Household Solid Fuel Use Increases Frailty Risk in Chinese Middle-Aged and Older Adults: A Prospective Cohort Study

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Highlights:

Association of household fuel use and frailty in older Chinese adults.

Forty health deficit items were used to assess the frailty index.

Using solid fuels for cooking and heating increases the risk of frailty.

Transitioning to clean fuels reduces frailty risk.

Abstract

Background:

With the aggravation of population aging, frailty has become a major public health issue. However, the association between indoor air pollution from solid fuels and frailty is unclear.

Methods:

We analyzed data collected from 13233 middle-aged and older adults (>45 years) who were non-frail at baseline survey (2011, 2013, 2015, and 2018) from the China Health and Retirement Longitudinal Study (CHARLS) to investigate the association between the use of solid fuels for cooking and frailty. After excluding 1 853 participants with missing data on heating fuel, 11 380 individuals surveyed in 2011, 2013, and 2015 were retained for the heating-fuel analyses. We constructed the frailty index (FI) based on 40 health deficit items. Frailty was defined as FI>0.25. The seven fuel types surveyed were categorized as clean and solid fuels. Time-dependent Cox proportional hazards models were used to analyze the association of solid fuel use for cooking or heating, alone or in combination, with frailty. Cox models were also used to explore the association of fuel type switching. Covariates included individual characteristics, health behaviors, socioeconomic factors, and household dwelling characteristics. Sensitivity analyses were performed to test the robustness of the main results, and interaction and subgroup analyses were performed to explore the influence of potential confounding factors on the results.

Results:

Compared with participants using clean fuels, those using solid fuels had a higher risk of frailty (cooking: HR=1.46,95% Cl: 1.28-1.67, p<0.001; heating: HR=1.58,95% Cl: 1.29-1.94, p<0.001). Participants who switched from solid to clean fuel showed a reduction in the risk of frailty. (HR=0.61, 95% Cl: 0.51-0.73, p<0.001).

Conclusion:

Indoor air pollution caused by solid fuels is associated with an increased risk of frailty among middle-aged and older adults in China. Our findings provide evidence supporting the restriction of solid fuel use and improvement of indoor air quality to protect this population from frailty risk.

Keywords:

Solid fuel use; Indoor air pollution; Frailty; Cox analyses

Introduction

Frailty is an emerging global health burden and represents one of the most challenging consequences of population aging. It is a state of vulnerability to poor resolution of homeostasis after a stressor event and is a consequence of the cumulative decline in many physiological systems during their lifetime [1][2]. Frailty significantly increases the risk of adverse outcomes, such as falls, hospitalization, disability, and mortality. Middle-aged and older adults are particularly vulnerable to these adverse consequences of frailty, as age-related physiological, psychological, and social factors compound risk over time [3]. A systematic review and meta-analysis involving over 120,000 individuals from 28 countries revealed that approximately one in six older adults experienced frailty [3]. Furthermore, frailty imposes substantial economic burdens on individuals, families, and healthcare systems. In an England primary care cohort study of adults aged 50 years and over, compared with the fit category, individual annual costs doubled in mild frailty, tripled in moderate and quadrupled in severe [4]; Similar patterns are observed in developing countries, where frailty contributed to a significantly increased likelihood of Catastrophic health expenditure [5].Moreover, the prevalence of frailty is expected to increase with continued population aging. This presents not only a challenge to individual health but also a major issue for the healthcare system[30]. Therefore, investigating frailty is increasingly important, particularly in identifying prevalent and modifiable factors that may influence its development.

Numerous studies have focused on the association between ambient air pollution and frailty, and exposure to particulate matter (PM_1, $PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), and ozone (O_3),not only has associations with respiratory and cardiovascular systems but also triggers mechanisms implicated in frailty, such as inflammation and mitochondrial dysfunction [6][7]. There have been solid studies showing an association between air pollution and increased risk of frailty [8].However, few studies have examined the association between of indoor air pollution (IAP) on frailty in older adults, despite its significant contribution to health risks. Household solid fuel use is a major contributor to IAP [9]. This underscores the urgency of studying IAP, with a particular focus on solid fuel use as a primary target. Solid fuels primarily include biomass fuels (such as charcoal, fuelwood, dung, agricultural residues, and wood waste) and coal. Their combustion generates substantial emissions, such as particulate matter (PM) [10], carbon monoxide, and nitrogen oxides, leading to high levels of indoor air pollution. In low- and middle-income countries (LMICs), approximately 3.8 billion people rely primarily on solid fuels for household energy [11]. In China, over 700 million people still use solid fuels as their primary household energy sources [12]. Indoor air pollution from solid fuels is an urgent public health issue. Previous studies have established associations between solid fuel use and various health conditions, including cardiovascular disease, diabetes, depression, cognitive impairment, chronic liver disease, gastrointestinal diseases, and respiratory problems [12][13][14][15][16]. These associations indicate that the use of solid fuel significantly increases the risk of adverse health events, suggesting a potential link with frailty.

Moreover, compared with ambient air pollution, household solid fuel use represents a more readily modifiable factor that may be associated with potentially faster improvements in health outcomes following intervention. Therefore, investigating the association between fuel use and frailty is of utmost importance. A systematic review cited in reference [7] identified only five studies that directly examined this association. Notably, none of these studies focused on solid heating fuels, which constitute a critical yet frequently overlooked component of household energy use. Furthermore, the primary research design employed in most of these studies is cross-sectional analysis [17], which limits the ability to assess future incidence and precludes definitive conclusions about causal relationships. Previous cohort studies on fuel-frailty associations have successfully demonstrated such associations;

however, limitations remain, including a short exposure duration (≤3 years) and a sole focus on biomass fuels in one study [18], while another did not specifically examine the incidence of frailty [19]. In summary, previous studies mainly used cross-sectional designs, which could not determine causality, were susceptible to time factors, and the results may be unstable. They also had problems with short follow-up time and insufficient sample size, and heating fuel was an important component of household fuel, which was not included in the analysis in previous studies.

To overcome these limitations and fill the research gap. This study used a longitudinal cohort study to overcome the causal uncertainty and unstable results of the cross-sectional design of previous studies. We used data from CHARLS (follow-up period: 2011-2018, age ≥ 45) to overcome the limitations of the short follow-up period and small sample size of previous studies. The inclusion of heating fuel, which is the other half of household fuel, greatly expands the comprehensiveness of the study. In addition, by observing the conversion of fuel type and the co-use of cooking fuel and heating fuel, the singularity of previous research was broken through. Therefore, the results of this study provide a more comprehensive explanation for the association between household solid fuel consumption and frailty in middle-aged and elderly people.

Methods

2.1 Participants

The China Health and Retirement Longitudinal Study (CHARLS) is led by Peking University [20] and aims to collect high-quality microdata representative of households and individuals aged ≥45 years in China, to analyze population aging issues and promote interdisciplinary research on aging. The national baseline survey of CHARLS started in 2011, covering 150 county-level units and 450 village-level units across 28 provinces, with approximately 17,000 participants included. The CHARLS questionnaire refers to the experience of international similar surveys, such as the U.S. Health and Retirement Study (HRS), the English Longitudinal Study of Ageing (ELSA), and the Survey of Health, Ageing, and Retirement in Europe (SHARE). Its contents include personal basic information, family structure, chronic disease status, health status, physical measurement, medical service utilization and medical insurance, work, retirement and pension, income, consumption, assets, and basic community conditions.

Considering that the COVID-19 pandemic may have significantly influenced health status in 2020, potentially altering frailty status, this study excluded the follow-up data of 2020 and used the CHARLS follow-up survey data from 2011, 2013, 2015, and 2018. Participants were tracked using the unique identification ID from the 2011 baseline survey. The initial sample size in 2011 was 16,816 participants. After excluding 1,215 individuals who were already frail in 2011 and 329 participants with a missing rate of frailty index (FI) assessment items exceeding 20%, 15,272 participants remained. To ensure consistent baseline time and complete follow-up, participants who were newly enrolled after 2011 were excluded; further excluding 1,409 lost to follow-up, 164 with missing data on cooking fuel use, and 466 with missing data on 2011 baseline covariates, a total of 13,233 participants were finally included in the Cox analysis of cooking fuel. For the analysis of heating fuel, an additional 1,853 participants with missing data were excluded, resulting in 11,380 participants. For covariates missing in the 2013, 2015, or 2018 waves, after excluding participants with missing data on key variables, there were 1,643 participants remaining. Among them, 1643 participants had some missing covariate data. Missing values were imputed using the last observation carried forward (LOCF) method, as these variables were generally stable over time.

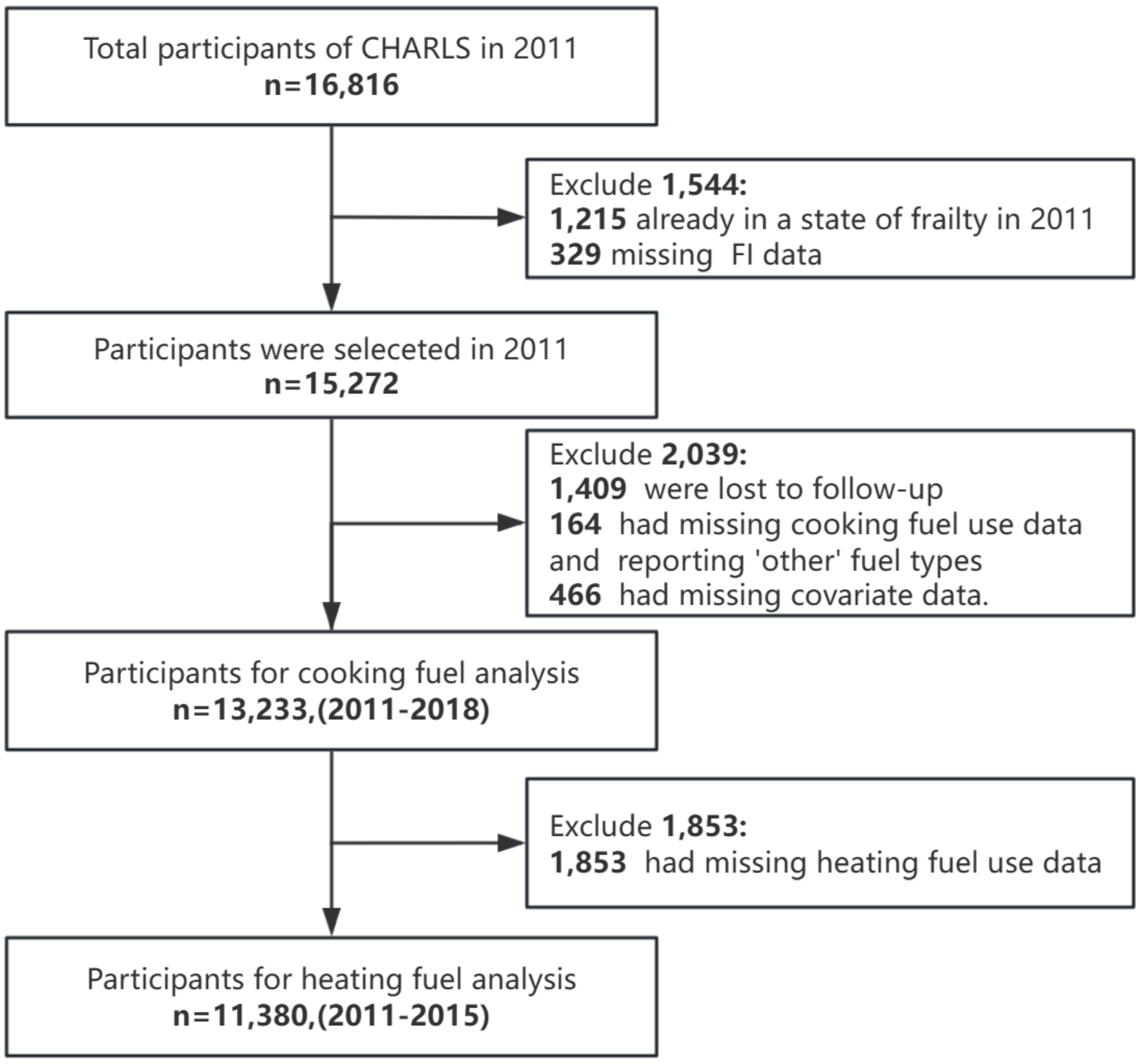


Figure 1 - Flowchart of Participant Inclusion

2.2 Frailty assessment

Frailty status was assessed using the Rockwood frailty index (FI), which aggregates multiple, reliable health deficits. The FI was constructed and calculated based on standard procedures used in previous studies [8][21], comprising 40 items across six dimensions: chronic disease history (14 items), physical function status (5 items), activities of daily living (9 items), physical activity level (6 items), mental health status (4 items), and self-subjective assessment (2 items) (see Appendix Table 1). Participants with more than eight missing items (20%) in the frailty index assessment [22] were excluded from the study. The FI was calculated as the sum of the scores of existing health deficit items divided by the total number of items, with a range of 0-1. Higher scores indicate a more severe degree of frailty. Frailty status was defined using common cut-offs: ROBUST (FI < 0.1), Pre-frail (0.1 ≤ FI ≤ 0.25), Frail (FI > 0.25). FI was calculated at each wave to assess the progression of frailty status [23]. The study endpoint was defined as the first occurrence of frailty, death, or the end of the 2018 follow-up survey, whichever occurred first, for participants enrolled in 2011[8].

2.3 Fuel Types

In the CHARLS questionnaire, there are two survey questions regarding fuel: I021 (What is the main heating energy source?) and I022 (What is the main source of cooking fuel?). The missing rate of heating fuel data at baseline was higher than that of cooking fuel, and the missing rate of heating fuel data in the 2018 follow-ups was as high as 80%. However, data on frailty and covariates were not missing. Consequently, the 2018 data were not included in the heating fuel analysis. For the Cox analysis of heating fuel, the periods considered were 2011-2013 and 2013-2015. The 2015-2018 period was not included in the study because data on heating fuel type were available for only about 1500 participants in 2018. For cooking fuel, the time interval included 2015-2018. In the analysis where both heating fuel and cooking fuel are involved, the year is up to 2015. Additionally, the participant cohorts differed between the cooking and heating fuel analyses, as depicted in Figure 1.

There are seven main types of fuel collected by CHARLS: coal, natural gas, marsh gas, liquefying petroleum gas, electric, solar, and crop residue/wood burning. Marsh gas is used only for cooking, and solar gas is used only for heating. These fuels are divided into solid fuels and clean fuels according to their degree of pollutant emission (see Table 1). According to the CHARLS household data from 2011, approximately 11% of the participants used coal for cooking, and 42% used biomass fuels for cooking, indicating that nearly half relied on solid fuels for cooking. In 2011, approximately 36% used coal for heating and 38% used biomass fuels for heating, meaning that over 70% used solid fuels for heating. As shown in Table 1, biomass fuels include crop residue and wood burning. To accurately define fuel types, participants reporting "other" fuel types were excluded.

Table 1 - Introduction to fuel types and classifications

Source of Cooking Fuel	Clean or Solid	Introduce
1 Coal	Solid	Highly polluting fossil fuels emit large amounts of CO_2 and pollutants.
2 Natural gas	Clean	Relatively clean fossil fuel; emits less CO_2 and air pollutants upon combustion.
3 Marsh gas (Only use for cooking)	Clean	Those derived from biomass (such as methane produced by anaerobic digestion) have low emissions and are sustainable.
4 Liquefied Petroleum Gas	Clean	Petroleum by-products (such as propane and butane) have high combustion efficiency and low pollutant emissions.
5 Electric	Clean	Electricity: Generally clean, with no on-site emissions (such as smoke or particulate matter).
6 Solar (Only use for heating)	Clean	Solar: No direct emissions during operation; uses sunlight for heating; eco-friendly and sustainable.
7 crop residue/Wood burning (biomass fuel)	Solid	Traditional biomass burning typically causes high levels of indoor air pollution [18].

2.4 Covariates

Covariate selection was based on evidence from previous CHARLS studies [24], including (1) individual characteristics: age, gender, and marital status; (2) individual health behaviors: smoking status and alcohol consumption; (3) socioeconomic factors: household registration type (hukou) and education level; and (4) household dwelling characteristics: housing area, housing structure, and housing type.

2.5 Statistical analysis

The baseline characteristics of the study participants are presented according to frailty status (frail or non-frail). Categorical variables are presented as numbers (percentages). The Kolmogorov-Smirnov test was used to assess the normality of the continuous variables.

Before starting the cox analysis, we counted total person-years of follow-up for each analysis sample and incident frailty cases per 1,000 person-years for exposure groups (and overall), both for cooking and heating. Then the Kaplan-Meier plots: KM for main exposures (clean vs solid cooking; clean vs solid heating). Include number at risk table below each plot and log-rank p-values.

The time scale was defined as the survey year (2011, 2013, 2015, 2018). At each follow-up survey, exposure status for both cooking and heating fuels was re-assigned according to the concurrent questionnaire responses, thereby implementing time-dependent updating. For both cooking fuel and heating fuel, time-dependent Cox proportional hazards models, with adjustment for covariates, were utilized to examine the associations between solid fuel use and frailty. Four models were constructed: Model I: Unadjusted. Model II: Adjusted for age and gender. Model III: Additionally adjusted for marital status, hukou, education level, smoking status, and alcohol consumption. Model IV: Further adjusted for housing area, housing structure, and housing type. Cooking fuel and heating fuel were not mutually adjusted for in their primary respective Cox analyses, because heating fuel data was only available for 2011-2013 and 2013-2015, with substantial missingness in later years precluding reliable imputation. To explore their combined association, a separate Cox analysis (Model IV) compared participants based on whether they used solid or clean fuels for both, cooking clean, heating clean and both clean. In addition, we conducted a Cox analysis with mutual adjustment for the two fuel types using data from the 2011-2013 and 2013-2015 intervals.

In our analysis, "fuel switching" refers to the change in household fuel type from solid to clean or clean to solid during the follow-up period. We defined participants who switched to cooking fuels as those who reported solid fuel use and switched to clean fuels after completing 4 years or more of solid fuel use (2011-2015, 2013-2018, 2011-2018). The same is true for switching from clean fuels to solid fuels. For heating fuel, we did not explore it because the short follow-up period generated too few samples.

For cooking fuel, participants were grouped based on whether they experienced a change in fuel type during the follow-up. Cox analysis (Model IV) compared these groups to those who "Always used solid fuels" to examine the association of fuel switching with frailty risk. This approach allowed us to assess whether the transition might be associated with a reduced risk of frailty.

We conducted interaction analyses to assess if the association of fuel type with frailty risk varies across subgroups defined by age, gender, education level, and rural/urban residence. This approach aids in tailoring interventions for those most at risk, enhancing the precision and effectiveness of public health strategies aimed at preventing frailty. Interaction and subgroup analyses were performed by stratifying data across all covariates, applying Cox models akin to Model IV within each subgroup for both cooking and heating fuel analyses.

Finally, multiple sensitivity analyses were conducted to assess the robustness of the results. (1) Excluding participants who became frail within the first two follow-up surveys, to ensure the stability of long-term exposure associations. (2) Defining the endpoint to include both frail and pre-frail status (FI > 0.1), to further test result stability. (3) Using a Cox model where frailty was not treated as a terminal event (i.e., participants remained in the risk set after becoming frail), to account for potential "immortal time" bias.

For all analyses that included heating fuels, only the 2011-2013, 2013-2015 intervals were included.

All analyses were performed using R version 4.4.1.

Results

The baseline characteristics of the 13,233 participants included in the cooking fuel study were categorized by fuel type (solid or clean) at baseline, and the data of the 1,164 participants who developed frailty during the entire follow-up period are presented in Table 2. Among the

13,233 participants included in the cooking fuel analysis, 6,031 (45.56%) used clean fuels and 7,202 (54.44%) used solid fuels at baseline. A total of 1,164 participants developed frailty, with 370 (31.79%) and 794 (68.21%) in the clean and solid fuel groups, respectively. Thus, frailty was more likely to occur in participants who used solid fuel for cooking. Compared with those using clean fuels, participants using solid fuels were more likely to reside in rural areas, be illiterate or have only received basic education, and live in brick-and-wood or one-story buildings (judged by the significant increase in Total% in Table 2).

Between participants who used solid and clean fuels for cooking, those who preferred solid fuels were males, individuals over 60 years old, unmarried individuals, smokers, non-drinkers, rural residents, primary education and below, those who don't live in concrete-and-steel buildings, with a housing area of 0–120□, and those in one-story buildings (judged by the rise in Total% in Table 2).

Among participants using clean fuels for cooking, those more likely to develop frailty were females, individuals over 60 years old, married individuals, non-smokers, non-drinkers, rural residents, primary education and below, those living in concrete-and-steel buildings, with a housing area of 60–120□, and those in one-story buildings (judged by the highest Frail% in Table 2).

Among participants using solid fuels for cooking, those more likely to develop frailty were females, individuals over 60 years old, married individuals, non-smokers, non-drinkers, rural residents, primary education and below, those living in brick-and-wood buildings, with a housing area of 60-120□, and those in one-story buildings (judged by the highest Frail% in Table 2).

Table 2 - Baseline characteristics of cooking fuel participants (n=13,233) stratified by frailty status and cooking fuel type

Variables	Clean Cooking Fuel		Solid Cooking Fuel	
	Total (%) (n=6,031)	**Frail (%) (n=370)**	**Total (%) (n=7,202)**	**Frail (%) (n=794)**
Gender				
male	2,899(48.07%)	146(39.46%)	3,500(48.60%)	312(39.29%)
female	3,132(51.93%)	224(60.54%)	3,702(51.40%)	482(60.71%)
Age(years)				
≤60	3,980(65.99%)	159(42.97%)	4,153(57.66%)	306(38.54%)
>60	2,051(34.01%)	211(57.03%)	3,049(42.34%)	488(61.46%)
Marital status				
Married	5,047(83.68%)	272(73.51%)	5,975(82.96%)	622(78.34%)
Unmarried	984(16.32%)	98(26.49%)	1,227(17.04%)	172(21.66%)
Smoke status				
Current smoking	2,260(37.47%)	132(35.68%)	2,979(41.36%)	288(36.27%)
Not smoking	3,771(62.53%)	238(64.32%)	4,223(58.64%)	506(63.73%)
Drink status				

Current drinking	1561(25.88%)	74(20.00%)	1,862(25.85%)	140(17.63%)
Not drink recently	4470(74.12%)	296(80.00%)	5,340(74.15%)	654(82.37%)
Resident type				
Rural	3,825(63.42%)	243(65.68%)	6,642(92.22%)	739(93.07%)
Urban	2,206(36.58%)	127(34.32%)	560(7.78%)	55(6.93%)
Education level				
Primary Education and below	3,246(53.83%)	262(69.81%)	5502(76.40%)	705(88.79%)
Junior Secondary Education	1,558(25.83%)	63(17.03%)	1,263(17.53%)	70(8.82%)
Senior Secondary and above*	1,227(20.34%)	45(12.16%)	437(6.07%)	19(2.39%)
Structure of building				
Concrete and steel	3,087(51.19%)	161(43.51%)	1,522(21.13%)	115(14.48%)
Bricks and wood	1,992(33.03%)	128(34.59%)	3,442(47.79%)	376(47.36%)
Adobe/Mixed structure/Cave dwelling/Stone	790(13.10%)	64(17.31%)	1,875(26.03%)	235(29.60%)
Wood, bamboo, grass/Woolen felt/Sheet iron/Mongolian Yurt	162(2.68%)	17(4.59%)	363(5.05%)	68(8.56%)
Area of building(□)				
□60	850(14.09%)	62(16.76%)	1,040(14.44%)	143(18.01%)
60-120	3,280(54.39%)	217(58.65%)	4,026(55.90%)	439(55.29%)
□120	1,901(31.52%)	91(24.59%)	2,136(29.66%)	212(26.70%)
One story or multi-level building				
One-story building	2,708(44.90%)	193(52.16%)	5,427(75.35%)	622(78.34%)
multi-level building	3,323(55.10%)	177(47.84%)	1,775(24.65%)	172(21.66%)

Senior Secondary and above: high school graduate, vocational/technical, junior college (Associate), Bachelor's, Master's, PhD. **Frail**: "Frailty" refers to conditions developing during follow-up. At baseline, no participants were frail.

The baseline characteristics of the 11,380 participants included in the heating fuel analysis were stratified in the same manner, shown in Table 3. Among the participants included, 3,250 (28.56%) used clean fuels and 8,130 (71.44%) used solid fuels at baseline. Compared with the cooking fuel category, the proportion of solid heating fuel users was higher. A total of 713 participants developed frailty, with 127 (17.81%) in the clean fuel group and 586 (82.19%) in the solid fuel group. Compared with solid cooking fuel users, the proportion of frailty was higher among solid heating fuel users. Compared with clean fuel users, those using solid fuels were more likely to reside in rural areas, be illiterate or have received only basic education, and live in brick-and-wood or one-story buildings.

Between participants who used solid and clean fuels for heating, those who preferred solid fuels were males, individuals over 60 years old, unmarried individuals, smokers, non-drinkers, rural residents, primary education and below, those who don't live in concrete-and-steel buildings, with a housing area of 0–120㎡, and those in one-story buildings (judged by the rise in Total% in Table 3).

Among participants using clean heating fuels, those more likely to develop frailty were females, individuals aged >60 years, married individuals, non-smokers, non-drinkers, rural residents, primary education and below, those living in concrete-and-steel buildings, with a housing area of 60–120㎡, and those in multi-level buildings.

Among participants using solid heating fuels, those more likely to develop frailty were females, individuals aged >60 years, married individuals, non-smokers, non-drinkers, rural residents, primary education and below, those living in brick-and-wood buildings, with a housing area of 60–120㎡, and in one-story buildings.

The baseline characteristics stratified by frailty status revealed substantial similarities between the cooking fuel and heating fuel groups.

Table 3 - Baseline characteristics of heating fuel participants (n=11,380) stratified by frailty status and heating fuel type

Variables	Clean Heating Fuel		Solid Heating Fuel	
	Total (%) (n=3,250)	**Frail (%) (n=127)**	**Total (%) (n=8,130)**	**Frail (%) (n=586)**
Gender				
male	1,571 (48.34%)	53 (41.73%)	3,958 (48.68%)	225 (38.40%)
female	1,679 (51.66%)	74 (58.27%)	4,172 (51.32%)	361 (61.60%)
Age(years)				
≤60	2,137 (65.75%)	45 (35.43%)	4,872 (59.93%)	207 (35.32%)
>60	1,113 (34.25%)	82 (64.57%)	3,258 (40.07%)	379 (64.68%)
Marital status				
Married	2,718 (83.63%)	91 (71.65%)	6,763 (83.19%)	443 (75.60%)
Unmarried	532 (16.37%)	36 (28.35%)	1,367 (16.81%)	143 (24.40%)
Smoke status				
Current smoking	1,213 (37.32%)	48 (37.80%)	3,361 (41.34%)	207 (35.32%)
Not smoking	2,037 (62.68%)	79 (62.20%)	4,769 (58.66%)	379 (64.68%)
Drink status				
Current drinking	856 (26.34%)	14 (11.02%)	2,125 (26.14%)	105 (17.92%)
Not drink recently	2,394 (73.66%)	113 (88.98%)	6,005 (73.86%)	481 (82.08%)
Resident type				
Rural	2,225 (68.46%)	85 (66.93%)	7,286 (89.62%)	542 (92.49%)
Urban	1,025 (31.54%)	42 (33.07%)	844 (10.38%)	44 (7.51%)
Education level				
Primary Education and below	1,934 (59.51%)	100 (78.74%)	5,903 (72.61%)	508 (86.69%)

Junior Secondary Education	795 (24.46%)	14 (11.02%)	1,567 (19.27%)	56 (9.56%)
Senior Secondary and above*	521 (16.03%)	13 (10.24%)	660 (8.12%)	22 (3.75%)
Structure of building				
Concrete and steel	1,792 (55.14%)	63 (49.61%)	1,730 (21.28%)	80 (13.65%)
Bricks and wood	1,046 (32.18%)	36 (28.35%)	3,928 (48.31%)	281 (47.95%)
Adobe/Mixed structure/Cave dwelling/Stone	375 (11.54%)	21 (16.54%)	2,032 (25.00%)	235 (40.10%)
Wood, bamboo, grass/Woolen felt/Sheet iron/Mongolian Yurt	37 (1.14%)	7 (5.51%)	440 (5.41%)	54 (9.22%)
Area of building(□)				
□60	381 (11.72%)	24 (18.90%)	1,165 (14.33%)	101 (17.24%)
60-120	1,660 (51.08%)	64 (50.39%)	4,566 (56.16%)	328 (56.00%)
□120	1,209 (37.20%)	39 (30.71%)	2,399 (29.51%)	157 (26.79%)
One story or multi-level building				
One-story building	1,247 (38.37%)	63 (49.61%)	6,315 (77.68%)	459 (78.33%)
multi-level building	2,003 (61.63%)	64 (50.39%)	1,815 (22.32%)	127 (21.67%)

Senior Secondary and above: high school graduate, vocational/technical, junior college (Associate), Bachelor's, Master's, PhD. **Frail**: "Frailty" refers to conditions developing during follow-up. At baseline, no participants were frail.

Based on the results in Table 4, solid fuel use was associated with a significantly increased risk of frailty. As shown in Table 4, the incidence of frailty among solid cooking fuel users was 16.48 per 1000 person-years, markedly higher than among clean fuel users (8.97 per 1000 person-years). Similarly, the incidence was 15.55 per 1000 person-years for solid heating fuel users, compared to 8.10 per 1000 person-years for clean heating fuel users.

Statistical analyses in Table 4 further confirmed that these differences were highly significant. Kaplan-Meier analysis revealed substantially higher cumulative frailty incidence among solid fuel users for both cooking (log-rank $\chi^2 = 98.3$, $p < 0.0001$) and heating (log-rank $\chi^2 = 67.1$, $p < 0.0001$). Incidence rate ratios indicated that solid fuel use was associated with an 84% and 93% increase in frailty risk for cooking and heating, respectively (IRR = 1.84 and 1.93). Notably, the adjusted incidence-rate difference (solid vs. clean fuel) was 7.51 cases (95 % CI 4.12–10.90) per 1000 person-years for cooking fuel and 7.46 cases (95 % CI 3.05–11.87) per 1000 person-years for heating fuel, indicating approximately 7.5 additional frailty events for every 1000 person-years of follow-up among solid-fuel users. These results consistently show that household fuel type is an important contributor to incident frailty, with use of solid fuels (whether for cooking or heating) associated with significantly increased risk for frailty.

The KM plots see Appendix Figure 1, 2.

Table 4 - Statistical analyses between Fuel Use and Frailty Incidence

Group					Kaplan-Meier

	Number of events/Person-Years	Incidence rate per 1000 person-years (95% CI)	Incidence Difference	Incidence Rate Ratio	Log-rank χ^2	p
Cooking fuel						
Clean fuel	370/41257	8.96	reference	reference	reference	
Solid fuel	794/48188	16.47	7.509/1000 PY	1.84	98.3	<0.001
Heating fuel						
Clean fuel	180/22235	8.09	reference	reference	reference	
Solid fuel	849/54592	15.55	7.456/1000 PY	1.93	67.1	<0.001

Table 5 - Summary of the cox analysis

Group	Number of events/Number of participants	Model I (Unadjusted)		Model Ⅱ		Model Ⅲ		Model Ⅳ	
		HR (95% Cl)	p	HR (95% Cl)	p	HR (95% Cl)	p	HR (95% Cl)	p
Cooking fuel									
Clean fuel	370/6031	reference		reference		reference		reference	
Solid fuel	794/7202	1.90 (1.70-2.10)	□0.001	1.80 (1.60-2.00)	□0.001	1.60 (1.40-1.82)	□0.001	1.46 (1.28-1.67)	□0.001
Cooking Fuel Type Switch									
Always Solid fuel	203/3123	reference		reference		reference		reference	
Always Clean fuel	103/4740	0.39 (0.31-0.50)	□0.001	0.43 (0.33-0.54)	□0.001	0.49 (0.39-0.64)	□0.001	0.55 (0.43-0.71)	□0.001
From Solid to Clean	40/2231	0.55 (0.46-0.65)	□0.001	0.58 (0.45-0.76)	□0.001	0.60 (0.51-0.72)	□0.001	0.61 (0.51-0.73)	□0.001
From Clean to Solid	39/780	0.65 (0.51-0.72)	0.048	0.68 (0.52-0.75)	0.037	0.73 (0.55-0.87)	0.027	0.75 (0.56-0.89)	0.024
Heating fuel									
Clean fuel	180/3250	reference		reference		reference		reference	
Solid fuel	849/8130	1.94 (1.60-2.35)	□0.001	1.86 (1.53-2.26)	□0.001	1.75 (1.43-2.14)	□0.001	1.58 (1.29-1.94)	□0.001
Co-use of Cooking fuel and Heating fuel									
Both Clean	123/2505	reference		reference		reference		reference	
Both Solid	685/6011	2.10 (1.65-2.68)	□0.001	1.85 (1.48-2.31)	□0.001	1.76 (1.29-2.14)	□0.001	1.68 (1.31-2.17)	□0.001
Heating Clean	57/745	0.95 (0.65-1.39)	0.568	0.88 (0.60-1.30)	0.527	0.86 (0.58-1.21)	0.379	0.82 (0.54-1.24)	0.354
Cooking Clean	164/2119	1.35 (1.05-1.74)	0.486	1.25 (0.98-1.59)	0.435	1.21 (0.92-1.57)	0.357	1.15(0.86-1.53)	0.333

Following the completion of all the statistical analyses, Table 5 was generated. In the Cox analysis (Model IV) comparing clean fuels with solid fuels, the risk of frailty was 46% higher for solid cooking fuel than for clean cooking fuel (HR=1.46, 95% CI:1.28-1.67, p<0.001), and 58% higher for solid heating fuel than for clean heating fuel (HR=1.58, 95% CI:1.29-1.94, p<0.001). The results were significant across all Cox models I–IV, and the proportional hazards (PH) test was significant (p>0.05).

Cox analysis showed that the risk of frailty in the group switching from solid fuel to clean fuel was significantly reduced (HR=0.61, 95% CI:0.51-0.73, p<0.001). Furthermore, switching from clean fuels to solid fuels is associated with higher risks than always using clean fuels.

Cox analysis of scenarios where cooking and heating fuels were solid or clean, either separately or jointly, showed that the "both solid" group had a 68% higher risk compared with the "both clean" group (HR=1.68, 95 % CI: 1.31-2.17, p<0.001). In most cases, the same type of fuel is used for both cooking and heating, resulting in a small number of participants using clean fuel for only one purpose, which leads to poor significance. However, the upper limit of the 95% confidence interval was still lower than the HR value of the "both solid" group.

Results from the mutually adjusted model, which included both cooking and heating fuel types, remained consistent with the main findings (Appendix Table S2). After mutual adjustment, the hazard ratios for solid fuel use were attenuated but remained statistically significant (cooking fuel: HR = 1.31, 95% CI: 1.09–1.57; heating fuel: HR = 1.43, 95% CI: 1.16–1.75). This attenuation suggests an overlap in the populations exposed to solid fuels for cooking and heating, as well as shared confounding factors. Crucially, the persistence of significant associations indicates that the use of solid fuels for either purpose is an independent risk factor for frailty, thereby reinforcing the robustness of our primary conclusions.

The results of the sensitivity analysis were consistent with the main analysis, supporting the robustness of the findings (see Table 6).

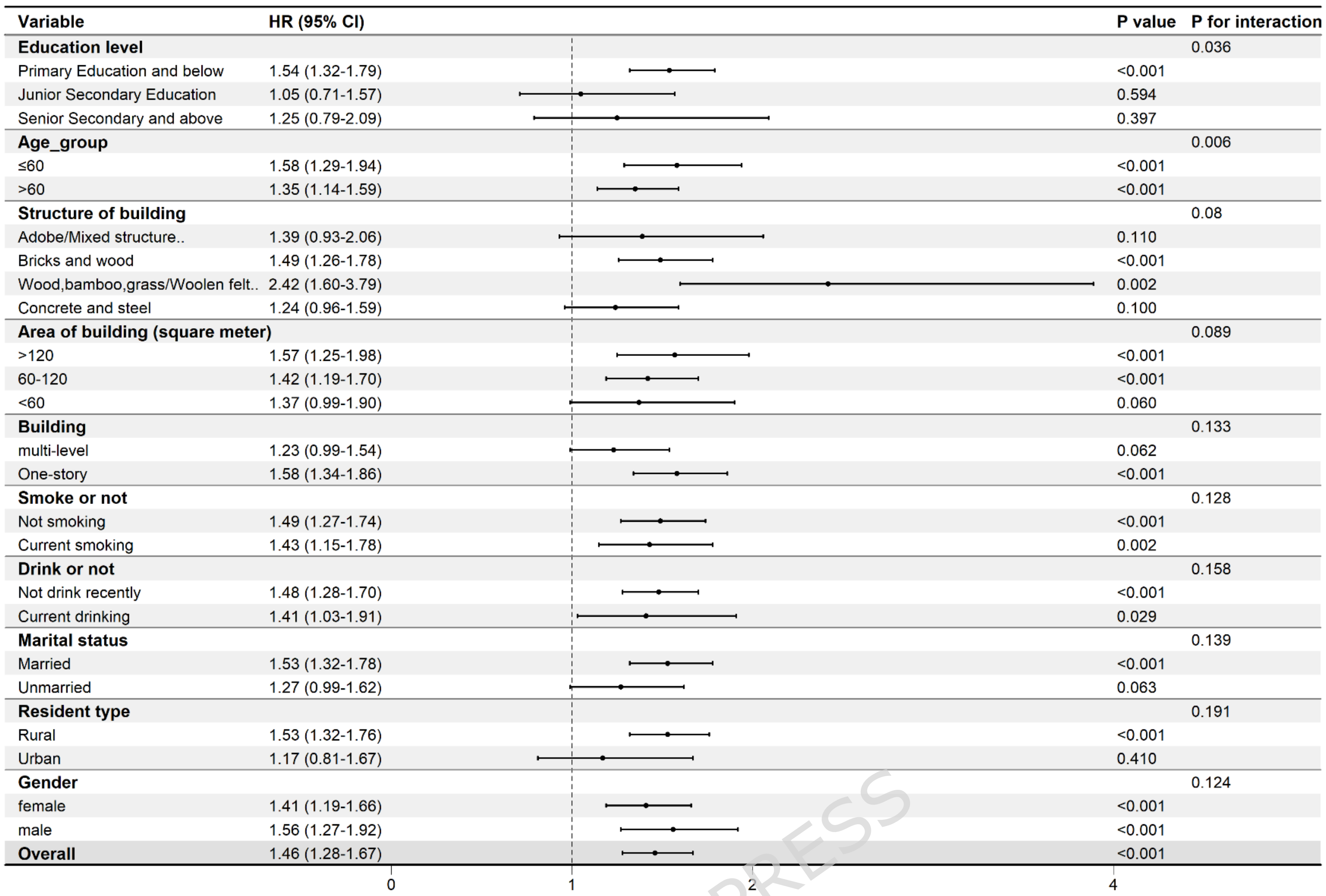
Table 6. Association of solid fuel use with frail by sensitivity analysis

Solid compared with Clean (Model Ⅳ)	HR (95% Cl)	p-value
The sensitivity analysis of cooking fuel (1)	1.42(1.21-1.67)	<0.001
The sensitivity analysis of cooking fuel (2)	1.32(1.22-1.41)	<0.001
The sensitivity analysis of cooking fuel (3)	1.29(1.10-1.51)	<0.001
The sensitivity analysis of heating fuel (1)	1.61(1.13-2.27)	0.007
The sensitivity analysis of heating fuel (2)	1.39(1.24-1.56)	<0.001
The sensitivity analysis of heating fuel (3)	1.56(1.28-1.91)	<0.001

(1) Excluding participants who became frail within the first two follow-up surveys, to ensure long-term exposure effects. (2) Defining the endpoint to include both frail and pre-frail status (FI > 0.1), to further test result stability. (3) Using a Cox model where frailty was not treated as a terminal event (i.e., participants remained in the risk set after becoming frail), to account for potential "immortal time" bias.

Subgroup and interaction analyses were performed (Figures 2 and 3). The subgroup analysis of cooking fuel showed that the use of solid fuels increased the risk of frailty compared with clean fuels in all subgroups. Factors that exacerbated the frailty risk from solid fuel use included: being female, married, aged ≤60 years, residing in rural areas, having primary education and below, living in houses made of wood/bamboo/grass/woolen felt/sheet iron/Mongolian yurt, having a larger housing area, and having a one-story structure. No significant changes in frailty risk were observed in the subgroup analysis of smoking and alcohol consumption. Interaction analysis indicated that education level and age group attenuated the exposure–outcome relationship.

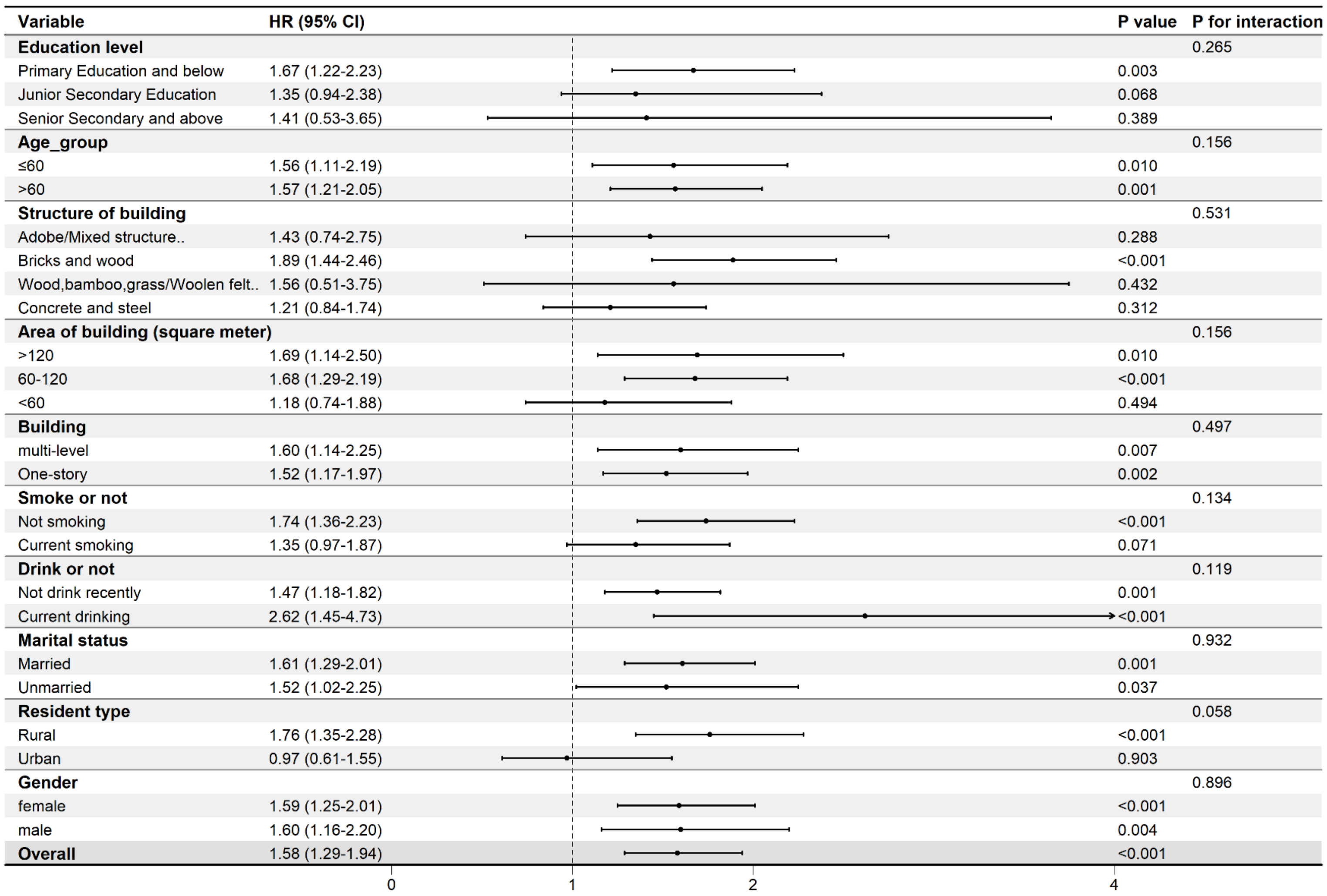
The subgroup analysis of heating fuel showed that the use of solid fuels increased the risk of frailty compared with clean fuels in all subgroups except the urban subgroup, where significance was poor. Factors that exacerbated the frailty risk from solid fuel use included: being married, residing in rural areas, having primary education and below, living in brick-and-wood houses, larger housing area, multi-level structure, alcohol consumption, and non-smoking. No significant changes in frailty risk were observed in the subgroup analyses of age and gender. Interaction analysis indicated that no factors attenuated the exposure-outcome relationship.



[1] Models were adjusted for age, sex, marital status, education level, smoking status, alcohol consumption, housing area, structure, type, and urban/rural residence.

Figure 2. Subgroup and Interaction Analysis for Cooking Fuel (n=13,233): **Hazard ratios (95% CI) for frailty associated with solid vs. clean cooking fuel use, stratified by covariates.**

1



[2] Models were adjusted for age, sex, marital status, education level, smoking status, alcohol consumption, housing area, structure, type, and urban/rural residence.

Figure 3. Subgroup and Interaction Analysis for Heating Fuel (n=11,380): Hazard ratios (95% CI) for frailty associated with solid vs. clean heating fuel use, stratified by covariates.

Discussion

In this large, prospective cohort, we found that sustained household use of solid fuels for cooking and heating was independently associated with an increased risk of frailty in middle-aged and older adults. This finding extends the existing, predominantly cross-sectional evidence by establishing a temporal association and quantifying longitudinal risk.

The precise mechanisms linking solid fuel use and frailty have not been fully elucidated. The primary solid fuels, coal and biomass, release pollutants upon combustion that increase indoor air pollution concentrations, including particulate matter (PM), carbon monoxide, carbon dioxide, and organic compounds [25][26]. These pollutants can trigger oxidative stress and the formation of reactive oxygen species (ROS). PM can induce inflammatory responses, partly through ROS generation, adversely affecting various chronic diseases [27].

Our subgroup analyses move beyond establishing an association to illuminate the critical roles of exposure patterns and environmental context in modifying the risk of solid fuel-related frailty. In this subgroup analysis, the risk was higher among the female group, which was related to their assumption of the main responsibility for household cooking. Although this interaction was not significant in this study, this phenomenon has been fully confirmed in the literature as involving a disproportionate exposure situation [28][29]. For the two subgroups with significant interaction effects. Solid fuel use is more harmful for people with an educational level of primary school or below, which is strongly associated with lack of public

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health knowledge. For people younger than 60, solid fuels may pose a greater risk. However, more information is needed on the underlying mechanisms, such as the duration of cooking in different age groups. This also reflects our insufficient attention to the hazards of solid fuels, and more observation and research are still needed. For households where an immediate transition is economically or culturally unfeasible, secondary prevention through engineering controls is critical. Therefore, promoting and subsidizing the installation of low-cost, sufficient ventilation systems, such as exhaust fans, represents a vital and immediately actionable intervention to reduce indoor pollutant concentrations.

Concurrently, behavioral and educational interventions are essential. Public health campaigns must specifically target women and people with an educational level of primary school or below—to raise awareness of IAP health risks. Furthermore, initiatives should encourage a more equitable distribution of cooking responsibilities within families to avoid the concentration of exposure to a single individual. For populations with strong cultural attachments to solid fuels, empathetic messaging that focuses on the harms of "indoor air pollution" rather than condemning traditions, along with culturally sensitive compromises (e.g., designating specific ceremonial occasions for use), may foster greater acceptance and sustained behavior change.

In contrast to other single-fuel or cross-sectional studies, this study used both cooking and heating fuel samples, used a large cohort, and used Cox analysis to estimate prospective prevalence of frailty. Our results align with and substantially advance previous research. While earlier studies have linked solid fuel use to various adverse health outcomes, prospective data on frailty—a critical geriatric syndrome—remain scarce. The robust associations observed here, even after mutual adjustment for co-exposure, strengthen the causal inference suggested by prior cross-sectional work. More importantly, our longitudinal observation that transitioning from solid to clean fuels was associated with a reduced frailty risk offers crucial preliminary evidence for the potential benefits of such intervention—a dimension entirely missing from prior cross-sectional studies.

Limitations include self-reported fuel use, lack of direct indoor air pollution measurement, and a shorter follow-up for heating fuel exposure. Future studies incorporating environmental monitoring and detailed behavioral data are needed to precisely quantify exposure and confirm the exposure-response relationship. Without further intervention and research, the harm of solid fuels will continue and lead to more frailty.

Conclusion and Recommendations

As this study is observational, our findings indicate a positive association between solid fuel use and frailty risk. Well-designed randomized or quasi-experimental studies are warranted to test: (1) clean fuel promotion, (2) home-ventilation installation, and (3) supporting energy-transition policies. Should stronger evidence emerge, these measures might help reduce the burden of frailty in ageing populations.

Declarations

1.List of abbreviations

CHARLS: China health and retirement longitudinal study
HR: Hazard ratio
FI: Frail index
Cox: Time-dependent Cox proportional hazards models
IAP: Indoor air pollution

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3.Author information

Authors' contributions

Yihan Liu: Conceptualization, Formal analysis, Visualization, Writing - original draft. **Zhenbo Li:** Investigation, Data curation. **Lei Wu:** Validation, Data curation**. Pengfei Ren:** Writing – original draft, Formal analysis. **Ming Liu:** Writing – review & editing. **Yuxin He:** Visualization. **Zhoubo Yu:** Visualization. **Qing Liu**: Data curation. **Jing Yang:** Writing – review & editing**,** Methodology**. Rui Wang (corresponding author):** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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4.Ethics declarations

Ethics approval and consent to participate

The data used in this study were approved by the Biomedical Ethics Review Committee of Peking University (The ethical approval number is IRB00001052-11015.). Written informed consent was obtained from all participants. All research procedures involving human participants complied with the institutional and/or national research committee ethical standards, as well as with the 1964 Declaration of Helsinki and its subsequent amendments or similar ethical standards.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

5.Acknowledgment

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6.Human Ethics and Consent to Participate declarations

not applicable.

7.Data availability

Support the results of the study of the data can be through https://charls.charlsdata.com/pages/data/111/zh-cn.html China health and retirement longitudinal study publicly available.

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Legends

The order is based on the order in which the articles appear:

Figure 1 - Flowchart of Participant Inclusion

Table 1 - Introduction to fuel types and classifications

Table 2 - Baseline characteristics of cooking fuel participants (n=13,233) stratified by frailty status and cooking fuel type

Table 3 - Baseline characteristics of heating fuel participants (n=11,380) stratified by frailty status and heating fuel type

Table 4 - Statistical analyses between Fuel Use and Frailty Incidence

Table 5 - Summary of the cox analysis

Table 6 - Association of solid fuel use with frail by sensitivity analysis

Figure 2. Subgroup and Interaction Analysis for Cooking Fuel (n=13,233): Hazard ratios (95% CI) for frailty associated with solid vs. clean cooking fuel use, stratified by covariates.

Figure 3. Subgroup and Interaction Analysis for Heating Fuel (n=11,380): Hazard ratios (95% CI) for frailty associated with solid vs. clean heating fuel use, stratified by covariates.

Table S1. Frailty index assessment form

Table S2. Cox analysis results of mutual adjustment of heating fuel and cooking fuel on the basis of model Ⅳ

Appendix Figure 1 – KM Curves for Frailty by Cooking Fuel Type

Appendix Figure 2 – KM Curves for Frailty by Heating Fuel Type