

Solid fuel use and heart disease in middle-aged and older Chinese populations: a prospective cohort study

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ABSTRACT

BACKGROUND Solid fuel use for cooking and heating is a major environmental risk factor, yet its association with new-onset heart disease (HD) remains unclear. The aim of this study was to investigate the relationship between solid fuel exposure and new-onset HD in a large cohort.

METHODS Multivariable logistic regression models assessed associations between cooking/heating fuel types (coal, crop residue/wood, liquefied petroleum gas, natural gas, and others) and new-onset HD. Subgroup analyses explored effect modification by age, sex, education, smoking, alcohol use, and region.

RESULTS A prospective cohort study included 5915 participants, with 781 participants (13.2%) developing new-onset HD. Coal use for cooking showed an initial association with new-onset HD risk (OR = 1.41, 95% CI: 1.06–1.86, $P = 0.02$), which attenuated after full adjustment (OR = 1.28, 95% CI: 0.96–1.72, $P = 0.10$). Coal use for heating demonstrated robust associations across all models (OR = 1.86, 95% CI: 1.42–2.43, $P < 0.001$). Crop residue/wood burning for heating was also significant (Model 2: OR = 1.40, 95% CI: 1.06–1.86, $P = 0.02$). Subgroup analyses revealed stronger associations among females, non-smokers, non-drinkers, and less-educated participants. Geographic stratification showed significant associations in southern but not northern regions.

CONCLUSIONS Solid fuel use, particularly coal for heating, is associated with increased new-onset HD risk. Reducing solid fuel exposure is crucial for HD prevention in low-resource settings.

Heart disease (HD) remains the leading cause of morbidity and mortality worldwide, accounting for nearly 18 million deaths annually.^[1] In China, the burden of HD has escalated dramatically over the past three decades, driven by urbanization, aging populations, and shifts in lifestyle factors.^[2] While traditional risk factors such as hypertension, diabetes mellitus (DM), and smoking have been extensively studied,^[3] emerging evidence suggests that the environmental exposure, particularly indoor air pollution from solid fuel use, may play a significant role in the development of HD.^[4] Solid fuels, including coal, wood, and crop residues, are widely used for cooking and heating in rural and low-income households in China.^[5] Combustion of these fuels generates high levels of harmful pollutants, including fine particulate matter (PM_{2.5}), carbon monoxide, and polycyclic aromatic hydrocarbons, which have been linked to systemic inflammation, oxidative stress, and endothelial dysfunction.^[6]

However, the association between solid fuel use and new-onset HD, especially among middle-aged and older adults, a population at heightened risk for cardiovascular events, remains underexplored.^[7]

Prior studies have primarily focused on respiratory outcomes or all-cause mortality related to solid fuel use,^[8] with limited longitudinal evidence on its cardiovascular implications.^[9] Furthermore, most research has been conducted in high-income countries or urban settings,^[10] neglecting the unique socio-environmental context of rural China, where solid fuel use remains prevalent.^[11] Given the rapid demographic transition in China, understanding the cardiovascular risks associated with solid fuel use is crucial for informing public health interventions and policy de-

cisions aimed at reducing the burden of HD.^[12] The China Health and Retirement Longitudinal Study (CHARLS) provides a unique opportunity to address this gap.^[13] As a nationally representative cohort, CHARLS offers detailed data on household fuel use, health outcomes, and potential confounders, enabling a robust examination of the relationship between solid fuel use and new-onset HD. Leveraging this rich dataset, our study aims to investigate whether the use of solid fuels for cooking or heating is associated with an increased risk of new-onset HD among Chinese adults aged 45 years and older.

We hypothesize that solid fuel use is independently associated with a higher incidence of HD, mediated by prolonged exposure to indoor air pollution.^[14] By elucidating this relationship, our findings will contribute to the growing body of evidence on the cardiovascular risks of environmental exposure and underscore the urgent need for policies promoting clean energy adoption in vulnerable populations.^[15,16]

This study is particularly timely, as China's ongoing transition from traditional to modern energy sources presents a critical window of opportunity to mitigate the health impacts of solid fuel use. Our findings will provide actionable insights for public health strategies aimed at reducing the burden of HD in China and other low- and middle-income countries facing similar challenges.

METHODS

Study Population

The CHARLS study is a prospective cohort that is nationally representative, covering 450 communities and villages in 150 counties throughout China.^[17] The national baseline survey was first executed in 2011, and four more tracking surveys were conducted from 2011 through 2020.^[17] In similar global projects, CHARLS stands out with its high access response rate and data quality, offering an accurate portrayal of the older adult population in China. Approval for this study has been granted by the Ethics Committee at Peking University School of Medicine, with informed consent acquired from each participant prior to their involvement.

The initial cohort comprised 10,697 participants free of HD at baseline. After applying the inclusion criterion (age ≥ 45 years), 10,529 individuals remained following the exclusion of those with missing values in key variables: sex ($n = 7$), alcohol consumption ($n = 4$), DM ($n = 80$), chronic

kidney disease ($n = 29$), hypertension ($n = 33$), education ($n = 10$), and stroke history ($n = 5$). Excluding participants with missing systolic blood pressure (SBP) values further reduced the cohort to 8589 individuals ($n = 1940$ excluded). A further 2281 participants were excluded due to missing low-density lipoprotein cholesterol (LDL-C) data, reducing the sample to 6308 individuals. Finally, 393 participants were excluded due to missing data on heating-related variables, yielding a final analytical sample of 5915 participants (supplemental material, Figure 1S).

Assessment of Fuel

Data on primary household energy sources for heating and cooking were collected using a structured questionnaire. The assessment of solid fuel exposure was based on self-reported data. Participants were specifically asked to identify their primary energy sources for household heating (Question I021) and cooking (Question I022) within the study questionnaire. Participants selected their main heating energy source from seven options: solar energy, coal/honeycomb coal, natural gas (pipeline or coal-derived), liquefied petroleum gas (LPG), electricity, crop residue/wood burning, or "other". Similarly, cooking fuel sources were categorized as coal/honeycomb coal, natural gas, marsh gas (biogas), LPG, electricity, crop residue/wood burning, or "other". Fuel types were classified as solid fuels (coal, crop residue, wood burning) or clean fuels (natural gas, LPG, electricity, solar, biogas, and unspecified "other") based on World Health Organization criteria. This classification guided exposure analysis in subsequent heart health assessments.

Assessment of New-onset HD

New-onset HD is identified in patients who were not diagnosed with the condition at the start of the follow-up but acquired it during the follow-up period. To diagnose HD, doctors ask if the patient has been diagnosed with a heart attack, coronary HD, angina, congestive heart failure, or other heart problems. This survey excluded patients diagnosed with HD in 2011, while those diagnosed post-2011 were considered new-onset HD.

Covariates

Based on existing literature and clinical experience, the covariates considered in this survey include age, sex (male, female), education level (no formal education, primary school, middle school, college or above), residential status



(rural, urban), geographical region (south, north), smoking status (no, yes), drinking status (no, yes), high-density lipoprotein cholesterol (HDL-C), LDL-C, triglyceride (TG), total cholesterol, glucose, serum creatinine, urea, body mass index, SBP and diastolic blood pressure (DBP). Moreover, chronic disease status including stroke, hypertension, DM, dyslipidemia and chronic kidney diseases were included to facilitate our investigation. The data of stroke is from self-reported information. Hypertension patient refers to individual with at least one of these situations: self-reported hypertension, using of antihypertensive drugs recently or the three or more consecutive blood pressure measurement results that SBP ≥ 140 mmHg and/or DBP ≥ 90 mmHg.^[18] DM means recent use of hypoglycemic drugs or fasting blood glucose over 7 mmol/L or postprandial blood glucose over 11 mmol/L.^[19] Dyslipidemia is defined as the presence of LDL-C ≥ 3.4 mmol/L or HDL-C ≤ 0.9 mmol/L, as well as TG ≥ 2 mmol/L.^[20] Chronic kidney disease is diagnosed by glomerular filtration rate ≤ 90 mL/min per 1.73 m² for more than 3 months.^[21]

Statistical Analysis

Baseline characteristics were obtained from the 2011 CHARLS dataset, with continuous variables presented as mean $\pm$ SD and categorical variables expressed as counts (percentages). To address the potential influence of missing data, covariates were imputed using the multiple imputation by chained equations. The independent samples *t*-tests were used to compare characteristics between participants with and without new-onset HD. Three multivariable models were constructed: Model 1 (unadjusted any variables), Model 2 [adjusted for demographic factors (age, sex) and lifestyle factors (smoking status, alcohol consumption, education level)], and Model 3 [adjusted for variables in Model 2 plus the serum creatinine, fasting glucose, lipid profile (HDL-C, LDL-C, total cholesterol, TG, urea, hemoglobin A1c), cardiovascular risk factors (hypertension, DM, stroke history), SBP, DBP, body mass index, and residential status]. The analysis was conducted using two approaches: (1) fuel type-specific analysis, where multiple logistic regression examined the association between specific fuel types (solid vs. clean fuels) and new-onset HD; and (2) solid fuel analysis, where logistic regression models calculated odds ratios (ORs) with 95% CI for the association between solid fuel use and new-onset HD. Subgroup analyses were performed to evaluate potential effect modification by sex, education level, residence (urban/rural), geog-

raphic region, smoking status, alcohol consumption, and comorbidities (history of stroke, hypertension, DM, dyslipidemia, and chronic kidney disease). All analyses were performed using R statistical software 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria), with a two-sided *P*-value < 0.05 considered statistically significant.

RESULTS

Study Population Characteristics

The study included 5915 participants (supplemental material, Figure 1S), of whom 781 participants (13.2%) developed new-onset HD. Participants with new-onset HD were significantly older (59.73 ± 8.42 years vs. 57.64 ± 8.54 years, $P < 0.001$) and had higher hemoglobin A1c levels (5.34 ± 0.96 vs. 5.22 ± 0.71 , $P < 0.001$) compared to those without HD (Table 1). No significant differences were observed in serum creatinine (0.76 ± 0.18 mg/dL vs. 0.77 ± 0.18 mg/dL, $P = 0.22$) or urea levels (4.38 ± 1.28 mmol/L vs. 4.41 ± 1.21 mmol/L, $P = 0.51$) between the two groups (Table 1). Participants with new-onset HD exhibited higher total cholesterol (198.03 ± 37.88 mg/dL vs. 193.28 ± 37.48 mg/dL, $P < 0.01$) and LDL-C levels (120.92 ± 34.92 mg/dL vs. 116.00 ± 34.24 mg/dL, $P < 0.001$), while HDL-C (51.26 ± 15.36 mg/dL vs. 51.82 ± 15.22 mg/dL, $P = 0.34$) and TG (131.33 ± 84.32 mg/dL vs. 129.17 ± 99.11 mg/dL, $P = 0.52$) showed no significant differences (Table 1). Blood pressure measures also differed significantly, with higher SBP (132.90 ± 21.48 mmHg vs. 128.09 ± 20.54 mmHg, $P < 0.001$) and DBP (77.11 ± 12.47 mmHg vs. 75.01 ± 11.85 mmHg, $P < 0.001$) in the new-onset group (Table 1). Smoking and alcohol consumption patterns also differed significantly, with a lower proportion of smokers (33.80% vs. 38.12%, $P = 0.02$) and drinkers (30.35% vs. 34.36%, $P = 0.03$) in the HD group (Table 1). Participants with new-onset HD had a higher prevalence of stroke (2.82% vs. 1.44%, $P < 0.01$), hypertension (30.99% vs. 17.78%, $P < 0.001$), and DM (6.66% vs. 3.60%, $P < 0.001$) compared to those without HD (Table 1). Pooled solid fuel exposure for cooking showed a borderline significant difference (63.00% vs. 59.41%, $P = 0.06$), while solid fuel exposure for heating was significantly higher in the new-onset group (68.89% vs. 57.64%, $P < 0.001$) (Table 1). More detailed information regarding the characteristics of our study population is presented in Table 1. The baseline characteristics of the study population, following multiple imputation for missing data, are summarized in supplemental material, Table 5S.



Table 1 Baseline characteristics of study participants stratified by incident heart disease status.

Variable	Total (n = 5915)	No (n = 5134)	Yes (n = 781)	P-value
Age, yrs	57.92 ± 8.55	57.64 ± 8.54	59.73 ± 8.42	< 0.001
Hemoglobin A1c	5.24 ± 0.75	5.22 ± 0.71	5.34 ± 0.96	< 0.001
Serum creatinine, mg/dL	0.77 ± 0.18	0.77 ± 0.18	0.76 ± 0.18	0.22
Urea, mg/dL	4.40 ± 1.22	4.41 ± 1.21	4.38 ± 1.28	0.51
Total cholesterol, mg/dL	193.91 ± 37.56	193.28 ± 37.48	198.03 ± 37.88	< 0.01
HDL-C, mg/dL	51.75 ± 15.24	51.82 ± 15.22	51.26 ± 15.36	0.34
LDL-C, mg/dL	116.65 ± 34.37	116.00 ± 34.24	120.92 ± 34.92	< 0.001
TG, mg/dL	129.46 ± 97.28	129.17 ± 99.11	131.33 ± 84.32	0.52
Body mass index, kg/m ²	23.33 ± 3.63	23.24 ± 3.58	23.91 ± 3.91	< 0.001
Waist, cm	83.64 ± 12.12	83.35 ± 11.93	85.57 ± 13.16	< 0.001
SBP, mmHg	128.72 ± 20.73	128.09 ± 20.54	132.90 ± 21.48	< 0.001
DBP, mmHg	75.28 ± 11.96	75.01 ± 11.85	77.11 ± 12.47	< 0.001
Sex				< 0.001
Female	3211 (54.29%)	2732 (53.21%)	479 (61.33%)	
Male	2704 (45.71%)	2402 (46.79%)	302 (38.67%)	
Education				< 0.01
College or above	53 (0.90%)	43 (0.84%)	10 (1.28%)	
Middle school	1623 (27.44%)	1447 (28.18%)	176 (22.54%)	
No formal education	2881 (48.71%)	2482 (48.34%)	399 (51.09%)	
Primary school	1358 (22.96%)	1162 (22.63%)	196 (25.10%)	
Smoke				0.02
No	3694 (62.45%)	3177 (61.88%)	517 (66.20%)	
Yes	2221 (37.55%)	1957 (38.12%)	264 (33.80%)	
Drink				0.03
No	3914 (66.17%)	3370 (65.64%)	544 (69.65%)	
Yes	2001 (33.83%)	1764 (34.36%)	237 (30.35%)	
Stroke				< 0.01
No	5819 (98.38%)	5060 (98.56%)	759 (97.18%)	
Yes	96 (1.62%)	74 (1.44%)	22 (2.82%)	
Hypertension				< 0.001
No	4760 (80.47%)	4221 (82.22%)	539 (69.01%)	
Yes	1155 (19.53%)	913 (17.78%)	242 (30.99%)	
DM				< 0.001
No	5678 (95.99%)	4949 (96.40%)	729 (93.34%)	
Yes	237 (4.01%)	185 (3.60%)	52 (6.66%)	
Dyslipidemia				< 0.001
No	5484 (92.71%)	4792 (93.34%)	692 (88.60%)	
Unclear	67 (1.13%)	63 (1.23%)	4 (0.51%)	
Yes	364 (6.15%)	279 (5.43%)	85 (10.88%)	
Chronic kidney disease				0.12
No	5622 (95.05%)	4889 (95.23%)	733 (93.85%)	
Yes	293 (4.95%)	245 (4.77%)	48 (6.15%)	
Age, yrs				< 0.001

Continued

Variable	Total (n = 5915)	No (n = 5134)	Yes (n = 781)	P-value
< 65	4640 (78.44%)	4074 (79.35%)	566 (72.47%)	
≥ 65	1275 (21.56%)	1060 (20.65%)	215 (27.53%)	
Cooking fuel				< 0.01
Coal	655 (11.07%)	552 (10.75%)	103 (13.19%)	
Crop residue/Wood burning	2887 (48.81%)	2498 (48.66%)	389 (49.81%)	
Electric	1041 (17.60%)	919 (17.90%)	122 (15.62%)	
Liquefied petroleum gas	779 (13.17%)	693 (13.50%)	86 (11.01%)	
Marsh gas	109 (1.84%)	98 (1.91%)	11 (1.41%)	
Natural gas	404 (6.83%)	346 (6.74%)	58 (7.43%)	
Other	40 (0.68%)	28 (0.55%)	12 (1.54%)	
Heating fuel				< 0.001
Coal	1677 (28.35%)	1386 (27.00%)	291 (37.26%)	
Crop residue/Wood burning	1820 (30.77%)	1573 (30.64%)	247 (31.63%)	
Electric	845 (14.29%)	757 (14.74%)	88 (11.27%)	
Liquefied petroleum gas	101 (1.71%)	92 (1.79%)	9 (1.15%)	
Natural gas	101 (1.71%)	91 (1.77%)	10 (1.28%)	
Other	1233 (20.85%)	1112 (21.66%)	121 (15.49%)	
Solar	138 (2.33%)	123 (2.40%)	15 (1.92%)	
Cooking group				0.06
Clean	2373 (40.12%)	2084 (40.59%)	289 (37.00%)	
Solid	3542 (59.88%)	3050 (59.41%)	492 (63.00%)	
Heating group				< 0.001
Clean	2418 (40.88%)	2175 (42.36%)	243 (31.11%)	
Solid	3497 (59.12%)	2959 (57.64%)	538 (68.89%)	

Data are presented as means $\pm$ SD or *n* (%). DBP: diastolic blood pressure; DM: diabetes mellitus; HDL-C: high-density lipoprotein cholesterol; LDL-C: low-density lipoprotein cholesterol; SBP: systolic blood pressure; TG: triglyceride.

New-onset HD Associated with Cooking Fuel Use

In unadjusted analyses, coal use was associated with significantly increased odds of new-onset HD (OR = 1.41, 95% CI: 1.06–1.86, $P = 0.02$). This association remained significant after adjustment for demographic and lifestyle factors (Model 1: OR = 1.36, 95% CI: 1.02–1.81, $P = 0.04$) but was attenuated following additional adjustment for clinical biomarkers, comorbidities, anthropometric measures, and residential status (Model 2: OR = 1.28, 95% CI: 0.96–1.72, $P = 0.10$) (Table 2). The “other” fuel category demonstrated consistently elevated risks across all models, with progressively stronger associations: unadjusted model (OR = 3.23, 95% CI: 1.60–6.51, $P = 0.001$), Model 1 (OR = 3.59, 95% CI: 1.76–7.30, $P < 0.001$), and Model 2 (OR = 3.36, 95% CI: 1.62–6.95, $P = 0.001$) (Table 2). No significant associations were observed for crop residue/wood burning (Model 2: OR = 1.11,

95% CI: 0.88–1.39, $P = 0.39$), marsh gas (Model 2: OR = 0.95, 95% CI: 0.49–1.84, $P = 0.88$), or LPG (Model 2: OR = 0.90, 95% CI: 0.67–1.22, $P = 0.49$) (Table 2). To address the potential bias introduced by missing data, multiple imputation was performed prior to assessing the association of solid fuel use for cooking with HD (supplemental material, Table 3S).

New-onset HD Associated with Heating Fuel Use

Coal heating showed consistent and robust associations across all analytical models: unadjusted model (OR = 1.81, 95% CI: 1.40–2.33, $P < 0.001$), Model 1 (OR = 1.80, 95% CI: 1.39–2.33, $P < 0.001$), and Model 2 (OR = 1.86, 95% CI: 1.42–2.43, $P < 0.001$) (Table 3). Crop residue/wood burning demonstrated a significant association in Model 2 (OR = 1.40, 95% CI: 1.06–1.86, $P = 0.02$), whereas the association was non-significant in Model 1 (OR = 1.27, 95% CI:



Table 2 Adjusted odds ratios for incident heart disease associated with long-term solid fuel use for cooking, stratified by age and sex.

Character	Model 1		Model 2		Model 3	
	OR (95% CI)	P-value	OR (95% CI)	P-value	OR (95% CI)	P-value
All						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.17 (0.94–1.46)	0.15	1.1 (0.88–1.37)	0.42	1.11 (0.88–1.39)	0.39
Marsh gas	0.85 (0.44–1.62)	0.61	0.9 (0.47–1.74)	0.76	0.95 (0.49–1.84)	0.88
Natural gas	1.26 (0.90–1.77)	0.17	1.22 (0.87–1.72)	0.24	1.13 (0.80–1.60)	0.50
Liquefied petroleum gas	0.93 (0.70–1.25)	0.65	0.93 (0.70–1.25)	0.65	0.9 (0.67–1.22)	0.49
Other	3.23 (1.60–6.51)	0.001	3.59 (1.76–7.30)	< 0.001	3.36 (1.62–6.95)	0.001
Coal	1.41 (1.06–1.86)	0.02	1.36 (1.02–1.81)	0.04	1.28 (0.96–1.72)	0.10
Male						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.06 (0.76–1.49)	0.71	0.96 (0.68–1.35)	0.79	0.99 (0.69–1.42)	0.95
Marsh gas	0.87 (0.33–2.30)	0.78	0.91 (0.35–2.42)	0.86	0.91 (0.34–2.45)	0.86
Natural gas	0.96 (0.55–1.67)	0.88	0.93 (0.53–1.63)	0.81	0.87 (0.48–1.56)	0.64
Liquefied petroleum gas	0.78 (0.49–1.25)	0.31	0.79 (0.49–1.26)	0.32	0.81 (0.50–1.30)	0.38
Other	3.08 (1.15–8.23)	0.02	3.23 (1.19–8.77)	0.02	2.64 (0.93–7.52)	0.07
Coal	1.21 (0.78–1.90)	0.39	1.19 (0.75–1.86)	0.46	1.24 (0.78–1.98)	0.37
Female						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.26 (0.95–1.67)	0.11	1.21 (0.90–1.61)	0.20	1.2 (0.89–1.62)	0.24
Marsh gas	0.83 (0.34–2.00)	0.68	0.87 (0.36–2.12)	0.77	0.95 (0.39–2.32)	0.91
Natural gas	1.5 (0.98–2.30)	0.06	1.45 (0.94–2.22)	0.09	1.35 (0.87–2.09)	0.18
Liquefied petroleum gas	1.06 (0.73–1.55)	0.75	1.04 (0.71–1.52)	0.85	0.98 (0.66–1.45)	0.91
Other	3.52 (1.28–9.68)	0.01	3.71 (1.34–10.25)	0.01	3.64 (1.29–10.23)	0.01
Coal	1.55 (1.08–2.24)	0.02	1.5 (1.04–2.17)	0.03	1.34 (0.92–1.96)	0.12
< 65 yrs						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.16 (0.91–1.49)	0.23	1.1 (0.85–1.42)	0.46	1.1 (0.85–1.44)	0.46
Marsh gas	0.56 (0.24–1.31)	0.18	0.6 (0.25–1.41)	0.24	0.62 (0.26–1.48)	0.28
Natural gas	1.36 (0.93–1.97)	0.11	1.3 (0.89–1.89)	0.18	1.18 (0.80–1.73)	0.41
Liquefied petroleum gas	0.92 (0.66–1.28)	0.62	0.93 (0.66–1.30)	0.66	0.88 (0.63–1.24)	0.47
Other	2.52 (1.11–5.72)	0.03	2.89 (1.26–6.65)	0.01	2.66 (1.14–6.21)	0.02
Coal	1.44 (1.04–1.98)	0.03	1.37 (0.99–1.89)	0.06	1.26 (0.91–1.76)	0.17
≥ 65 yrs						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.02 (0.65–1.61)	0.93	1.07 (0.67–1.69)	0.78	1.08 (0.66–1.76)	0.75
Marsh gas	2.61 (0.83–8.24)	0.10	2.79 (0.88–8.83)	0.08	2.86 (0.88–9.30)	0.08
Natural gas	0.93 (0.42–2.05)	0.86	0.96 (0.44–2.13)	0.93	0.99 (0.44–2.25)	0.98
Liquefied petroleum gas	0.96 (0.52–1.79)	0.90	0.97 (0.52–1.81)	0.92	1.03 (0.54–1.95)	0.94
Other	10.44 (1.82–59.90)	0.01	11.81 (2.04–68.38)	0.01	11.74 (1.99–69.46)	0.01
Coal	1.23 (0.67–2.25)	0.51	1.24 (0.67–2.28)	0.50	1.24 (0.66–2.33)	0.51
All						
Clean	Reference		Reference		Reference	
Solid	1.16 (1.00–1.36)	0.06	1.1 (0.94–1.29)	0.25	1.12 (0.94–1.33)	0.19
Male						

Continued

Character	Model 1		Model 2		Model 3	
	OR (95% CI)	P-value	OR (95% CI)	P-value	OR (95% CI)	P-value
Clean	Reference		Reference		Reference	
Solid	1.15 (0.90–1.48)	0.26	1.05 (0.82–1.35)	0.70	1.1 (0.84–1.44)	0.50
Female						
Clean	Reference		Reference		Reference	
Solid	1.17 (0.96–1.43)	0.13	1.14 (0.93–1.41)	0.21	1.14 (0.92–1.43)	0.24
< 65 yrs						
Clean	Reference		Reference		Reference	
Solid	1.18 (0.99–1.41)	0.07	1.12 (0.93–1.35)	0.24	1.14 (0.94–1.39)	0.19
≥ 65 yrs						
Clean	Reference		Reference		Reference	
Solid	0.97 (0.71–1.33)	0.84	0.99 (0.72–1.37)	0.96	0.96 (0.68–1.37)	0.84

Model 1: unadjusted any variables. Model 2: adjusted for age, sex, smoking status, alcohol consumption, and education level. Model 3: adjusted for variables in Model 2 plus the serum creatinine, fasting glucose, HDL-C, LDL-C, total cholesterol, TG, urea, hemoglobin A1c, hypertension, DM, stroke history, SBP, DBP, body mass index, and residential status. DBP: diastolic blood pressure; DM: diabetes mellitus; HDL-C: high-density lipoprotein cholesterol; LDL-C: low-density lipoprotein cholesterol; SBP: systolic blood pressure; TG: triglyceride.

0.97–1.65, $P = 0.08$) (Table 3). No significant associations were observed for other fuel types, including LPG (Model 2: OR = 0.87, 95% CI: 0.42–1.81, $P = 0.72$) and natural gas (Model 2: OR = 0.81, 95% CI: 0.40–1.65, $P = 0.57$) (Table 3). Among male participants, coal heating maintained significant associations in both Model 1 (OR = 1.85, 95% CI: 1.19–2.86, $P = 0.01$) and Model 2 (OR = 1.94, 95% CI: 1.22–3.06, $P = 0.005$). Similarly, female participants showed slightly attenuated but still significant associations in Model 1 (OR = 1.78, 95% CI: 1.29–2.45, $P < 0.001$) and Model 2 (OR = 1.82, 95% CI: 1.30–2.53, $P < 0.001$) (Table 3). Crop residue/wood burning demonstrated borderline significance in male participants (Model 2: OR = 1.60, 95% CI: 1.00–2.56, $P = 0.05$) but not in female participants (Model 2: OR = 1.29, 95% CI: 0.91–1.83, $P = 0.16$) (Table 3). In participants aged ≥ 65 years, coal heating maintained significant associations in both Model 1 (OR = 1.97, 95% CI: 1.11–3.49, $P = 0.02$) and Model 2 (OR = 1.94, 95% CI: 1.07–3.51, $P = 0.03$), whereas crop residue/wood burning showed no significant association (Model 2: OR = 1.43, 95% CI: 0.79–2.59, $P = 0.24$) (Table 3). Solid fuel exposure significantly increased the risk of new-onset HD: overall cohort (OR = 1.70, 95% CI: 1.43–2.01, $P < 0.001$), males (OR = 1.56, 95% CI: 1.19–2.05, $P = 0.001$), females (OR = 1.79, 95% CI: 1.43–2.23, $P < 0.001$), participants aged < 65 years (OR = 1.68, 95% CI: 1.37–2.05, $P < 0.001$), and those aged ≥ 65 years (OR = 1.69, 95% CI: 1.20–2.37, $P = 0.003$) (Table 3 & Figure 1). Multiple imputation was carried out to counteract the bias from missing data before analyzing the relationship between heating with solid fuels and HD (supplemental material, Table 4S).

Subgroup Analysis

Subgroup analyses demonstrated significant associations between cooking-related solid fuel use and new-onset HD across multiple demographic and clinical strata (Figure 2 & supplemental material, Table 1S). Significant associations were observed among non-smokers (OR = 1.216, 95% CI: 1.005–1.476, $P = 0.046$) but not among smokers (OR = 1.080, 95% CI: 0.830–1.413, $P = 0.570$) (Figure 2 & supplemental material, Table 1S). Similarly, significant associations were found among non-drinkers (OR = 1.244, 95% CI: 1.031–1.505, $P = 0.023$) but not among drinkers (OR = 0.997, 95% CI: 0.758–1.315, $P = 0.981$) (Figure 2 & supplemental material, Table 1S). Subgroup analyses of heating-related solid fuel use revealed stronger and more consistent associations with new-onset HD (Figure 2 & supplemental material, Table 2S). Among male participants, solid fuel use was associated with a 51.5% increased odds of new-onset HD (OR = 1.515, 95% CI: 1.176–1.964, $P = 0.001$), and female participants showed a 72.6% increased odds (OR = 1.726, 95% CI: 1.404–2.130, $P < 0.0001$) (Figure 2 & supplemental material, Table 2S). Education-stratified analyses showed significant associations across all subgroups except college or above: primary school (OR = 1.804, 95% CI: 1.302–2.528, $P < 0.001$), no formal education (OR = 1.551, 95% CI: 1.236–1.956, $P < 0.001$), and middle school (OR = 1.635, 95% CI: 1.183–2.279, $P = 0.003$) (Figure 2 & supplemental material, Table 2S). Geographic stratification revealed significant associations in southern regions (OR = 1.406, 95% CI: 1.139–1.736, $P = 0.002$) but not in nor-



Table 3 Adjusted odds ratios for incident heart disease associated with long-term solid fuel use for heating, stratified by age and sex.

Character	Model 1		Model 2		Model 3	
	OR (95% CI)	P-value	OR (95% CI)	P-value	OR (95% CI)	P-value
All						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.35 (1.04–1.75)	0.02	1.27 (0.97–1.65)	0.08	1.4 (1.06–1.86)	0.02
Other	0.94 (0.70–1.25)	0.65	0.9 (0.67–1.21)	0.48	0.95 (0.70–1.28)	0.72
Solar	1.05 (0.59–1.87)	0.87	1.05 (0.58–1.88)	0.87	1.02 (0.56–1.83)	0.96
Liquefied petroleum gas	0.84 (0.41–1.73)	0.64	0.84 (0.41–1.73)	0.64	0.87 (0.42–1.81)	0.72
Natural gas	0.95 (0.47–1.88)	0.87	0.84 (0.42–1.69)	0.63	0.81 (0.40–1.65)	0.57
Coal	1.81 (1.40–2.33)	< 0.0001	1.8 (1.39–2.33)	< 0.0001	1.86 (1.42–2.43)	< 0.0001
Male						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.65 (1.07–2.54)	0.02	1.48 (0.95–2.30)	0.08	1.6 (1.00–2.56)	0.05
Other	1.23 (0.76–1.97)	0.40	1.12 (0.69–1.81)	0.65	1.18 (0.71–1.95)	0.52
Solar	1.4 (0.56–3.55)	0.47	1.41 (0.55–3.59)	0.47	1.39 (0.54–3.59)	0.49
Liquefied petroleum gas	1.14 (0.38–3.39)	0.82	1.1 (0.37–3.31)	0.87	1.11 (0.36–3.40)	0.85
Natural gas	1.19 (0.40–3.57)	0.75	1.17 (0.39–3.50)	0.79	1.13 (0.37–3.49)	0.83
Coal	1.85 (1.20–2.84)	0.01	1.85 (1.19–2.86)	0.01	1.94 (1.22–3.06)	0.005
Female						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.21 (0.88–1.68)	0.25	1.15 (0.82–1.60)	0.41	1.29 (0.91–1.83)	0.16
Other	0.79 (0.55–1.15)	0.22	0.78 (0.54–1.14)	0.20	0.82 (0.56–1.20)	0.30
Solar	0.87 (0.41–1.83)	0.72	0.89 (0.42–1.87)	0.75	0.85 (0.40–1.82)	0.68
Liquefied petroleum gas	0.7 (0.27–1.82)	0.46	0.66 (0.25–1.74)	0.40	0.71 (0.27–1.88)	0.50
Natural gas	0.82 (0.34–1.99)	0.66	0.69 (0.28–1.70)	0.42	0.66 (0.26–1.64)	0.37
Coal	1.82 (1.33–2.50)	< 0.001	1.78 (1.29–2.45)	< 0.001	1.82 (1.30–2.53)	< 0.001
< 65 yrs						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.28 (0.95–1.72)	0.11	1.22 (0.90–1.65)	0.20	1.37 (1.00–1.89)	0.05
Other	0.93 (0.67–1.30)	0.67	0.91 (0.65–1.28)	0.59	0.95 (0.67–1.34)	0.77
Solar	0.98 (0.50–1.91)	0.96	0.98 (0.50–1.93)	0.96	0.92 (0.46–1.82)	0.81
Liquefied petroleum gas	0.84 (0.37–1.88)	0.66	0.82 (0.36–1.87)	0.64	0.82 (0.36–1.87)	0.63
Natural gas	0.93 (0.41–2.11)	0.87	0.89 (0.39–2.02)	0.77	0.77 (0.33–1.77)	0.53
Coal	1.76 (1.32–2.34)	< 0.0001	1.74 (1.30–2.32)	< 0.001	1.79 (1.33–2.43)	< 0.001
≥ 65 yrs						
Electric	Reference		Reference		Reference	
Crop residue/Wood burning	1.33 (0.77–2.30)	0.31	1.4 (0.80–2.45)	0.24	1.43 (0.79–2.59)	0.24
Other	0.85 (0.46–1.56)	0.60	0.89 (0.48–1.66)	0.72	0.92 (0.49–1.75)	0.80
Solar	1.27 (0.39–4.13)	0.70	1.31 (0.40–4.30)	0.66	1.34 (0.40–4.48)	0.63
Liquefied petroleum gas	0.84 (0.18–4.01)	0.83	0.9 (0.19–4.27)	0.89	1.06 (0.22–5.17)	0.94
Natural gas	0.86 (0.23–3.18)	0.83	0.87 (0.23–3.24)	0.84	0.95 (0.25–3.60)	0.94
Coal	1.91 (1.08–3.36)	0.03	1.97 (1.11–3.49)	0.02	1.94 (1.07–3.51)	0.03
All						
Clean	Reference		Reference		Reference	
Solid	1.63 (1.38–1.91)	< 0.0001	1.62 (1.38–1.91)	< 0.0001	1.7 (1.43–2.01)	< 0.0001
Male						

Continued

Character	Model 1		Model 2		Model 3	
	OR (95% CI)	P-value	OR (95% CI)	P-value	OR (95% CI)	P-value
Clean	Reference		Reference		Reference	
Solid	1.51 (1.17–1.96)	0.001	1.5 (1.16–1.95)	0.002	1.56 (1.19–2.05)	0.001
Female						
Clean	Reference		Reference		Reference	
Solid	1.73 (1.40–2.13)	< 0.0001	1.7 (1.38–2.10)	< 0.0001	1.79 (1.43–2.23)	< 0.0001
< 65 yrs						
Clean	Reference		Reference		Reference	
Solid	1.59 (1.32–1.92)	< 0.0001	1.57 (1.30–1.90)	< 0.0001	1.68 (1.37–2.05)	< 0.0001
≥ 65 yrs						
Clean	Reference		Reference		Reference	
Solid	1.69 (1.23–2.33)	0.001	1.72 (1.24–2.37)	0.001	1.69 (1.20–2.37)	0.003

Model 1: unadjusted any variables. Model 2: adjusted for age, sex, smoking status, alcohol consumption, and education level. Model 3: adjusted for variables in Model 2 plus the serum creatinine, fasting glucose, HDL-C, LDL-C, total cholesterol, TG, urea, hemoglobin A1c, hypertension, DM, stroke history, SBP, DBP, body mass index, and residential status. DBP: diastolic blood pressure; DM: diabetes mellitus; HDL-C: high-density lipoprotein cholesterol; LDL-C: low-density lipoprotein cholesterol; SBP: systolic blood pressure; TG: triglyceride.

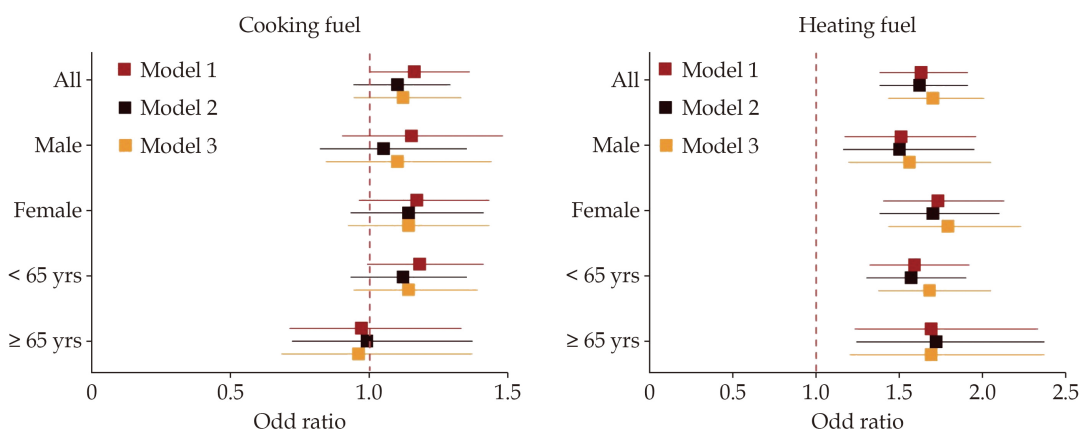


Figure 1 Adjusted odds ratios of heart disease associated with long-term solid fuel use. Model 1: unadjusted any variables. Model 2: adjusted for age, sex, smoking status, alcohol consumption, and education level. Model 3: adjusted for variables in Model 2 plus the serum creatinine, fasting glucose, HDL-C, LDL-C, total cholesterol, TG, urea, hemoglobin A1c, hypertension, DM, stroke history, SBP, DBP, body mass index, and residential status. DBP: diastolic blood pressure; DM: diabetes mellitus; HDL-C: high-density lipoprotein cholesterol; LDL-C: low-density lipoprotein cholesterol; SBP: systolic blood pressure; TG: triglyceride.

them regions (OR = 1.089, 95% CI: 0.797–1.514, $P = 0.600$) (Figure 2 & supplemental material, Table 2S). Significant associations were observed among both smokers (OR = 1.622, 95% CI: 1.229–2.159, $P < 0.001$) and non-smokers (OR = 1.651, 95% CI: 1.358–2.015, $P < 0.0001$), as well as among non-drinkers (OR = 1.802, 95% CI: 1.483–2.199, $P < 0.0001$), while drinkers showed borderline significance (OR = 1.307, 95% CI: 0.988–1.740, $P = 0.063$) (Figure 2 & supplemental material, Table 2S).

DISCUSSION

Solid fuel use is associated with an increased risk of new-

onset HD in middle-aged and older adult populations. While cooking-related solid fuel use showed no significant association with HD risk, heating-related solid fuel use was significantly associated with increased HD risk in this population. Notably, the risk of new-onset HD associated with solid fuel use demonstrates significant geographic variation, with elevated risk observed in urban compared to rural areas and in southern versus northern regions.

The association between the use of solid fuels and HD has garnered significant attention in recent years. Studies have shown that cooking and heating with solid fuels can lead to indoor air pollution, thereby increasing the risk of HD.^[22] In a study in China, the incidence of non-fatal HDs



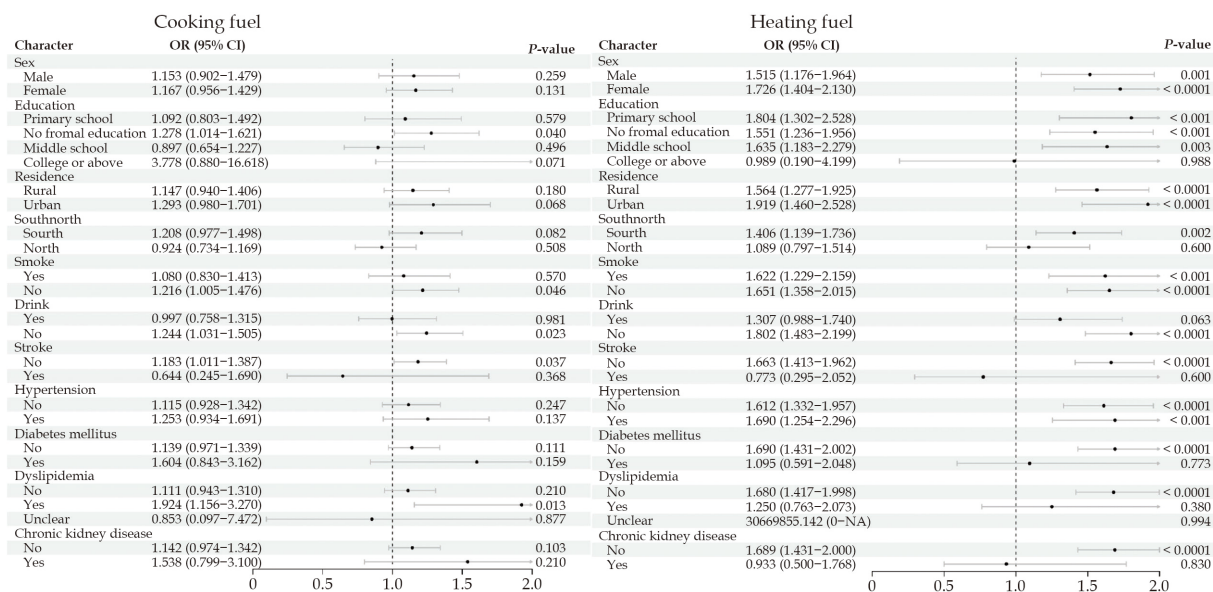


Figure 2 Subgroup analysis of solid fuel use and incident heart disease.

was significantly higher among middle-aged and elderly populations using solid fuels.^[23,24] Additionally, another study pointed out that there is a synergistic effect between the use of solid fuels and the high risk of HD, especially when exposed to high levels of environmental air pollution.^[24] Not only that, long-term use of solid fuels is also associated with an increased mortality rate from HDs. In a study conducted in rural Sichuan, households using solid fuels for cooking or heating had significantly higher all-cause mortality and mortality related to HD compared to those using clean fuels.^[25] Additionally, the study found that the use of solid fuels is linked to an increased risk of atherosclerotic HD, which is particularly evident when exposed to high levels of environmental air pollution.^[26] Globally, the impact of solid fuel use on heart health has also been confirmed. In a study involving 11 countries, households using solid fuels had higher all-cause mortality and incidence of HD compared to those using electricity or gas.^[27] These findings suggest that reducing solid fuel use and improving indoor air quality are crucial for lowering the risk of HD. The association between solid fuel use and HD has been confirmed in a number of studies. By promoting the use of clean energy and improving indoor air quality, the risk of HD can be effectively reduced and public health can be improved.^[28] While previous studies have investigated the association between solid fuel use and HD, most lack longitudinal follow-up data necessary to establish causal relationships. Our findings demonstrate a significant association between solid fuel use and risk of HD. Notably, by focusing on a population free of HD at baseline, this longitudinal study pro-

vides robust evidence that solid fuel use may contribute to new-onset HD. However, as this is an observational study rather than a randomized controlled trial, the evidence for a causal relationship should be interpreted with caution. Further experimental or quasi-experimental studies are warranted to confirm causality.

The use of solid fuels, such as coal and wood, for cooking and heating is prevalent in many parts of the world, particularly in the low- and middle-income countries. This practice is associated with household air pollution, which has been linked to a variety of health issues, including HD. The potential mechanisms through which solid fuel use may contribute to HD are multifaceted and involve both direct and indirect pathways. One of the primary mechanisms is the exposure to fine particulate matter (PM_{2.5}) and other pollutants generated during the combustion of solid fuels.^[7] These pollutants can lead to systemic inflammation and oxidative stress, which are known contributors to the development of atherosclerosis, a major underlying cause of HD. Studies have shown that exposure to indoor air pollution from solid fuels is associated with increased levels of inflammatory markers and oxidative stress, which can damage the heart system and lead to conditions such as hypertension and HD.^[24,26] Moreover, the combustion of solid fuels releases a variety of toxic compounds, including carbon monoxide, polycyclic aromatic hydrocarbons, and volatile organic compounds, which can impair cardiovascular function. Our analysis revealed a more pronounced association between solid fuel use for heating and HD than for cooking. This may be attributab-

le to the typically greater fuel consumption, longer daily exposure periods, and consequently higher indoor pollutant concentrations associated with heating practices compared to cooking.

These compounds can lead to endothelial dysfunction, a precursor to atherosclerosis, by reducing the availability of nitric oxide, a critical molecule for vascular health. The resulting endothelial damage can promote the formation of atherosclerotic plaques and increase the risk of heart attacks and strokes.^[25,27] Another potential mechanism is the impact of solid fuel use on blood pressure. The inhalation of pollutants from solid fuels can lead to an increase in both SBP and DBP, contributing to the development of hypertension, a significant risk factor for HD. A systematic review and meta-analysis have highlighted the association between biomass fuel exposure and elevated blood pressure, further supporting the link between solid fuel use and cardiovascular risk.^[29,30] In addition to direct physiological effects, the use of solid fuels is often associated with socioeconomic factors that can indirectly influence cardiovascular health. For instance, individuals relying on solid fuels may have limited access to healthcare and lower socioeconomic status, which are themselves risk factors for HD. Furthermore, the use of solid fuels is often linked to poor indoor air quality and inadequate ventilation, exacerbating the exposure to harmful pollutants and increasing the risk of heart events.^[31] The evidence suggests that the use of solid fuels for cooking and heating is a significant risk factor for HDs, mediated through pathways involving inflammation, oxidative stress, endothelial dysfunction, and hypertension.^[32,33] Efforts to reduce solid fuel use and promote cleaner energy alternatives could have substantial public health benefits by mitigating these risks and improving heart health outcomes.^[24,31]

In rural area of China, the use of solid fuels remains widespread, significantly impacting the risk of HD and all-cause mortality. Studies show that households using solid fuels for cooking or heating have a markedly increased risk of all-cause mortality.^[25] Therefore, reducing the use of solid fuels and switching to clean energy is a crucial measure to lower the risk of HD. To address the health risks associated with solid fuel use, health policies need to be adjusted accordingly. On the one hand, policymakers should promote the adoption of clean energy, particularly in rural and economically underdeveloped areas. On the other hand, governments can encourage households to switch from solid fuels to more environmentally friendly energy sources through subsidies and incentives. Additionally, enhanc-

ing public awareness of the hazards of solid fuel use and increasing acceptance of clean energy are also crucial directions for policy adjustments. To sum up, the use of solid fuels is closely related to an increased risk of HD, and health policy adjustments should focus on promoting clean energy and raising public awareness to reduce the resulting health burden.

LIMITATIONS

This study had several limitations. Firstly, as a prospective cohort study rather than a randomized controlled trial, our study cannot account for all potential confounders. Nevertheless, we utilized logistic models to adjust for established HD risk factors, thereby substantiating the association between solid fuel use and new-onset HD. Secondly, despite our efforts to control for a range of confounders through multivariable adjustment and sensitivity analyses, residual confounding may still exist. Unmeasured factors, such as more detailed socioeconomic indicators, dietary habits, physical activity levels, and differential access to healthcare, could potentially influence the observed associations between fuel use and cardiovascular outcomes. Thirdly, the exclusion of participants with missing values may introduce selection bias, as their household fuel use patterns were not analyzed. This limitation, inherent to observational studies, was unavoidable due to incomplete data availability. Fourthly, self-reported fuel use data may not fully capture actual pollution exposure variability due to differences in ventilation systems, climatic conditions, and fuel properties. The lack of detailed information on indoor ventilation and stove types further constrained our ability to adjust for these exposure modifiers. Last but not least, although this study employed a prospective cohort design and has established a significant association between solid fuel use and HD, it cannot definitively establish a causal relationship between solid fuel exposure and the incidence of HD. The observational nature of the evidence necessitates cautious interpretation, and further investigations utilizing randomized or quasi-experimental designs are warranted to elucidate causality.

CONCLUSIONS

The use of solid fuels is significantly associated with new-onset HD. While the association between the use of solid fuels for cooking and new-onset HD remains inconclusive, the use of solid fuels for heating is clearly associated with an increased risk of new-onset HD. The HD risk associat-



ed with solid fuel use shows significant geographic variation, with higher risk observed in urban versus rural areas and in southern versus northern regions. Transitioning from solid fuels to clean energy may represent an effective public health intervention for reducing the risk of incident HD.

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