

Living Environmental Quality and Incident Cardiometabolic Multimorbidity: A Prospective Cohort Study in China

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Abstract

Background

Cardiometabolic multimorbidity (CMM) imposes a substantial burden on aging populations. While single environmental exposures are known risk factors, the joint effect of multidimensional living environments remains unclear. This study aimed to construct a comprehensive Living Environmental Quality (LEQ) index and investigate its association with incident CMM in China.

Methods

We included 6,330 adults aged 45 years or older without CMM at baseline from the China Health and Retirement Longitudinal Study (CHARLS). A composite LEQ index (range 0–6) was constructed using housing type, indoor temperature suitability, tap water source, household energy fuel type, and outdoor PM_{2.5} exposure to reflect the multidimensional aspects of living environments, and further categorized into high-, medium-, and low-risk groups. Cox proportional hazards models were used to estimate hazard ratios (HRs) and 95% confidence intervals (CIs) for incident CMM. Extensive sensitivity analyses were conducted, including excluding individuals with baseline hypertension and removing PM_{2.5} from the LEQ index, to assess the robustness of the non-air-quality factors.

Results

Over a median follow-up of 7 years, 426 participants developed incident CMM. In the fully adjusted model, compared with the high-risk group, the medium-risk group had a 22% reduction in CMM risk (HR: 0.78, 95% CI: 0.64–0.95, $P = 0.016$), and the low-risk group had a 48% reduction (HR: 0.52, 95% CI: 0.37–0.72, $P = 0.001$). Multi-storey building (HR: 0.75, 95% CI: 0.65–0.87, $P < 0.001$) and tap water source (HR: 0.79, 95% CI: 0.69–0.90, $P < 0.001$) significantly reduced incident CMM risk. Extensive sensitivity analyses were conducted, including excluding individuals with baseline hypertension and removing PM_{2.5} from the LEQ index, to assess the robustness of the non-air-quality factors.

Conclusion

Better residential environmental quality was independently associated with a lower risk of incident CMM among middle-aged and older Chinese adults in China. These findings support the potential importance of housing and basic household infrastructure in strategies for CMM prevention.

1 Introduction

Cardiometabolic multimorbidity (CMM) represents one of the most prevalent and severe forms of multimorbidity globally ^[1], defined as the co-occurrence of two or more cardiometabolic conditions, including diabetes, heart disease, and stroke^[2]. Epidemiological studies in China have reported CMM prevalence ranging from 5.94% to 16.9%, creating a heavy and growing public health burden ^[3, 4]. Notably, CMM diagnosed at age 60 is associated with a 15-year reduction in life expectancy, and individuals with three cardiometabolic diseases at age 40 face a 23-year shorter lifespan^[2], underscoring the urgent need for effective preventive strategies.

A growing body of evidence supports that residential environmental factors contribute substantially to the development of cardiometabolic diseases. For instance, long-term PM_{2.5} exposure increases the risk of diabetes and cardiovascular disorders ^[3], exacerbating the burden of CMM. Use of clean household energy fuels is associated with slower physiological aging compared with solid fuel use for cooking and heating ^[5]. Yet nearly 3 billion people worldwide still rely on solid fuels for daily life ^[6]. Other residential characteristics—such as room type, room temperature, and drinking water source—have also been linked to elevated risks of cardiovascular disease and stroke ^[6, 7], while low magnesium levels in drinking water are associated with reduced cardiovascular and stroke mortality ^[8].

However, most prior studies have focused on single environmental exposures or individual diseases, largely ignoring the cumulative and combined effects of multidimensional living environments. To date, few studies have constructed a comprehensive living environmental quality score that integrates indoor conditions, outdoor air quality, and household infrastructure to explore its association with incident CMM. Most available evidence is from high-income countries, limiting its generalizability to the Chinese population.

This study aimed to develop a comprehensive Living Environmental Quality (LEQ) index and investigate its association with incident CMM among middle-aged and older Chinese adults. We hypothesized that a higher LEQ score (better environmental quality) would be associated with a lower risk of CMM. We further explored the magnitude and pattern of the association between overall living environmental quality and CMM risk.

2 Methods

Study Population

We used data from the 2011 baseline survey and the 2013, 2015, and 2018 follow-up waves of the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative cohort of Chinese adults aged 45 years or older. After excluding participants with missing data on environmental exposures, covariates, or follow-up information, and those with CMM at baseline, 6,330 participants were included in the prospective analysis. Details of participant selection are shown in Fig. 1.

This research protocol was approved by the Peking University Institutional Review Board (Approval No.: IRB 00001052–11015), and all participants provided written informed consent. Additionally, all procedures involving human subjects complied with institutional and/or national research ethics standards, as well as the 1964 Declaration of Helsinki and its subsequent amendments or similar ethical guidelines.

Assessment of Living Environmental Factors

The LEQ composite score, derived from the 2011 CHARLS housing characteristics module, captures cumulative residential environmental advantage/disadvantage. It includes housing type (one-storey = 0, multi-storey = 1), indoor temperature suitability (unsuitable = 0, suitable = 1), tap water access (unavailable = 0, available = 1), household energy fuel use (all solid fuels = 0, mixed fuels = 1, all clean fuels = 2). Household fuel use was assigned 0, 1, or 2 points to reflect an ordinal gradient from solid fuels to mixed use and exclusive clean fuel use. Ambient air pollution, with annual PM_{2.5} exposure obtained from the China High Air Pollutants (CHAP) (available at <https://weijing-rs.github.io/product.html>).^[9,10] dataset linked via participants' residential addresses; concentrations below 35 µg/m³ were scored 1, and those equal to or above 35 µg/m³ scored 0^[11]. Scores were summed to yield a total LEQ score ranging from 0 to 6, with higher values indicating better residential conditions. Participants were categorized into high-risk (0–2), medium-risk (3–4), and low-risk (5–6) groups. Detailed scoring algorithms are provided in Table S1.

CMM Definition

The primary outcome was incident CMM, defined as the co-occurrence of at least two of the following conditions: diabetes, heart disease, and stroke^[2]. The diagnosis of diabetes was evaluated according to the following criteria: fasting plasma glucose (FPG) ≥ 7.0 mmol/L, glycated hemoglobin (HbA1c) level ≥ 6.5%, current utilization of antidiabetic medications, or self-reported diagnosis (e.g., 'Have you been diagnosed with diabetes or hyperglycemia by a physician?')^[12]. The identification of patients with heart disease or stroke mainly depended on self-reported data collected during baseline surveys and follow-up surveys, or the use of any cardiovascular medications. Information regarding heart disease and stroke was obtained through standardized questions: ('Have you ever been diagnosed with coronary heart disease, angina pectoris, congestive heart failure, or other cardiac conditions by a physician?') and ('Have you ever been diagnosed with stroke by a physician?'). Event time was defined as the interval between the previous interview and the interview reporting a new CMM diagnosis. For patients who did not report CMM during the follow-up period, the follow-up duration was determined by the interval between the baseline assessment and the final survey date^[13].

Covariates

Covariates were selected a priori based on previous literature and their potential roles as confounders in the association between residential environment and CMM. Demographic characteristics were categorized as follows: gender (male/female), educational attainment (illiterate, primary school

education, middle school education and above), marital state (married vs. single), smoking status (never smoked, former smoker, current smoker), and residential area (urban vs. rural). Alcohol consumption status: (non-drinker vs. drinker). Continuous demographic and hematological variables encompassed age (in years), sleep duration (in hours), C-reactive protein (CRP, mg/L), body mass index (BMI, kg/m²)^[14], triglycerides (mg/dL), total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C, mg/dL), high-density lipoprotein cholesterol (HDL-C, mg/dL)^[15]. Hypertension was defined as systolic blood pressure ≥ 140 mmHg, diastolic pressure ≥ 90 mmHg, current use of antihypertensive medications, or self-reported diagnosis^[16].

Statistical Analysis

Continuous variables were summarized as median (interquartile range, IQR) and compared using the Kruskal–Wallis test, while categorical variables were presented as frequencies (%) and compared using the chi-square (χ^2) test. Associations between environmental risk factors and incident CMM were assessed using Cox proportional hazards models, with Kaplan–Meier survival curves plotted concurrently. Sensitivity analyses excluded participants with baseline hypertension, those diagnosed with CMM in 2013, and accounted for PM_{2.5} exposure. Subgroup analyses were stratified by age, gender, and housing type. Logistic regression analyses were performed as supplementary analyses. Three models were specified: Model 1 unadjusted; Model 2 adjusted for age, gender, marital status, education, and place of residence; Model 3 further adjusted for smoking, alcohol use, body mass index, sleep duration, hypertension, HDL-C, LDL-C, total cholesterol, triglycerides, and C-reactive protein. High-risk groups in the residential environment score served as reference. Analyses were conducted using R software (v4.5.0), with two-tailed $P < 0.05$ considered statistically significant.

3 Results

Baseline Characteristics of the Population

The baseline characteristics of the study population are summarized in Table 1. The final analysis included 6,330 participants (mean age: 58.0 years; women accounted for 54.7%). During the follow-up period, CMM occurred in 426 participants (7.5%). Compared with the high-risk residential environment group, participants in the low-risk group were younger, more likely to reside in urban areas, had higher education levels, were non-smokers, and exhibited a lower incidence of hypertension ($P < 0.05$). As shown in Table 2, participants who experienced CMM were more likely to reside in single-storey buildings and use non-tap water sources.

Table 1
The Characteristics of Participants in the Baseline

Variable	Overall	High risk (0–2)	Middle risk (3–4)	Low risk (5–6)	P*
No.of participants	6330	2295	3154	881	
Age,years	58.0 [52.0, 64.0]	59.0 [53.0, 66.0]	57.0 [51.0, 63.0]	56.0 [50.0, 62.0]	< 0.001
Gender, n(%)					
Male	2866 (45.3)	1035 (45.1)	1440 (45.7)	391 (44.4)	0.780
Female	3464 (54.7)	1260 (54.9)	1714 (54.3)	490 (55.6)	
Marital status, n(%)					
Single	666 (10.5)	262 (11.4)	314 (10.0)	90 (10.2)	0.211
Married	5664 (89.5)	2033 (88.6)	2840 (90.0)	791 (89.8)	
Smoking status, n(%)					
Nonsmokers	3908 (61.7)	1372 (59.8)	1947 (61.7)	589 (66.9)	0.006
Ever-smokers	502 (7.9)	183 (8.0)	254 (8.1)	65 (7.4)	
Current smokers	1920 (30.3)	740 (32.2)	953 (30.2)	227 (25.8)	
Drinking status, n(%)					
No	3901 (61.6)	1382 (60.2)	1977 (62.7)	542 (61.5)	0.181
Yes	2429 (38.4)	913 (39.8)	1177 (37.3)	339 (38.5)	
Education level, n(%)					
Illiterate	1900 (30.0)	863 (37.6)	877 (27.8)	160 (18.2)	< 0.001
Primary school	2688 (42.5)	993 (43.3)	1319 (41.8)	376 (42.7)	
Middle school and above	1742 (27.5)	439 (19.1)	958 (30.4)	345 (39.2)	
Family residence, n(%)					
Rural	4409 (69.7)	2002 (87.2)	2094 (66.4)	313 (35.5)	< 0.001
Urban	1921 (30.3)	293 (12.8)	1060 (33.6)	568 (64.5)	
Hypertension, n(%)					

Variable	Overall	High risk (0–2)	Middle risk (3–4)	Low risk (5–6)	<i>P</i> *
No	5285 (83.5)	1936 (84.4)	2612 (82.8)	737 (83.7)	0.315
Yes	1045 (16.5)	359 (15.6)	542 (17.2)	144 (16.3)	
BMI ^a	23.1 [20.8, 25.7]	22.5 [20.4, 25.2]	23.3 [20.9, 25.9]	23.7 [21.6, 26.0]	< 0.001
Sleep time	6.0 [5.0, 8.0]	6.0 [5.0, 8.0]	7.0 [5.0, 8.0]	7.0 [5.0, 8.0]	0.001
TG ^b	103.5 [74.3, 152.0]	99.1 [71.7, 146.0]	106.2 [75.2, 152.2]	108.9 [77.0, 163.7]	< 0.001
HDL-C ^c	49.9 [41.0, 60.3]	52.2 [42.5, 62.6]	49.1 [40.2, 59.1]	48.3 [39.8, 57.6]	< 0.001
LDL-C ^d	114.8 [93.9, 138.0]	113.7 [93.6, 135.7]	115.2 [92.8, 138.0]	117.9 [97.4, 142.7]	0.004
CRP ^e	1.0 [0.5, 2.1]	0.9 [0.5, 1.9]	1.0 [0.6, 2.1]	1.1 [0.6, 2.2]	0.003
TC ^f	191.0 [167.4, 215.7]	190.6 [167.0, 216.5]	190.6 [166.6, 214.6]	195.2 [171.7, 217.7]	0.006

a BMI, body mass index; b TG, triglycerides; c HDL-C, high-density lipoprotein cholesterol; d LDL-C, low-density lipoprotein cholesterol; e CRP, C-reactive protein; f TC, total cholesterol.

Table 2
Distribution of Living Environmental Risk Factors in the Baseline

Variable	Overall	Normal	CMM ^a	P*
No.of participants	6330	5903	426	
LEQ score				
High risk	2295 (36.3)	2121 (35.9)	174 (40.8)	0.006
Middle risk	3154 (49.8)	2940 (49.8)	213 (50.0)	
Low risk	881 (13.9)	842 (14.3)	39 (9.2)	
Household energy fuel, n(%)				
All solid	1593 (25.2)	1484 (25.1)	109 (25.6)	0.967
Mixed fuel	1892 (29.9)	1764 (29.9)	128 (30.0)	
All clean	2845 (44.9)	2655 (45.0)	189 (44.4)	
Housing type, n(%)				
One-storey building	4394 (69.4)	4050 (68.6)	343 (80.5)	< 0.001
Multi-storey building	1936 (30.6)	1853 (31.4)	83 (19.5)	
Indoor temperature, n(%)				
Unsuitable	985 (15.6)	916 (15.5)	69 (16.2)	0.761
Suitable	5345 (84.4)	4987 (84.5)	357 (83.8)	
Water source, n(%)				
Non-tap water use	2778 (43.9)	2567 (43.5)	210 (49.3)	0.022
Tap water use	3552 (56.1)	3336 (56.5)	216 (50.7)	
Outdoor PM _{2.5} , n(%)				
PM _{2.5} ^b (≥ 35µg/m ³)	5675 (89.7)	5292 (89.6)	383 (89.9)	0.932
PM _{2.5} (<35µg/m ³)	655 (10.3)	611 (10.4)	43 (10.1)	

a CMM:Cardiometabolic multimorbidity; b PM_{2.5}, particulate matter with an aerodynamic diameter < 2.5 µm.

Association Between Composite Living Environmental Factors and CMM

The association between LEQ and incident CMM was further visualized using Kaplan-Meier survival curves (Fig. 2). Over the 7-year follow-up period, the curves for the three LEQ risk strata diverged

significantly (log-rank test, $P = 0.021$). In Cox models (Table 3), compared with the high-risk reference, the fully adjusted hazard ratios (HRs) for incident CMM were 0.52 (95% CI: 0.37–0.72, $P < 0.001$) for the low-risk group and 0.78 (95% CI: 0.64–0.95, $P = 0.016$) for the middle-risk group, with a significant trend across categories ($P < 0.001$). Per unit increase in continuous LEQ was associated with a 26% lower incident CMM hazard (HR: 0.74, 95% CI: 0.64–0.86, $P < 0.001$; Table S2). Supplementary logistic regression analyses showed a similar inverse association between LEQ and incident CMM status (Table S3–S4).

Table 3
Association between LEQ and incident CMM in a cohort study

Variable	Model 1 ^a HR (95% CI)	P^*	Model 2 ^b HR (95% CI)	P^*	Model 3 ^c HR (95% CI)	P^*
High risk	Reference	—	Reference	—	Reference	—
Middle risk	0.88 (0.73–1.06)	0.187	0.84 (0.69–1.02)	0.078	0.78 (0.64–0.95)	0.016
Low risk	0.65 (0.47–0.88)	0.006	0.55 (0.39–0.77)	< 0.001	0.52 (0.37–0.72)	< 0.001
P for trend						< 0.001

a Model 1 was unadjusted. b Model 2 was adjusted for age, sex, marital status, educational level, and residence. c Model 3 was further adjusted for smoking status, drinking status, body mass index, sleep duration, hypertension, TG, HDL-C, LDL-C, CRP, and TC. P for trend was calculated by modeling LEQ risk group as an ordinal variable in the fully adjusted model.

Association Between Individual Environmental Factors and CMM

As presented in Table 4, Cox regression analysis indicated that two environmental factors were consistently and significantly correlated with a reduced risk of CMM. In Model 3, individuals living in multi - building areas presented a 25% reduction in risk (HR = 0.75, 95% CI: 0.65–0.87, $P < 0.001$), and the use of tap water was associated with a 21% lower risk ((HR = 0.79, 95% CI: 0.69–0.90, $P < 0.001$). In the cross - sectional analysis (Table S5), multi - building environments (OR: 0.50, 95% CI: 0.39–0.64, $P < 0.001$) and tap water (OR: 0.74, 95% CI: 0.60–0.91, $P = 0.004$) continued to demonstrate robust protective effects, which were in line with the prospective findings. Conversely, no significant associations were observed between household energy fuel type and outdoor PM_{2.5} level, potentially attributable to its intricate interaction with other environmental factors. The association between suitable indoor temperature and reduced CMM risk was of borderline significance in the fully adjusted model (HR = 0.86, 95% CI: 0.73–1.20, $P = 0.083$).

Table 4
Association between Living Environmental Factors and CMM

Variable	Model 1 HR (95% CI)	P*	Model 2 HR (95% CI)	P*	Model 3 HR (95% CI)	P*
Housing type (Multi vs one)	0.75 (0.65–0.86)	< 0.001	0.75 (0.65–0.87)	< 0.001	0.75 (0.65–0.87)	< 0.001
P for trend	< 0.001		< 0.001		< 0.001	
Indoor temperature (Suitable vs Unsuitable)	0.89 (0.76–1.05)	0.175	0.89 (0.76–1.06)	0.187	0.86 (0.73–1.20)	0.083
P for trend	0.175		0.187		0.083	
Water Source (Tap vs Non-tap)	0.76 (0.67–0.86)	< 0.001	0.76 (0.67–0.87)	< 0.001	0.79 (0.69–0.90)	< 0.001
P for trend	< 0.001		< 0.001		< 0.001	
Household energy fuel						
Mixed fuel (vs Solid)	0.95 (0.80–1.13)	0.563	0.96 (0.81–1.14)	0.669	0.90 (0.76–1.07)	0.223
All clean (vs Solid)	0.99 (0.85–1.16)	0.933	1.11 (0.94–1.31)	0.214	0.98 (0.83–1.15)	0.780
P for trend	0.676		0.770		0.526	
Outdoor PM _{2.5} (< 35 vs ≥ 35 µg/m ³)	0.93 (0.75–1.15)	0.496	0.96 (0.78–1.19)	0.736	0.92 (0.76–1.14)	0.444
P for trend	0.496		0.736		0.444	

Reference categories were one-storey building, unsuitable room temperature, non-tap water use, solid fuel use, and PM_{2.5} ≥35 µg/m³, respectively.

4 Sensitive Analysis

First, the exclusion of participants with baseline hypertension ensured that the observed associations were not driven by pre-existing conditions, reinforcing the robustness of the environmental quality-CMM link. The results indicated that the inverse association between higher LEQ scores and incident CMM remained significant. Specifically, in the fully adjusted model (Model 3), participants in the low-risk LEQ

group exhibited a 30% reduction in CMM risk compared with the high-risk group (HR = 0.70, 95% CI: 0.53–0.92, $P = 0.010$), whereas the middle-risk group showed no significant difference (HR = 0.97, 95% CI: 0.83–1.15, $P = 0.759$), with a significant linear trend across categories (P for trend = 0.036) (Table S6). Using LEQ as a continuous variable, each one-unit increase in LEQ was associated with a 7% reduction in incident CMM hazard in the fully adjusted model (HR = 0.93, 95% CI: 0.87–0.99, $P = 0.018$) (Table S7).

Second, to reduce potential reverse causation from early events, participants who developed CMM during the 2013 follow-up were excluded. The protective association of LEQ with incident CMM remained materially unchanged. In the fully adjusted categorical model, low-risk participants had a 53% lower risk compared to high-risk participants (HR = 0.47, 95% CI: 0.32–0.68, $P < 0.001$), and a significant trend persisted across LEQ categories (P for trend < 0.001) (Table S8). Similarly, continuous LEQ analysis yielded a consistent inverse association (Table S9).

Third, to examine the influence of ambient air pollution, $PM_{2.5}$ was removed from the LEQ index. The association between non-air-quality residential factors and incident CMM remained robust. In fully adjusted models, the low-risk categorical group showed a 48% reduced risk compared to the high-risk group (HR = 0.52, 95% CI: 0.29–0.93, $P = 0.027$), with the trend test remaining significant (P for trend = 0.021). Moreover, each unit increase in continuous LEQ corresponded to a 24% lower hazard of incident CMM (HR = 0.76, 95% CI: 0.66–0.88, $P < 0.001$), (Tables S10–S11).

Overall, these sensitivity analyses indicate that the observed protective effect of higher residential environmental quality on incident CMM is robust across different model specifications, after excluding participants with baseline hypertension, early incident cases, and when air pollution was not included in the LEQ score.

5 Subgroup Analyses

Subgroup analyses were conducted by gender, age (< 60 vs. ≥ 60 years), and family residence (rural vs. urban). Using categorical LEQ, low-risk females showed a 52% lower risk of incident CMM (HR = 0.48, 95% CI: 0.31–0.73), whereas the association in males was attenuated (HR = 0.60, 95% CI: 0.34–1.04; P for interaction = 0.884). Participants < 60 and ≥ 60 years had similar protective effects (HR = 0.54 and 0.47, respectively; P for interaction = 0.005). Rural residents benefited most (HR = 0.31, 95% CI: 0.15–0.64), whereas the effect in urban residents was nonsignificant (HR = 0.70, 95% CI: 0.42–1.14; P for interaction = 0.12) (Table S12). Continuous LEQ analyses yielded consistent results, with each one-unit increase associated with lower CMM risk across all subgroups. Overall, the protective effect of higher LEQ was robust, most pronounced in females and rural residents, with no significant interactions for gender or age (Table S13).

6 Discussions

This study used a comprehensive evaluation methodology by integrating various residential environmental dimensions, such as housing type, indoor temperature suitability, tap water supply, household fuel usage, and ambient PM_{2.5} exposure, into a single LEQ index. We identified a significant association between higher residential environmental quality and a reduced incidence of cardiovascular CMM. This inverse association remained consistent across multiple sensitivity analyses. Compared to analyses focusing solely on individual environmental factors, this multidimensional approach more accurately reflects real-world exposure patterns, particularly in low-and middle-income areas where environmental disadvantages are often concentrated. Consequently, the findings support the critical role of the cumulative residential environment framework in understanding cardiometabolic health.

Among the five influencing factors, both prospective studies and cross-sectional analyses have demonstrated a significant association between residing in multi-storey housing and a reduced risk of CMM, and this association persists even after full adjustment for variables. This finding aligns with recent China-based research, which indicates that poor housing conditions are associated with an increased risk of cardiovascular disease in middle-aged and elderly individuals^[17]; it also conforms to the public health theoretical framework that emphasizes housing as a core determinant of cardiovascular health^[18]. Meanwhile, access to tap water serves as a robust protective factor, likely reflecting both safer water quality and more robust local infrastructure—a conclusion consistent with previous studies linking piped water supply to reduced chronic disease risks^[19–22]. The modest protective trend observed for suitable indoor temperature may stem from self-reported data or seasonal behavior adaptation factors, thereby limiting the accuracy of exposure assessments^[23, 24–26]. After comprehensive adjustment, neither household energy fuel use nor ambient PM_{2.5} concentrations showed independent associations with CMM incidence, potentially reflecting simplified exposure assessment methods, residual confounding factors, or the complex nature of the CMM endpoint^[27–29]. These results suggest that environmental factors may not act independently but rather synergistically, highlighting the potential cumulative and interactive effects of housing conditions on cardiometabolic health and reinforcing the view that housing and household infrastructure are upstream social determinants of cardiometabolic health^[23, 18].

The strong correlation between the LEQ composite index identified in this study and CMM risk suggests that adverse living environments may exert cumulative effects through multi-level, interconnected biological, behavioral, and psychosocial mechanisms, particularly predisposing to multisystem comorbidities. First, at the biological level, prolonged exposure to poor living conditions (e.g., suboptimal temperature, indoor air pollution) induces sustained physiological stress responses. Chronic low-grade inflammation and oxidative stress triggered by environmental stressors accelerate vascular damage and insulin resistance^[18, 30–33]. Oxidative stress impairs vascular endothelial function, promotes atherosclerosis progression, and contributes to hypertension. Studies demonstrate that low-grade inflammatory markers such as CRP and interleukin-6 (IL-6) exacerbate insulin resistance and vascular dysfunction, thereby facilitating CMM development. This systemic inflammation serves as a common underlying factor for both atherosclerosis and insulin resistance. Concurrently, thermal stress and

suboptimal living environments may disrupt autonomic nervous system function, leading to excessive sympathetic activation, vasoconstriction, and elevated blood pressure^[24, 25]. Additionally, prolonged exposure to poor living conditions may disrupt circadian rhythms, further increasing the risk of metabolic disorders and hypertension. Second, behavioral and lifestyle modifications constitute critical intermediate factors. Physical constraints of living environments—particularly the absence of staircases, lack of safe drinking water, and high outdoor pollution levels—directly reduce daily physical activity, limit healthy behaviors (e.g., exercise, hydration), and increase reliance on energy-intensive heating/cooling systems. These behavioral changes often contribute to the onset of metabolic diseases such as obesity, hypertension, and diabetes. From a societal perspective, adverse living conditions may reflect broader socioeconomic vulnerability: individuals simultaneously face challenges including environmental and material resource scarcity, lower educational attainment, and limited access to healthcare resources—all of which may indirectly increase the risk of CMM^[31]. Collectively, these biological and sociological mechanisms indicate that the occurrence of CMM is influenced not only by aging and individual lifestyle factors but also closely associated with prolonged exposure to suboptimal environments. These findings support an ecological explanation for CMM as the result of the interplay between individual susceptibility and cumulative environmental vulnerability—consistent with previous studies demonstrating that a combination of lifestyle risk factors, cumulative social disadvantages, and exposure to multiple pollutants predicts cardiovascular metabolic outcomes more effectively than any single factor^[34,31–33].

In the subgroup analysis, the protective effect associated with higher LEQ levels was more pronounced among women and rural residents, although the interaction test results did not reach statistical significance. This phenomenon is reasonable: women may spend more time in household settings, thereby experiencing prolonged cumulative exposure to home-based living conditions; meanwhile, rural residents in China are more susceptible to multiple infrastructure disadvantages, including poor housing conditions, lack of tap water supply, and limited access to environmental facilities. Consequently, improving living environments may yield more significant marginal health benefits for these populations. This interpretation is largely consistent with findings from several previous China studies, which indicate that environmental and infrastructure disadvantages remain key determinants of the chronic disease burden among rural populations^[35, 28, 19, 20].

Several limitations should also be acknowledged. First, some environmental variables were self-reported and measured only at baseline, which may have introduced exposure misclassification and prevented us from assessing temporal changes in residential conditions. Second, the composite LEQ score was based on a simple additive approach and did not account for potential differences in the relative importance of each component or their possible interactions. Third, heart disease and stroke were primarily identified using self-reported information, which may have led to under-ascertainment or misclassification. Fourth, our complete-case approach excluded a substantial number of participants with missing data, which may have introduced selection bias. Finally, residual confounding from unmeasured factors such as income, diet, occupation, or healthcare access cannot be ruled out.

7 Conclusion

The better living environmental quality was associated with a substantially lower risk of incident CMM among middle-aged and older Chinese adults. The most consistent protective associations were observed for housing type and tap-water access. Overall, these findings highlight the potential importance of healthy housing and basic household infrastructure in understanding environmental determinants of CMM and may inform future strategies for chronic disease prevention and healthy ageing.

Abbreviations

CMM Cardiometabolic multimorbidity

LEQ Living environmental quality

CVD Cardiovascular disease

CHARLS The China Health and Retirement Longitudinal Study

IQR Interquartile range

HR Hazard ratio

CI Confidence interval

BMI Body mass index

TG Triglyceride

TC, *Total cholesterol.*

HDL-C High-density lipoprotein cholesterol

LDL-C, *Low-density lipoprotein cholesterol*

CRP C-reactive protein

Declarations

CRedit Authorship Contribution Statement

Hao Chen was responsible for Data curation, Methodology, Software, Validation, Visualization, and Writing-original draft; **Shengnan Yue** was responsible for Investigation, Supervision, and Validation; **Shengyan Hou** was responsible for Data curation and Writing-review & editing; **Liying Wu** was responsible for Data curation, Writing-review & editing, and Formal analysis; **Yiqiang Wang** was

responsible for Writing-review & editing, Resources, and Project administration; **Jiajuan Guo** was responsible for Writing- review & editing, Supervision, and Project administration.

Ethical Approval

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and approved by the Biomedical Ethics Committee of Peking University (IRB 00001052-11015). Written informed consent was obtained from all participants included in this study.

Clinical trial number: not applicable

This study is a secondary analysis of data from the China Health and Retirement Longitudinal Study (CHARLS), a population-based prospective observational cohort study. No experimental interventions were performed, and thus this study is not a clinical trial requiring registration.

Consent for participation

Not applicable.

Consent for publication

Not Applicable. This study utilized publicly available, anonymized data from the China Health and Retirement Longitudinal Study (CHARLS). No identifying images or personal clinical details that could compromise participant anonymity were included in the manuscript, so individual informed consent for publication was not required.

Availability of Data and Materials

The datasets analyzed in the current study were derived from the China Health and Retirement Longitudinal Study (CHARLS), which is publicly accessible to qualified researchers upon application via the official website: <https://charls.pku.edu.cn/>. The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request, subject to the CHARLS data access policy and ethical requirements.

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Declaration of Competing Interest

The authors declare that there are no known financial conflicts of interest or personal connections that might have affected the research presented in this article.

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Figures

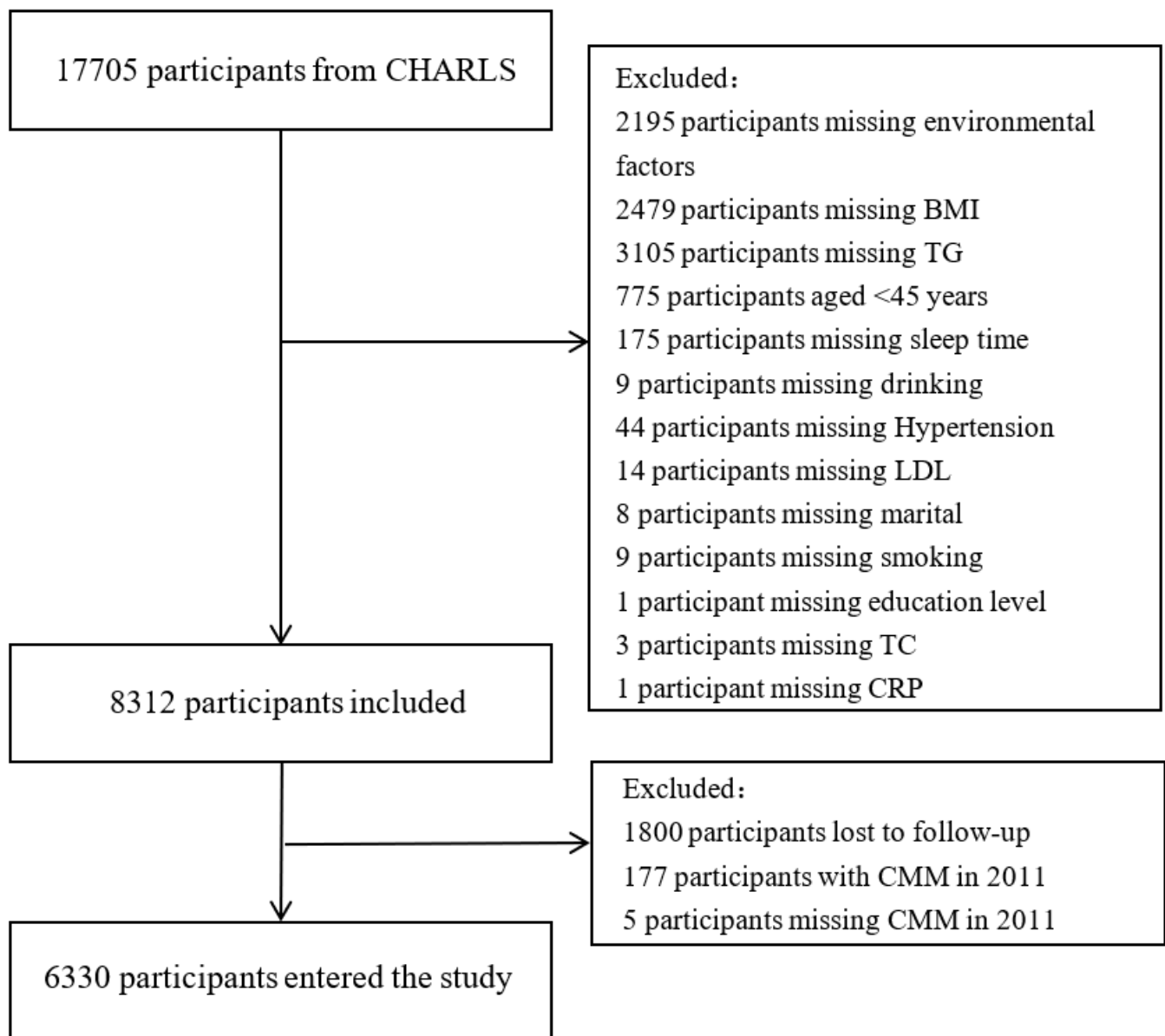


Figure 1

Flow chart of inclusion and exclusion of participants. CMM: Cardiometabolic multimorbidity.

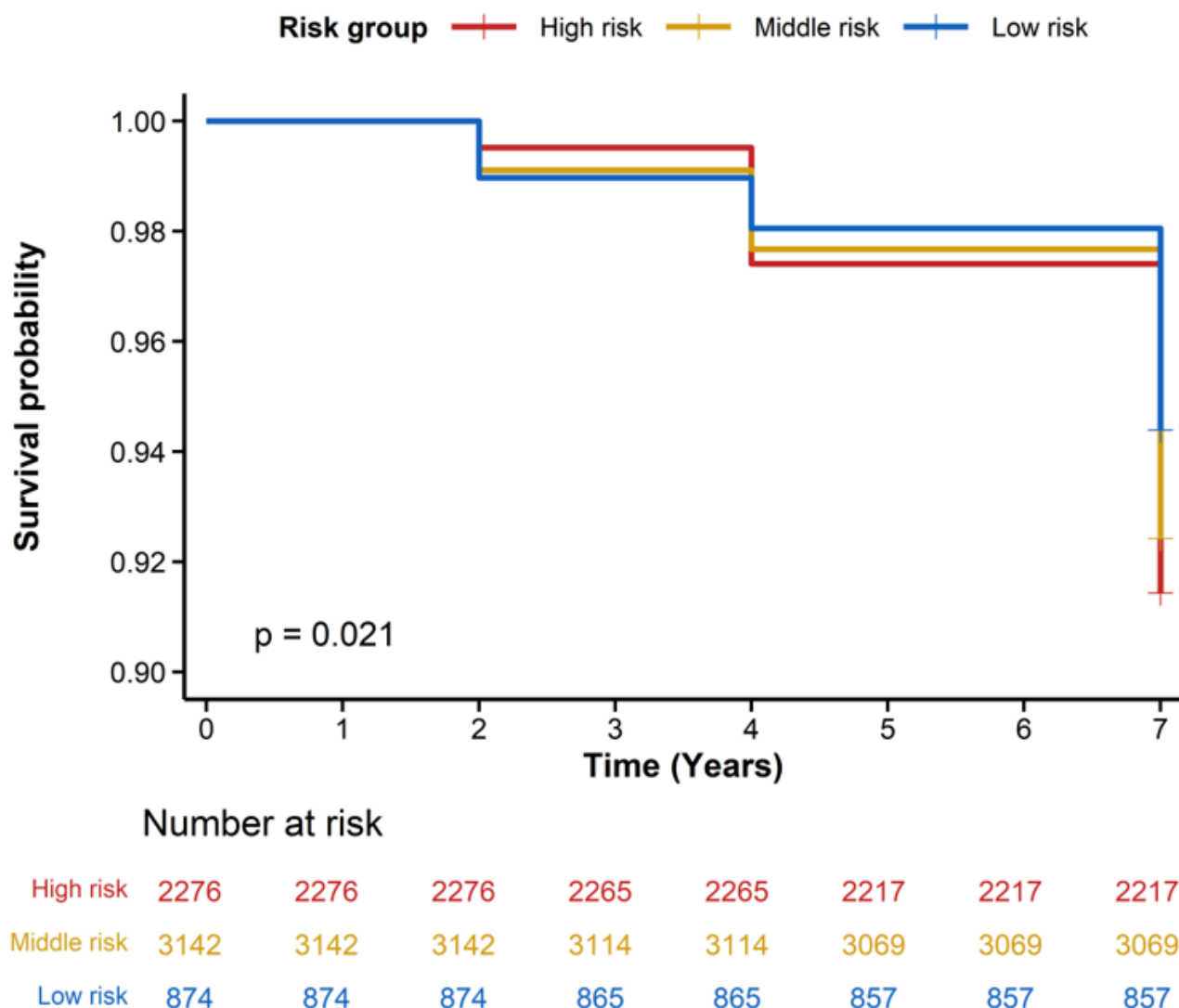


Figure 2

Kaplan-Meier curves of incident CMM according to LEQ risk groups.

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