants, including carbon monoxide, nitrogen dioxide, volatile organic compounds, and particulate matter, which have been associated with poorer cognitive outcomes in older adults [47]. Rural older adults may experience a combined burden of ambient particulate matter, household solid fuel use, poorer housing conditions, limited ventilation, and reduced access to preventive healthcare services [48]. These contextual disadvantages may increase susceptibility to the cognitive consequences of environmental exposures. In the context of population ageing and persistent environmental inequality, these findings underscore the need to accelerate the transition to clean and modern household fuels, particularly in rural areas. Such efforts may contribute to reducing environmental health disparities and advancing the health-related targets of the Sustainable Development Goals.

Our study makes four main contributions to the literature. First, this study adds to the limited evidence on the short- and long-term associations between air pollution exposure and cognitive function among older adults in China. Second, we used data from a nationally representative longitudinal survey, which enhances the generalisability of our findings to older Chinese adults. Third, the longitudinal design allowed us to examine associations across different exposure periods and cognitive domains, including global cognition, memory, and mental status. Fourth, by conducting urban–rural stratified analyses, this study further highlights the importance of residential context and environmental inequality in understanding the relationship between air pollution exposure and cognitive health. It's important to note that this study has some limitations. Although this study used longitudinal data and adjusted for a wide range of covariates, the observational design precludes definitive causal inference. Residual confounding from unmeasured or imperfectly measured factors remains possible. Additionally, outdoor air pollution exposure was assigned according to participants' residential addresses and therefore represented residential ambient exposure rather than direct personal exposure. Such exposure measurement error may have resulted in exposure misclassification. Also, household solid fuel use was measured using self-reported fuel type, without detailed information on ventilation, kitchen structure, duration and intensity of fuel use, or measured indoor pollutant concentrations. Lastly, the study focused on particulate matter, including PM1, PM2.5, and PM10, and did not include other ambient pollutants such as NO2, ozone, SO2, or CO. Residual confounding by correlated environmental exposures therefore cannot be excluded. Future studies incorporating multiple pollutants and using mixture-based approaches are needed to disentangle the independent and joint effects of air pollution components on cognitive function in older adults.

Practical implications

Few studies have examined the associations of outdoor particulate matter and household solid fuel use with subsequent cognitive function across multiple cognitive domains, particularly in the context of urban-rural disparities. Our findings suggest that both outdoor and indoor air pollution may contribute to poorer cognitive ageing among older adults, but the observed associations differed by pollutant source, cognitive domain, exposure period, and residential setting. The inverse associations of outdoor PM1, PM2.5, and PM10 exposure were more consistently observed for global cognition and memory than for mental status, indicating that pollution-related cognitive vulnerability may not be uniform across cognitive domains. Moreover, residence-stratified analyses showed that these adverse associations were more pronounced and more consistent among rural participants, especially for global cognition and memory. These findings highlight the need to incorporate rural older adults into air pollution control and healthy ageing strategies, rather than focusing exclusively on urban populations where ambient pollution has traditionally received greater policy attention.

For public health practice, the results support integrated interventions targeting both ambient particulate matter and household air pollution. In rural communities, reducing exposure to outdoor particulate matter should be accompanied by efforts to reduce reliance on solid fuels for cooking and heating, improve household ventilation, and expand access to affordable clean energy alternatives. Particular attention should be given to cooking-related solid fuel exposure, which showed associations with subsequent global cognition, memory, and mental status in later follow-up waves. In urban communities, although the associations between outdoor particulate matter and cognitive outcomes were less consistent, household solid fuel use remained relevant and should not be overlooked, especially among socioeconomically disadvantaged older adults who may continue to rely on polluting fuels.

From a policy perspective, air pollution reduction should be considered part of dementia prevention and healthy ageing policy. Environmental health interventions, clean household energy transitions, and community-based cognitive health programmes could be jointly implemented in high-exposure settings. Older adults living in rural areas or households using solid fuels may benefit from targeted risk assessment, health education, and cognitive screening. Overall, our findings underscore the importance of addressing both outdoor and indoor air pollution as modifiable environmental risk factors for cognitive decline in ageing populations.

CONCLUSIONS

Using nationally representative longitudinal data, this study found that higher exposure to outdoor particulate matter and household solid fuel use was associated with poorer subsequent cognitive function among older adults in China, particularly global cognition and memory. In residence-stratified analyses, inverse associations between air pollution exposure and cognitive function appeared more evident among rural participants, especially for global cognition and memory. Collectively, these findings highlight the relevance of both outdoor and household air pollution to cognitive ageing among older adults in China. Policies aimed at improving outdoor air quality and promoting clean household energy may have potential cognitive health relevance.

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Ethics statement: The CHARLS was approved by the Ethical Review Committee at Peking University (approval number IRB00001052–11015)

Data availability: Data sets are only distributable by the CHARLS team and are available in the public domain through registration on the CHARLS website: https://charls.charlsdata.com/pages/data/111/zh-cn.

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Additional material
Online Supplementary Document

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