GeroScience
https://doi.org/10.1007/s11357-026-02113-1

ORIGINAL ARTICLE

Polluting cooking fuels and life satisfaction among middle-aged and older adults: a cross-sectional study from the Longitudinal Ageing Study in India

Imnameren Longkumer · Soohyeon Ko · Priyanka deSouza · Rohit Bhatia · Rockli Kim · S. V. Subramanian

Received: 6 December 2025 / Accepted: 14 January 2026

Abstract Polluting cooking fuels are a major source of household air pollution and may reduce life satisfaction (LS). Yet, this relationship remains unexplored in India where polluting fuel use is still widespread. We utilized cross-sectional data from the Longitudinal Aging Study in India, a nationally representative study of individuals aged 45 years and above. Cooking fuel type was classified as households using clean fuels (CF) or non-CF. Based on kitchen type, non-CF was categorized into non-CF in separate kitchen, and non-CF without separate kitchen. We used multivariable regression to examine the association between polluting cooking fuels and LS and explored gender differences in this association. The analytical sample comprised 62,822 respondents (mean age 59.56 ± 10.52 years). The use of non-CF in separate and non-separate kitchen was 27.08% (n = 17,010) and 18.89% (n = 11,868), respectively. We observed that LS scores were highest among households using CF, followed by those using non-CF in separate kitchen, and lowest among households using non-CF without separate room for cooking. Additionally, in the fully adjusted model, a dose–response association with LS was observed corresponding to different levels of polluting cooking fuels (non-CF in separate kitchen: β = –0.51 [95% CI: –0.71, –0.31]; non-CF without separate kitchen: β = –1.42 [95% CI: –1.65, –1.19]). Multiple sensitivity analyses support the robustness of our findings. Gender was a significant effect modifier, with the interaction model revealing a stronger negative association between non-CF use and LS among women than among men. Our findings highlight the need for policies that promote an equitable clean fuel transition to enhance life satisfaction and well-being.

Highlights

- Use of polluting cooking fuel reduces LS (life satisfaction) among adults in India.
- Polluting fuels in non-separate kitchen is associated with greatest decline in LS.
- Negative association is stronger in women, indicating greater gender vulnerability.
- Underscores the need for equitable clean fuel access to uplift population well-being.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11357-026-02113-1.

I. Longkumer · S. Ko · S. V. Subramanian (✉)
Department of Social and Behavioral Sciences, Harvard T.H. Chan School of Public Health, Boston, MA, USA
e-mail: svsubram@hsph.harvard.edu

I. Longkumer
e-mail: ilongkumer@hsph.harvard.edu

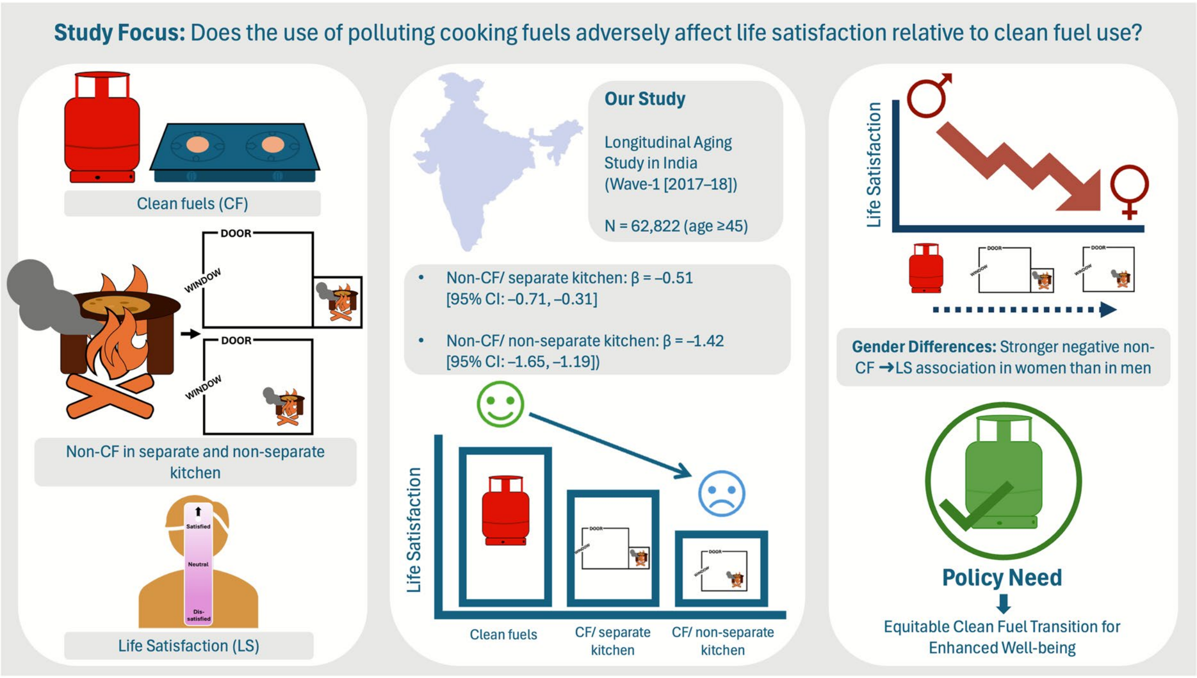
S. Ko
e-mail: soohyeonko@fas.harvard.edu

I. Longkumer · R. Bhatia
Department of Neurology, All India Institute of Medical Sciences, New Delhi, India
e-mail: rohitbhatia71@yahoo.com

S. Ko · S. V. Subramanian
Harvard Center for Population and Development Studies, Cambridge, MA, USA

Published online: 03 February 2026

Graphical Abstract



Keywords Polluting cooking fuels · Kitchen configuration · Household air pollution · Life satisfaction · Subjective well-being · Coarsened exact matching · Longitudinal Ageing Study in India

P. deSouza
Department of Urban and Regional Planning, University of Colorado Denver, Denver, CO, USA
e-mail: priyanka.desouza@ucdenver.edu

P. deSouza
CU Population Center, University of Colorado Boulder, Boulder, CO 80302, USA

R. Kim
Interdisciplinary Program in Precision Public Health, Korea University, Seoul, Republic of Korea
e-mail: rocklikim@korea.ac.kr

R. Kim
Division of Health Policy and Management, College of Health Science, Korea University, Seoul, Republic of Korea

Background

Pollution from particulate matter, including ambient and household sources is a leading risk factor for global disease burden [1]. The use of polluting fuels (coal or charcoal, firewood, crop waste, dung, and kerosene) for cooking and/or heating exposes individuals to high level of household air pollution from particulate matter, increasing the hazard of adverse health [2, 3]. Household air pollution has been estimated to account for 86 million healthy life years lost in 2019, disproportionately affecting women in low- and middle-income countries (LMICs) [2]. Moreover, evidence from India indicate that individuals in households where cooking takes place in non-separate kitchen – often integrated into the main living area – experiences higher and more prolonged exposure to particulate matter from polluting fuels [3, 4]. Kitchen configuration is found to be a key determinant of particulate matter levels in polluting fuel-using households, but not in those using clean fuels [5]. The lack of physical separation likely increases household air pollution exposure by allowing emissions to disperse more widely, thereby elevating risks for vulnerable household members. While much of the existing research has emphasized the adverse health effects of household air pollution due to polluting cooking fuel use [2, 6, 7], its broader impact on individuals beyond physical and psychological health remains largely understudied. In this context, subjective well-being may provide a valuable lens for measuring its comprehensive impact.

Life satisfaction is an important measure of an individual's well-being. It represents a person's overall, long-term, conscious, cognitive evaluation of their life [8–10]. It is affected by several factors, and previous research has paid much attention related to economic level, physical and mental health, personal or social circumstances, and the quality of the surrounding physical environment [11–14]. Recent studies show that both measured and perceived air pollution negatively influence emotional well-being [15–17]. Long-term exposure to fine particulate matter has been consistently linked to poorer mental health and lower life satisfaction across diverse settings [18–23]. However, despite the extensive research on ambient air pollution, the relationship between household air pollution due to polluting cooking fuel use and life satisfaction remains largely underexplored. Existing studies have largely examined the relationship between polluting fuel use and life satisfaction indirectly – either using proxies for exposure based on household income or "ability to pay" [24] or by focusing on reduced life satisfaction associated with health outcomes linked to household air pollution [12, 25]. To date, however, no study has directly examined these associations in the Indian context.

India, among other countries, has launched major policy efforts, most notably the Pradhan Mantri Ujjwala Yojana (PMUY), to improve access to clean cooking fuels and address the burden of household air pollution [26]. Research has shown that the PMUY program has resulted in a significant uptake in Liquified Petroleum Gas (LPG). Observational research has also shown that the change in prevalence in LPG usage at the district-level is associated with a significant reduction in diseases like hypertension [27]. However, no empirical evidence exists on the impact of polluting fuel use on life satisfaction. Understanding how polluting fuels that are used for cooking affects overall well-being, especially in older and vulnerable population groups like women, is crucial for capturing its full influence beyond physical health. Generating evidence in this area can guide targeted policies aimed at promoting healthy ageing, in line with the UN General Assembly's 2021–30 Decade of Healthy Ageing initiative [28]. We attempt to fill this gap in this study.

Methods

Data and participants

The study used data from the first wave of the Longitudinal Ageing Study in India (LASI Wave-1) conducted between 2017–2018. Although LASI is fundamentally planned as a longitudinal survey, the present analysis employs a cross-sectional design using the Wave 1 dataset. The dataset is obtained through the Gateway to Global Aging Data [29] and the Indian Institute of Population Sciences [30]. These procedures did not meet the regulatory definition of human participants' research. As such, review by an IRB was not required.

This cross-sectional dataset comprises a nationally representative sample of 72,277 individuals from all states and Union Territories (UTs) of India, providing comprehensive information on physical and psychological health, social determinants, and economic indicators. Details of the study design, sampling strategies, and data parameters have been reported previously [30]. Inclusion criteria were middle-aged and older adults aged 45 years and above (n = 65,576). From this initial sample, individuals with missing data on life satisfaction (n = 1,720), those with missing data on type of cooking fuel used (n = 233), those with main source of cooking fuel reported as 'do not cook at home' (n = 112) and 'other' (n = 27), and those with missing data on covariates (n = 662) were excluded. The final analytical dataset comprised of 62,822 individuals.

Outcome variable

Life satisfaction in the LASI survey assessed global quality of life and satisfaction using five items. Each item is rated by respondents on a 7-point Likert scale ranging from a score of 1 (strongly disagree) to 7 (strongly agree), to capture their subjective well-being. These five items included: (a) In most ways, my life is close to ideal, (b) The conditions of my life are excellent, (c) I am satisfied with my life, (d) So far, I have got the important things I want in life, and (e) If I could live my life again, I would change almost nothing. A composite life satisfaction score, ranging from 5 to 35, was constructed by combining the response score to the five items. Higher scores indicate greater life satisfaction. Although individual items are ordinal, additive scores are commonly used when items measure a single latent construct and show high internal consistency [8]. In our data, the scale shows strong reliability (Cronbach's $\alpha = 0.89$), indicating that the items function cohesively as indicators of a common underlying construct. We further categorized the composite score based on the following cutoffs [31]: score 30–35 as "extremely satisfied" (coded 6), 25–29 as "satisfied" (coded 5), 20–24 as "neutral" (coded 4), 15–19 as "slightly dissatisfied" (coded 3), 10–14 as "dissatisfied" (coded 2), and 5–9 as "extremely dissatisfied" (coded 1).

For sensitivity analysis, we used several alternative measures of life satisfaction. First, we used a single item statement "satisfied with life" from the LASI survey and the response in the dataset was reverse coded in our study as 1 "not at all satisfied", 2 "not very satisfied", 3 "somewhat satisfied", 4 "very satisfied", and 5 "completely satisfied." Second, the Cantril Ladder, a visual scale ranging from 0 (worst possible life) to 10 (best possible life), was used [32]. Respondents selected the step that best represented their life. Third, life satisfaction scores were categorized into quintiles, with higher quintiles corresponding to greater levels of life satisfaction.

Exposure variables

The study exposure (use of polluting cooking fuel) was divided into two groups: (i) Overall fuels used for cooking in the household and were classified into "clean fuels" if the housing respondent reports their main source of cooking fuel as liquefied petroleum gas (LPG), biogas, or electric; and "non-clean fuels" (non-CF) if the housing respondent reports their main source of cooking fuel as kerosene, charcoal/lignite/coal, crop residue, wood/shrub, or dung cake. Additionally, the LASI survey collected information on whether households had a separate room for cooking (yes/no), which we categorized as either separate or non-separate from the living area. (ii) The type of fuel used for cooking and the presence/absence of separate room for kitchen were combined in a three-level variable: clean fuels; non-CF in separate kitchen and non-CF in non-separate kitchen.

Covariates

To account for possible confounding biases in the association between type of cooking fuels and life satisfaction, a comprehensive set of covariates were included in the analysis including demographic, socioeconomic, and behavioral characteristics. They included age, gender (men/women), marital status (married/not married), religion (Hindu/Muslim/Christian/others), caste (Scheduled Caste/Scheduled Tribe/Other Backward Caste/others), working status (working/not working/retired), educational level (no education/primary (1–5 years)/secondary (6–9 years)/higher (10 and above years)), residence (rural/urban), monthly per-capita expenditure (quintile), *pucca* housing (yes/no), international poverty line (above/at or below), current excessive alcohol intake (yes/no), current use of tobacco – smoking/smokeless (yes/no), and physical inactivity (yes/no). Definitions of behavioral covariates are provided in previous research [33] and are summarized in Supplementary Text S1.

Data analysis

Descriptive statistics (mean with standard deviation or median with interquartile range and proportion) were calculated for each measure. Comparisons between different exposure groups (clean fuels, non-CF in separate kitchen, and non-CF in non-separate kitchen), were computed using Student's t-test, one-way ANOVA, Mann–Whitney *U* test, Kruskal–Wallis test, and Pearson's Chi-squared test, as appropriate. The median distribution of life satisfaction score across different types of cooking fuels was depicted using violin plot, and *P*-value from Kruskal–Wallis test was corrected using the Benjamini–Hochberg method to account for multiple pairwise comparisons. In our main analysis, we used univariable (model 1, unadjusted) and multivariable (model 2, adjusted for covariates) linear regression (reporting beta coefficients with 95% confidence intervals) to examine the association between polluting cooking fuels and life satisfaction. In all model 2 analyses, we included state/UTs as a fixed effect to account for potential state-level variations. Additionally, since life satisfaction was also treated as an ordinal variable, we employed an ordered logistic regression model under the proportional odds assumption, to examine its association with polluting cooking fuels, adjusted for covariates and state/UTs as a fixed effect. The validity of this assumption was assessed, and when evidence of violation of the proportional odds (parallel lines) assumption was detected for the exposure variables or the covariates, a generalized ordered logistic regression model with partial proportional odds was applied. This approach allows factors in the multivariable model that violate the proportional odds assumption to have effects that vary across outcome thresholds, while constraining those that satisfy the assumption to have constant effects. An automated model selection procedure was used to identify variables for which the proportional odds assumption was relaxed [34].

Further, we applied coarsened exact matching (CEM) on the covariates for three levels of exposures: group-1 (clean fuel as control vs. non-CF as treated units), group-2 (clean fuels as control vs. non-CF in separate kitchen as treated units), and group-3 (clean fuels as control vs. non-CF in non-separate kitchen as treated units). The matching solution was restricted to a *k*-to-*k* match, which involved pruning observations within each CEM stratum until an equal number of treated and control units were achieved within all strata of covariates. After matching for each exposure groups, covariate balance in the matched cohorts was assessed using two methods – through multivariate and univariate L1 measures, with value zero indicating perfect balance between groups [35]; and through standardized mean differences (SMD), with a value <0.1 indicating negligible difference between the groups. Using this matched sample with CEM weights, we conducted weighted linear regression with robust standard errors and states/UTs as fixed effects to examine the association of polluting fuel use with life satisfaction.

To explore gender-based heterogeneity, we performed stratified analysis to assess the association between polluting fuel use and life satisfaction separately for men and women. Additional subgroup analyses were explored based on age groups (45–69 years and ≥ 70 years), socioeconomic position (high and low) and place of residence (rural and urban). To test the robustness of our results, we also performed multiple sensitivity analyses using a single-item life satisfaction, Cantril Ladder, and life satisfaction score quintiles as alternative measures of life satisfaction. Multicollinearity was assessed using Variance Inflation Factors (VIF). We have incorporated sampling weights in all regression analyses to account for LASI's sampling design and differential non-response rates [29, 30]. All statistical analyses were performed using STATA version 14, and a P-value <0.05 was considered statistically significant. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

Results

The total analytical sample comprised of 62,822 respondents with a mean ($\pm$SD) age of 59.56 ($\pm$10.52) years. Women represented 53.49% (n = 33,603) of the sample. All selected covariates, except gender, showed differential distribution across the various types of cooking fuels ($P<0.001$) (Table 1). Overall life satisfaction score across the types of cooking fuels showed a progressive reduction (Fig. 1). Individuals using clean cooking fuels (n = 33,944) had the highest median life satisfaction score (26 [IQR: 20–30]), followed by those using polluting fuel in separate kitchen (n = 17,010) (24 [IQR: 20–29]), and the lowest among those using polluting fuels in non-separate kitchen (n = 11,868) (23 [IQR: 18–28]) (corrected P-values <0.001). Moreover, the mean differences in life satisfaction score between different demographic, socioeconomic, behavioral, and health characteristics are presented in Supplementary Table S1. Briefly, lower mean life satisfaction scores were observed among older adults (≥ 70 years), women, unmarried and currently working individuals, rural residents, Scheduled caste/tribe, those living at/below international poverty line, and current users of excessive alcohol and tobacco, compared to their counterparts. Conversely, higher mean life satisfaction scores were found in individuals with primary education or more, high SEP, living in a *pucca* house, and those in minority religious group and physically inactive group.

Table 1 Descriptive statistics of study participants stratified by type of cooking fuel used

Characteristics	Overall, n = 62,822	Clean fuels, n = 33,944 (54.03%)	Non-CF, n = 28,878 (45.97%)	*P*-value[a]	Non-CF in separate kitchen, n = 17,010 (27.08%)	Non-CF in non-separate kitchen, n = 11,868 (18.89%)	*P*-value[b]
Age							
Mean (SD)	59.56 (10.52)	59.34 (10.54)	59.82 (10.51)	< 0.001	59.65 (10.49)	60.07 (10.52)	< 0.001
Median (IQR)	58 (50–66)	58 (50–66)	59 (51–67)	< 0.001	59 (51–66)	60 (51–67)	< 0.001
Gender							
Men	29,219 (46.51)	15,815 (46.59)	13,404 (46.42)	0.660	7,939 (46.67)	5,565 (46.05)	0.52
Women	33,603 (53.49)	18,129 (53.41)	15,474 (53.58)		9,071 (53.33)	6,403 (53.95)	
Marital status							
Married	47,074 (74.93)	25,427 (74.91)	21,647 (74.96)	0.882	13,049 (76.71)	8,598 (72.45)	< 0.001
Not married	15,748 (25.07)	8,517 (25.09)	7,231 (25.04)		3,961 (23.29)	3,270 (27.55)	
Education level							
No education	29,518 (46.99)	11,848 (34.90)	17,670 (61.19)	< 0.001	9,456 (55.59)	8,214 (69.21)	< 0.001
Primary	11,506 (18.32)	6,007 (17.70)	5,499 (19.04)		3,545 (20.84)	1,954 (16.46)	
Secondary	9,974 (15.88)	6,366 (18.75)	3,608 (12.49)		2,441 (14.35)	1,167 (9.83)	
Higher	11,824 (18.82)	9,723 (28.64)	2,101 (7.28)		1,568 (9.22)	533 (4.49)	
Working status							
Not working	28,840 (45.91)	16,460 (48.49)	12,380 (42.87)	< 0.001	7,447 (43.78)	4,933 (41.57)	< 0.001
Working	31,082 (49.48)	15,142 (44.61)	15,940 (55.20)		9,124 (53.64)	6,816 (57.43)	
Retired	2,900 (4.62)	2,342 (6.90)	558 (1.93)		439 (2.58)	119 (1.00)	
MPCE							
Poorest	12,582 (20.03)	3,562 (10.49)	9,020 (31.23)	< 0.001	4,494 (26.42)	4,526 (38.14)	< 0.001
Poorer	12,593 (20.05)	5,677 (16.72)	6,916 (23.95)		3,978 (23.39)	2,938 (24.76)	
Middle	12,573 (20.01)	6,996 (20.61)	5,577 (19.31)		3,468 (20.39)	2,109 (17.77)	
Richer	12,551 (19.98)	8,209 (24.18)	4,342 (15.04)		2,940 (17.28)	1,402 (11.81)	
Richest	12,523 (19.93)	9,500 (27.99)	3,023 (10.47)		2,130 (12.52)	893 (7.52)	
Place of residence							
Rural	41,128 (65.47)	15,304 (45.09)	25,824 (89.42)	< 0.001	15,023 (88.32)	10,801 (91.01)	< 0.001
Urban	21,694 (34.53)	18,640 (54.91)	3,054 (10.58)		1,987 (11.68)	1,067 (8.99)	
Religion							
Hindu	46,097 (73.38)	25,197 (74.23)	20,900 (72.37)	< 0.001	11,860 (69.72)	9,040 (76.17)	< 0.001
Muslim	7,261 (11.56)	3,846 (11.33)	3,415 (11.83)		2,375 (13.96)	1,040 (8.76)	
Christian	6,217 (9.90)	2,810 (8.28)	3,407 (11.80)		2,080 (12.23)	1,327 (11.18)	
Others	3,247 (5.17)	2,091 (6.16)	1,156 (4.00)		695 (4.09)	461 (3.88)	
Social class							
Scheduled caste	10,472 (16.67)	4,938 (14.55)	5,534 (19.16)	< 0.001	2,723 (16.01)	2,811 (23.69)	< 0.001
Scheduled tribe	11,210 (17.84)	3,589 (10.57)	7,621 (26.39)		4,493 (26.41)	3,128 (26.36)	
Other backward caste	24,020 (38.24)	13,650 (40.21)	10,370 (35.91)		6,045 (35.54)	4,325 (36.44)	
Others	17,120 (27.25)	11,767 (34.67)	5,353 (18.54)		3,749 (22.04)	1,604 (13.52)	
Housing type (*pucca* house)							
No	28,722 (45.72)	9,360 (27.57)	19,362 (67.05)	< 0.001	10,165 (59.76)	9,197 (77.49)	< 0.001
Yes	34,100 (54.28)	24,584 (72.43)	9,516 (32.95)		6,845 (40.24)	2,671 (22.51)	
International poverty line							

Table 1 (continued)

Characteristics	Overall, n = 62,822	Clean fuels, n = 33,944 (54.03%)	Non-CF, n = 28,878 (45.97%)	*P*-value[a]	Non-CF in separate kitchen, n = 17,010 (27.08%)	Non-CF in non-separate kitchen, n = 11,868 (18.89%)	*P*-value[b]
Above	52,215 (83.12)	31,108 (91.65)	21,107 (73.09)	< 0.001	13,201 (77.61)	7,906 (66.62)	< 0.001
At/below	10,607 (16.88)	2,836 (8.35)	7,771 (26.91)		3,809 (22.39)	3,962 (33.38)	
Current excessive alcohol							
Yes	4,627 (7.37)	2,115 (6.23)	2,512 (8.70)	< 0.001	1,443 (8.48)	1,069 (9.01)	< 0.001
No	58,195 (92.63)	31,829 (93.77)	26,366 (91.30)		15,567 (91.52)	10,799 (90.99)	
Current use of tobacco[c]							
Yes	19,541 (31.11)	7,803 (22.99)	11,738 (40.65)	< 0.001	6,520 (38.33)	5,218 (43.97)	< 0.001
No	43,281 (68.89)	26,141 (77.01)	17,140 (59.35)		10,490 (61.67)	6,650 (56.03)	
Physical inactivity							
Yes	46,873 (74.61)	27,104 (79.85)	19,769 (68.46)	< 0.001	11,659 (68.54)	8,110 (68.34)	< 0.001
No	15,949 (25.39)	6,840 (20.15)	9,109 (31.54)		5,351 (31.46)	3,758 (31.66)	

Data presented as n (%) or otherwise indicated

BMI Body Mass Index, *SD* Standard Deviation, *IQR* Interquartile Range, *MPCE* Monthly Per Capita Expenditure

[a]Student's t-test; Mann–Whitney *U* test; Pearson's Chi-squared test – between clean fuels and non-CF

[b]One-way ANOVA; Kruskal–Wallis test; Pearson's Chi-squared test – across clean fuels, non-CF in separate kitchen, and non-CF in non-separate kitchen

[c]Current use of smoking/smokeless tobacco

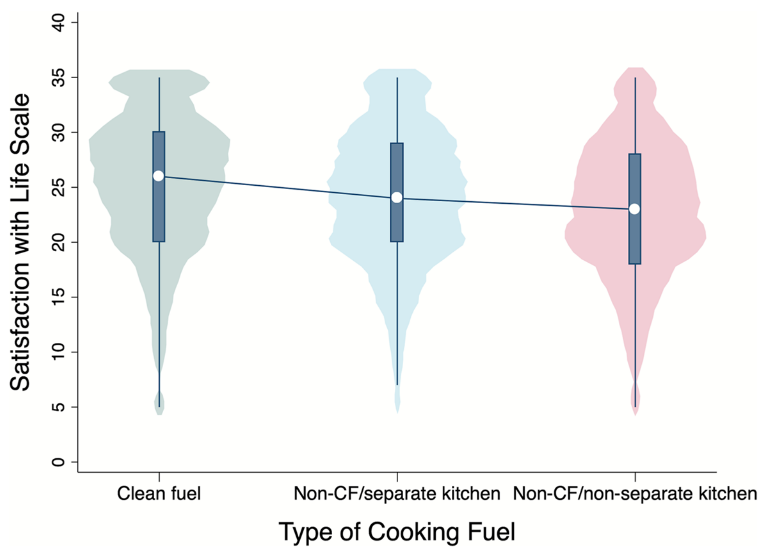


Fig. 1 Distribution of life satisfaction scores across cooking fuel use categories. Violin plots display the distribution, median (circle), and interquartile range of life satisfaction scores (range: 5–35) by cooking fuel categories. Corrected *P*-values < 0.001 (multiple pairwise comparisons using the Benjamini–Hochberg method between all fuel use categories, following Kruskal–Wallis test [*P* < 0.001])

Association of polluting fuel use and life satisfaction

Results of multicollinearity diagnostics are reported in Supplementary Text S2. VIF indicated absence of multicollinearity (VIF < 5). In model 1 individuals exposed to non-CF use for cooking, compared to those using clean fuels, were associated with lower life satisfaction score ($\beta = -1.97$ [95% CI: –2.12, –1.83] $P < 0.001$). After adjusting for covariates (model 2), the magnitude of association decreased, but the level of statistical significance remained consistent (β = –0.90 [95% CI: –1.08, –0.71] $P < 0.001$). Compared to individuals using clean fuel for cooking at home, those using non-CF in a non-separate kitchen were associated with the lowest life satisfaction score (β = –2.74 [95% CI: –2.93, –2.55] $P < 0.001$). This was followed by those using non-CF in a separate kitchen (β = –1.29 [95% CI: –1.46, –1.12] $P < 0.001$). Moreover, adjustment for covariates in Model 2 attenuated the magnitude of the association; however, the level of statistical significance and the dose–response association remained consistent (non-CF in non-separate kitchen: β = –1.42 [95% CI: –1.65, –1.19] $P < 0.001$; non-CF in separate kitchen: β = –0.51 [95% CI: –0.71, –0.31] $P < 0.001$) (Table 2). To assess the robustness of our weighted analysis, the unweighted regression estimates are presented in the Supplementary Table S2. The direction, magnitude, and statistical significance remained consistent across both analyses, indicating that the results are not sensitive to the application of survey weights.

Associations also remained unchanged in the generalized ordered logistic regression analysis, indicating that the linear regression results are robust (Table 3). In this analysis, the Wald test of parallel lines for the global multivariable model was $P < 0.05$ (Wald test $P_{\text{non-CF vs clean fuels}} = 0.004$; Wald test $P_{\text{non-CF in separate/non-separate kitchen vs clean fuels}} = 0.008$), indicating that some variables in the model had life satisfaction threshold-specific effects. Compared with clean fuels, use of non-CF and those in separate kitchen were associated with lower life satisfaction across all thresholds (OR = 0.79 [95% CI: 0.75, 0.83] $P < 0.001$) and OR = 0.87 [95% CI: 0.83, 0.92] $P < 0.001$), respectively. In contrast, for those using non-CF in non-seperate kitchen, the association varied by life satisfaction thresholds, indicating a stronger negative association at lower levels of life satisfaction.

CEM sample-weighted adjusted models also showed similar associations (non-CF users: β = −0.98 [95% CI: −1.17, −0.79] $P < 0.001$; non-CF in non-separate kitchen: β = −1.22 [95% CI: −1.50, −0.93] $P < 0.001$; non-CF in a separate kitchen: β = −0.59 [95% CI: −0.80, −0.38] $P < 0.001$) (Fig. 2). Since the matching solution was restricted to a *k*-to-*k* match, a substantial number of observations were pruned to achieve balanced covariate distributions between groups. The number of observations discarded during pruning was as follows: group-1 – clean fuel (22,684) and non-CF (17,618), group-2 – clean fuels (24,916) and non-CF in separate kitchen (7,982), and group-3 – clean fuels (28,375) and non-CF in non-separate kitchen (6,299). After exact matching, the multivariate L1 distance was zero for all exposure groups, indicating perfect balance across all covariates. Also, univariate L1 values and SMD test for individual covariates confirmed that the distributions of covariates were identical between each treatment and control groups (Supplementary Table S3).

Figure 3 depicts the gender-specific associations of polluting fuel use and life satisfaction, with detailed

Table 2 Sample-weighted regression coefficients and 95% confidence intervals for type of cooking fuel used with life satisfaction (overall life satisfaction score)

	Model-1[a] β (95% CI)	*P*-value	Model-2[b] β (95% CI)	*P*-value
Clean fuel	Reference		Reference	
Non-CF	–1.97 (–2.12, –1.83)	< 0.001	–0.90 (–1.08, –0.71)	< 0.001
Clean fuel	Reference		Reference	
Non-CF in separate kitchen	–1.29 (–1.46, –1.12)	< 0.001	–0.51 (–0.71, –0.31)	< 0.001
Non-CF in non-separate kitchen	–2.74 (–2.93, –2.55)	< 0.001	–1.42 (–1.65, –1.19)	< 0.001

[a]Unadjusted model

[b]Adjusted for covariates: age, gender, socioeconomic position, marital status, education level, working status, place of residence, religion, social class, housing type, international poverty line, states, current excessive alcohol intake, current use of tobacco, and physical inactivity

Table 3 Sample-weighted generalized ordered logistic regression (partial proportional odds) examining the association between types of cooking fuel used and ordinal life satisfaction

	Life satisfaction thresholds[a]				
	Extremely dissatisfied OR (95% CI)	Dissatisfied OR (95% CI)	Slightly dissatisfied OR (95% CI)	Neutral OR (95% CI)	Satisfied OR (95% CI)
Clean fuel	Reference	Reference	Reference	Reference	Reference
Non-CF	0.79*** (0.75, 0.83)	0.79*** (0.75, 0.83)	0.79*** (0.75, 0.83)	0.79*** (0.75, 0.83)	0.79*** (0.75, 0.83)
Clean fuel	Reference	Reference	Reference	Reference	Reference
Non-CF in separate kitchen	0.87*** (0.83, 0.92)	0.87*** (0.83, 0.92)	0.87*** (0.83, 0.92)	0.87*** (0.83, 0.92)	0.87*** (0.83, 0.92)
Non-CF in non-separate kitchen	0.59*** (0.52, 0.67)	0.66*** (0.61, 0.72)	0.70*** (0.65, 0.75)	0.71*** (0.67, 0.76)	0.69*** (0.64, 0.75)

[a]Although a single odds ratio (OR) is reported for both non-CF and those in a separate kitchen, their analyses were conducted using a generalized ordered logistic regression model. These exposures did not violate the proportional odds assumption in the multivariable analysis, but other covariates in the same model did (global model Wald test < 0.05), necessitating the use of the generalized model

***$P < 0.001$

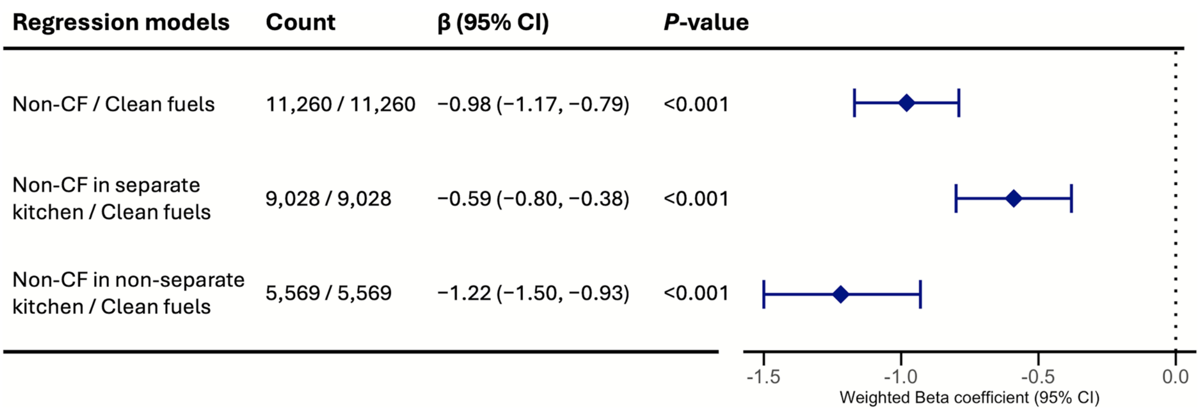


Fig. 2 Association of polluting fuel use with life satisfaction after coarsened exact matching. Each regression model is adjusted for the CEM weights and state/UTs. Matching was performed using all covariates as: age category (45–69, ≥ 70), gender, marital status, education (no education, ≥ primary), working status, religion, caste, residence, MPCE tertile, housing type, poverty status, current alcohol consumption, current tobacco use, and physical inactivity. Count = number of matched individuals

results shown in Supplementary Table S4. Overall, men exhibited higher life satisfaction score compared to women across the various types of cooking fuels. Notably, women showed the greatest reduction in life satisfaction score compared to men when exposed to non-CF (men: β = –0.79 [95% CI: –1.06, –0.51]; women: β = –0.98 [95% CI: –1.23, –0.73] $P_{interaction}$ = 0.018). In both men and women, exposure to non-CF in non-separate kitchen was associated with the lowest life satisfaction score, followed by exposure to non-CF in separate kitchen. However, the strength of the negative association was greater among women compared to men, exhibiting significantly lower life satisfaction scores when exposed to non-CF in non-separate kitchen ($P_{interaction}$ = 0.007). Additional subgroup analyses revealed that exposure to polluting fuels reduces life satisfaction irrespective of age group (45–69 years vs. ≥ 70 years), socioeconomic position (SEP, high vs. low), or area of residence (rural vs. urban). However, statistically significant sub-group differences in fully adjusted model-2 were observed by residence only, with non-CF in non-separate

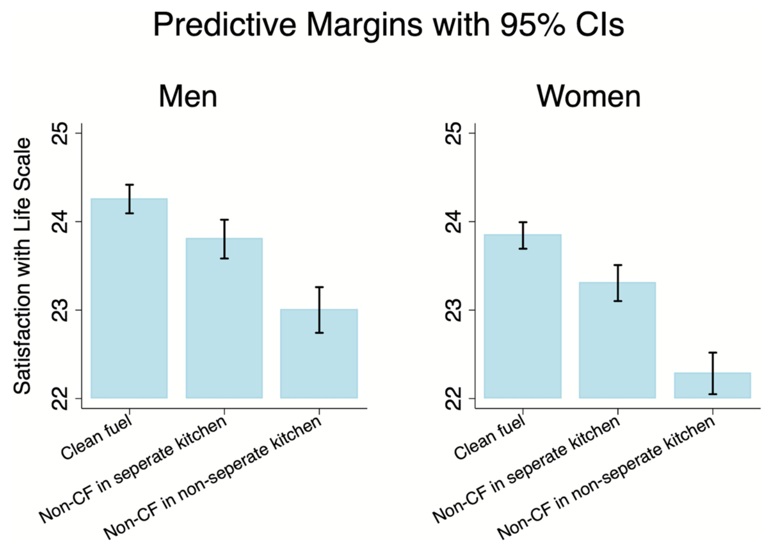


Fig. 3 Predictive values of life satisfaction based on cooking fuel categories, stratified by gender. *Note:* Marginal probabilities are estimated based on the fully adjusted interaction model (model 2) given in Supplementary Table S4

kitchen posing a greater negative association with life satisfaction among urban residents ($P_{\text{interaction}} < 0.05$) (Supplementary Table S5).

Several sensitivity analyses supported the robustness of our findings. Using the single item life satisfaction measure, Cantril Ladder, and life satisfaction score quintiles as alternative outcome measures, the results were consistent with those from the primary analysis, showing similar patterns of association and maintaining statistical significance in both linear and ordered logistic regression models. In the fully adjusted model, use of non-CF was associated with reduced life satisfaction ($\beta_{\text{single-item life satisfaction}} = -0.17$ [95% CI: –0.19, –0.14], $\beta_{\text{Cantril Ladder}} = -0.43$ [–0.47, –0.38]; $\beta_{\text{life satisfaction score quintiles}} = -0.17$ [–0.20, –0.13]), while a graded negative association was seen for non-CF in separate kitchen and non-separate kitchen (Supplementary Table S6).

Discussion

Based on a large representative sample from the LASI Wave-1 (2017–18), we evaluated associations between polluting fuel use for cooking and life satisfaction among middle-aged and older adults in India. Our study approach offers three key results. First, it examines the link between polluting fuel use and life satisfaction, an area that remains largely understudied, especially in the Indian context. We specifically look at this link in an aging population which other research has shown is a particularly vulnerable population to household air pollution [36]. Second, it uses a more nuanced definition of exposure to non-CF by incorporating information on if the kitchen was in a separate room. Third, it examines gender-specific associations, recognizing the gender disparity in exposure to polluting fuels in India. We observed a moderate reduction in life satisfaction by about 0.90 units among non-CF users. A dose–response negative association emerged based on kitchen type: individuals using non-CF in non-separate kitchen experienced the largest decline by about 1.42 units, compared to a 0.51 units reduction among those using non-CF in separate kitchen. The CEM analysis further confirmed that the use of polluting cooking fuels is an independent risk factor, significantly lowering life satisfaction. Additionally, the magnitude of negative association was more pronounced among women than men, indicating that women are most adversely affected by non-CF use.

Our study corroborates previously reported negative association of polluting fuel use with life satisfaction and overall well-being, aligning with the findings of Zhang et al. [37] and Yang et al. [38]. Previous analyses of LASI data similarly found that polluting fuel use was associated with poor self-rated health [39] and that health partially mediated effects on life satisfaction [40]. Studies have also documented associations between polluting fuel use and depression and cognitive impairment in Indian populations [7], underscoring the multifaceted impacts of polluting fuel use on well-being. Further, using polluting fuels and cooking within living spaces was linked to an elevated risk of poor self-rated health among older adults [40], emphasizing the hazards associated with non-CF use in households without separate kitchens. With nearly 40% of Indian households lacking a separate kitchen [41], promoting separate cooking spaces may help decrease adverse effects of polluting fuel use and enhance well-being. These improvements also align with national and international recommendations to address the heightened risks faced by vulnerable groups like elderly individuals and women from polluting fuel use, especially among those living in non-separate kitchens [4, 5].

Women face greater health risks from using polluting fuels due to their primary role in biomass collection, and longer time spent in the kitchen as the main cooks [2]. This is reflected in poorer self-rated health [42], life satisfaction and overall well-being compared to men [43]. Greater decline in life satisfaction among women observed in our study adds to the growing evidence of the negative impact of polluting fuel use on life satisfaction. This underscores the need to address the gendered impact of polluting fuel use and to promote equitable access to clean energy solutions [43]. Prioritizing women's empowerment plays a crucial role in advancing the clean energy transition [44], with the potential to yield transformative benefits for public health, gender equality, and overall population well-being. A previous study has indicated that physical health mediates the relationship between indoor air pollution and life satisfaction among older adults (60 + years) [39], while the negative effect of polluting fuels use on life satisfaction gradually increases with age [37]. However, our sub-group analysis found no difference in the association between polluting fuel use and life satisfaction for the 45–69 and 70 + age groups. This implies that the adverse association of polluting fuel use on life satisfaction are similarly significant for both middle-aged and older adults. This is particularly concerning, as individuals aged 45–69 are in their prime working years and often the main household earners; thus, reduced life satisfaction and health from polluting fuel use may lower labor supply and family income, amplifying socioeconomic consequences [37]. Similarly, no difference in the association between polluting fuel use and life satisfaction between SEP levels or area of residence indicates a uniform impact, except among urban households using non-CF in non-separate kitchens. Hence, categorizing polluting fuel use by kitchen type reveals a nuanced relationship with life satisfaction, suggesting that policymakers should consider addressing kitchen infrastructure alongside clean fuel transition [4]. This focus is especially crucial for urban residents, whose compact living spaces alongside high ambient air pollution exacerbate the negative effects of polluting fuel use in non-separate kitchens.

Although our observed associations are moderate at the individual level, their public health relevance is considerable given the widespread reliance on polluting cooking fuels in India. Previous studies have demonstrated notable improvements in physical health, life satisfaction, and overall well-being following transition to clean cooking fuels [27, 36, 45]. We reiterate policy implications that focus on improving clean fuel affordability through subsidies, strengthening supply chains, and increasing consumer awareness about health and well-being impact through education and community outreach programs [46–48]. Additionally, implementing targeted awareness campaigns to address gender inequalities [44] and cultural barriers [49] to facilitate behavioural changes for promoting sustained adoption is essential. Life satisfaction is also most sensitive to the use of polluting fuels in non-separate kitchen, underscoring the need to improve kitchen configuration and ventilation conditions, as the adverse effects of polluting fuels may be ameliorated through targeted policy interventions. Converging developmental programs such as PMUY and Pradhan Mantri Awaas Yojana-Gramin to jointly promote clean energy adoption and improved housing conditions may effectively address these challenges, enhancing both health and well-being.

Nonetheless, our findings should be interpreted in light of certain limitations. First, the LASI Wave 1 is based on an observational cross-sectional design, and thus our results do not warrant causal relationships. We sought to address this through our CEM analysis. The CEM-matched sample produced estimates consistent with those obtained from the full-sample regression models. However, unmeasured confounding warrants further determination of the independent risks of polluting fuel use on life satisfaction. Second, the subjective measure of life satisfaction may introduce reporting bias. Third, potential exposure misclassification may have occurred due to reliance on self-reported fuel type. Moreover, in the absence of direct indoor air quality or absolute personal exposure measurements, the results should be interpreted as indirect evidence, and the policy implications should be viewed as supportive rather than definitive. Fourth, we were unable to assess how the use of clean fuels specifically affects life satisfaction, limiting our ability to draw conclusions about this relationship. Finally, the survey did not capture households that uses fuel stacking which may have influenced the observed associations. The widespread practice of fuel stacking in India, whereby households use multiple cooking fuels rather than exclusively relying on a single fuel, may have biased the estimated associations. Classifying exposure based on primary fuel use alone could result in exposure misclassification, as those categorized as clean fuel users may still experience intermittent exposure to polluting fuels. This misclassification is likely to bias the associations toward the null, leading to an underestimation of the true magnitude of the relationship between polluting fuel use and life satisfaction. In settings where polluting fuels are used frequently alongside clean fuels, residual exposure may also introduce heterogeneity in exposure intensity, potentially obscuring stronger association among exclusive polluting fuel users. Future research would benefit from collecting granular data on fuel stacking practices.

Conclusion

Our study expands upon previous literature that exposure to polluting fuel use reduces overall life satisfaction, and especially among women. More importantly, the study shows household kitchen infrastructure influences the magnitude of association, implying greater reduction of individual life satisfaction among those households that uses polluting fuels in non-separate kitchen. Comparisons between middle-aged and older sub-groups revealed no significant differences, suggesting that the association of polluting fuel use with life satisfaction is consistent across age groups. Since the transitioning from non-clean to clean fuel use is conducive to enhancing well-being, this study emphasizes strengthening the implementation of clean fuel transitions and expanding their reach to mitigating the adverse impacts of polluting fuel use on individual well-being. Future policies should focus on integrated approaches that ensure equitable access to clean cooking solutions for a healthier population.

Acknowledgements First author IL is supported by the Narotam Sekhsaria Fellowship funded by the Harvard T.H. Chan School of Public Health India Research Center, an office of Harvard Global Research Support Centre India, and the Narotam Sekhsaria Foundation. This research used publicly accessible secondary data obtained from Longitudinal Aging Study in India (LASI), a program project directed by Sandy Chien, Codi Young, Drystan Phillips, Jenny Wilkens, Yuxuan Wang, Alden Gross, Erik Meijer, Marco Angrisani, and Jinkook Lee. "Harmonized LASI, Version A.3." The Gateway to Global Aging Data, 2023. https://doi.org/10.25549/h-lasi. Produced and distributed by the University of Southern California with funding from the National Institute on Aging (R01 AG042778, 2R01 AG030153, 2R01 AG051125).

Author contribution IL: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization.

SK: Writing – review & editing, Investigation, Formal analysis, Data curation.

PD: Writing – review & editing, Investigation, Supervision.

RB: Writing – review & editing, Investigation.

RK: Writing – review & editing, Investigation, Supervision.

SVS: Writing – review & editing, Investigation, Supervision, Conceptualization.

Funding None.

Data availability The authors do not have permission to share data.

Declarations

Competing interest All authors declare no conflicts of interest.

References

1. Brauer M, Roth GA, Aravkin AY, Zheng P, Abate KH, Abate YH, et al. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. Lancet. 2024;403(10440):2162–203. https://doi.org/10.1016/S0140-6736(24)00933-4.
2. World Health Organization. Household Air Pollution. 2024. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health. Accessed October 04, 2025.
3. Deepthi Y, Nagendra SS, Gummadi SN. Characteristics of indoor air pollution and estimation of respiratory

dosage under varied fuel-type and kitchen-type in the rural areas of Telangana state in India. Sci Total Environ. 2019;650:616–25. https://doi.org/10.1016/j.scitotenv.2018.08.381.
4. Balakrishnan K, Mehta S, Kumar P, Ramaswamy P, Sambandam S, Kumar KS, et al. Indoor air pollution associated with household fuel use in India: an exposure assessment and modeling exercise in rural districts of Andhra Pradesh, India. Washington, DC: World Bank; 2004.
5. Balakrishnan K, Ramaswamy P, Sambandam S, Thangavel G, Ghosh S, Johnson P, et al. Air pollution from household solid fuel combustion in India: an overview of exposure and health related information to inform health research priorities. Glob Health Action. 2011;4(1):5638. https://doi.org/10.3402/gha.v4i0.5638.
6. Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. Bull World Health Organ. 2000;78(9):1078–92. https://doi.org/10.1590/S0042-96862000000900004.
7. Jin Y, Zhou X, Deng L, Xiong X, Li Y, Wei Q, et al. Association between the domestic use of solid cooking fuel and increased prevalence of depression and cognitive impairment in a big developing country: a large-scale population-based study. Front Public Health. 2022;10:1038573. https://doi.org/10.3389/fpubh.2022.1038573.
8. Diener ED, Emmons RA, Larsen RJ, Griffin S. The satisfaction with life scale. J Pers Assess. 1985;1(49):71–5. https://doi.org/10.1207/s15327752jpa4901_13.
9. Graham C, Laffan K, Pinto S. Well-being in metrics and policy. Science. 2018;362(6412):287–8. https://doi.org/10.1126/science.aau5234.
10. Eger RJ, Maridal JH. A statistical meta-analysis of the wellbeing literature. Int J Wellbeing. 2015. https://doi.org/10.5502/ijw.v5i2.4.
11. Enkvist Å, Ekström H, Elmståhl S. What factors affect life satisfaction (LS) among the oldest-old? Arch Gerontol Geriatr. 2012;54(1):140–5. https://doi.org/10.1016/j.archger.2011.03.013.
12. Bramhankar M, Kundu S, Pandey M, Mishra NL, Adarsh A. An assessment of self-rated life satisfaction and its correlates with physical, mental and social health status among older adults in India. Sci Rep. 2023;13(1):9117. https://doi.org/10.1038/s41598-023-36041-3.
13. Abed Al Ahad M. Air pollution reduces the individuals' life satisfaction through health impairment. Eur J Public Health. 2024;34(Supplement_3):ckae144–915. https://doi.org/10.1093/eurpub/ckae144.915.
14. Raj T, Umenthala SR. Income rank and life satisfaction: examining the relationship with wealth inequality among middle-aged and older Indian adults. SSM Popul Health. 2025;29:101740. https://doi.org/10.1016/j.ssmph.2024.101740.
15. Liao PS, Shaw D, Lin YM. Environmental quality and life satisfaction: subjective versus objective measures of air quality. Soc Indic Res. 2015;124(2):599–616. https://doi.org/10.1007/s11205-014-0799-z.
16. Song Y, Zhou A, Zhang M. Exploring the effect of subjective air pollution on happiness in China. Environ Sci Pollut Res Int. 2020;27(34):43299–311. https://doi.org/10.1007/s11356-020-10255-8.
17. Xia X, Yu Y, Zou Y. Air pollution, social engagement and subjective well-being: evidence from the Gallup world poll. Environ Sci Pollut Res Int. 2022;29(34):52033–56. https://doi.org/10.1007/s11356-022-19451-0.
18. MacKerron G, Mourato S. Life satisfaction and air quality in London. Ecol Econ. 2009;68(5):1441–53. https://doi.org/10.1016/j.ecolecon.2008.10.004.
19. Ferreira S, Akay A, Brereton F, Cuñado J, Martinsson P, Moro M, et al. Life satisfaction and air quality in Europe. Ecol Econ. 2013;88:1. https://doi.org/10.1016/j.ecolecon.2012.12.027.
20. Dolan P, Laffan K. Bad air days: the effects of air quality on different measures of subjective well-being. J Benefit-Cost Anal. 2016;7(1):147–95. https://doi.org/10.1017/bca.2016.7.
21. Liu H, Hu T. How does air quality affect residents' life satisfaction? Evidence based on multiperiod follow-up survey data of 122 cities in China. Environ Sci Pollut Res Int. 2021;28(43):61047–60. https://doi.org/10.1007/s11356-021-15022-x.
22. Petrowski K, Bührer S, Strauß B, Decker O, Brähler E. Examining air pollution (PM10), mental health and well-being in a representative German sample. Sci Rep. 2021;11(1):18436. https://doi.org/10.1038/s41598-021-93773-w.
23. Zou X, He Y, Lu H. The hidden toll of air pollution: mental health effects on middle-aged and elderly individuals. Front Public Health. 2025;13:1610330. https://doi.org/10.3389/fpubh.2025.1610330.
24. Churchill SA, Smyth R, Farrell L. Fuel poverty and subjective wellbeing. Energy Econ. 2020;86:104650. https://doi.org/10.1016/j.eneco.2019.104650.
25. Liu G, Xue Y, Liu Y, Wang S, Geng Q. Multimorbidity in cardiovascular disease and association with life satisfaction: a Chinese national cross-sectional study. BMJ Open. 2020;10(12):e042950. https://doi.org/10.1136/bmjopen-2020-042950.
26. Goldemberg J, Martinez-Gomez J, Sagar A, Smith KR. Household air pollution, health, and climate change: cleaning the air. Environ Res Lett. 2018;13(3):030201. https://doi.org/10.1088/1748-9326/aaa49d.
27. deSouza P, Lee JJ, Németh J, Mani S, Jain A, Kar A, et al. Evaluating associations between the transition to cleaner cooking energy use and hypertension in India. Environ Res. 2025;3(4):045008. https://doi.org/10.1088/2752-5309/ae1755.
28. Mavrodaris A, Mattocks C, Brayne CE. Healthy ageing for a healthy planet: do sustainable solutions exist? Lancet Healthy Longev. 2021;2(1):e10-1. https://doi.org/10.1016/S2666-7568(20)30067-2.
29. Sandy Chien, CY, Phillips, D, Wilkens, J, Wang, Y, Gross, A, Meijer, E, Angrisani, M, Lee, J. Harmonized LASI, version A.3. In: The Gateway to Global Aging Data, vol. 2023. https://doi.org/10.25549/h-lasi.
30. International Institute for Population Sciences (IIPS), NPHCE, MoHFW, et al. (2020). Longitudinal ageing study in India (LASI) wave 1, 2017–18, India Report. Mumbai. https://www.iipsindia.ac.in/sites/default/files/LASI_India_Report_2020_compressed.pdf.
31. Diener, E. (2006). Understanding scores on the satisfaction with life scale. https://labs.psychology.illinois.edu/

~ediener/Documents/Understanding%20SWLS%20Scores.pdf. Accessed September 23, 2025.

32. Ortiz-Ospina, E., & Roser, M. (2017). "Happiness and Life Satisfaction". Data adapted from Wellbeing Research Centre. https://archive.ourworldindata.org/20250925-233948/grapher/happiness-cantril-ladder.html. Accessed October 17, 2025.
33. Ambade M, Kim R, Subramanian SV. Socio-economic distribution of modifiable risk factors for cardiovascular diseases: an analysis of the national longitudinal ageing study in India. Prev Med. 2023;175:107696. https://doi.org/10.1016/j.ypmed.2023.107696.
34. Williams R. Generalized ordered logit/partial proportional odds models for ordinal dependent variables. Stata J: Promot Communicat Statistic Stata. 2006;6(1):58–82.
35. Blackwell M, Iacus S, King G, Porro G. Cem: coarsened exact matching in Stata. Stata J. 2009;9(4):524–46. https://doi.org/10.1177/1536867X09009004.
36. Wang X, Bian Y, Zhang Q. The effect of cooking fuel choice on the elderly's well-being: evidence from two non-parametric methods. Energy Econ. 2023;125:106826. https://doi.org/10.1016/j.eneco.2023.106826.
37. Zhang L, Xiao Y, Wu Q, Li J. Will the use of solid fuels reduce the life satisfaction of rural residents—evidence from China. Energy Sustain Dev. 2022;68:94–102. https://doi.org/10.1016/j.esd.2022.03.006.
38. Yang X, Liu Z, Sun F, Feng H, You T, Chen C, et al. Association between solid cooking fuels and functional disability: evidence from a cross-sectional and longitudinal study. BMC Public Health. 2025;25(1):3064. https://doi.org/10.1186/s12889-025-24433-1.
39. Adhikary M, Goyal AK, Akhtar S. The mediating role of health status in the relationship between indoor air pollution and life satisfaction among older adults in India. BMC Public Health. 2025;25(1):3403. https://doi.org/10.1186/s12889-025-24256-0.
40. Halder M, Kasemi N. Household air pollution as a determinant of health status: a study on older adults in Siliguri Municipal Corporation, India. Sci Rep. 2025;15(1):10048. https://doi.org/10.1038/s41598-025-93311-y.
41. Das B, Mistri A. Household quality of living in Indian states: analysis of 2011 census. Environ Urbaniz Asia. 2013;4(1):151–71. https://doi.org/10.1177/0975425313477759.
42. Halder M, Kasemi N, Roy D, Majumder M. Impact of indoor air pollution from cooking fuel usage and practices on self-reported health among older adults in India: evidence from LASI. SSM Popul Health. 2024;25:101653. https://doi.org/10.1016/j.ssmph.2024.101653.
43. World Health Organization. (2016). Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. https://iris.who.int/server/api/core/bitstreams/a813dcb1-136d-47d5-ab5e-0dd50209f066/content. Accessed October 04, 2025.
44. Chakravarty D, Banerjee A. Choice of clean cooking fuel, peer effect and women empowerment: a village-level study from India. In: Gender (in) equality and social development: issues of health, education, environment and other SDG implications. Singapore: Springer Nature Singapore; 2025. p. 17–33. https://doi.org/10.1007/978-981-96-7979-9_2.
45. Ma W, Zheng H. Impacts of cooking fuel choices on subjective well-being: Insights from Rural China. 2021. https://ageconsearch.umn.edu/record/315149/files/0-0_Paper_18899_handout_298_0.pdf.
46. Gould CF, Hou X, Richmond J, Sharma A, Urpelainen J. Jointly modeling the adoption and use of clean cooking fuels in rural India. Environ Res Commun. 2020;2(8):085004. https://doi.org/10.1088/2515-7620/abaca9.
47. Roy K. Transition to cooking with clean fuels in rural households of India: studying the effect of policy and other factors. Energy Sustain Dev. 2024;80:101456. https://doi.org/10.1016/j.esd.2024.101456.
48. Thiyaharajan M, Bora K, Pandey R, Kumar V. Policy perspective for achieving the NDCs commitment: household fuel energy transition and attributable factors in a developing economy, India. Local Enviro. 2025:1–6. https://doi.org/10.1080/13549839.2025.2519363.
49. Malakar Y, Day R. Differences in firewood users' and LPG users' perceived relationships between cooking fuels and women's multidimensional well-being in rural India. Nat Energy. 2020;5(12):1022–31. https://doi.org/10.1038/s41560-020-00722-4.

Title: Polluting cooking fuels and life satisfaction among middle-aged and older adults: A cross-sectional study from the Longitudinal Ageing Study in India

Journal: GeroScience

Authors: Imnameren Longkumer[a,b], Soohyeon Ko[a,c], Priyanka deSouza[d,e], Rohit Bhatia[b], Rockli Kim[f,g], S.V. Subramanian[a,c,*]

[a]Department of Social and Behavioral Sciences, Harvard T.H. Chan School of Public Health, Boston, MA, United States of America

[b]Department of Neurology, All India Institute of Medical Sciences, New Delhi, India

[c]Harvard Center for Population and Development Studies, Cambridge, MA, United States of America

[d]Department of Urban and Regional Planning, University of Colorado Denver, Denver, CO, United States of America

[e]CU Population Center, University of Colorado Boulder, Boulder, CO 80302, United States of America

[f]Interdisciplinary Program in Precision Public Health, Korea University, Seoul, Republic of Korea

[g]Division of Health Policy and Management, College of Health Science, Korea University, Seoul, Republic of Korea

*Corresponding author

Corresponding author address

S.V. Subramanian, PhD

Professor of Population Health and Geography

Department of Social and Behavioral Sciences

Harvard T.H. Chan School of Public Health, Boston, MA, US

Corresponding author email address

svsubram@hsph.harvard.edu

Table S1: Mean differences of life satisfaction score by select covariates among the study respondents

Characteristics		Satisfaction With Life Scale Score		
		Mean (SD)	**Mean difference**	***P*-value[a]**
Age cohort	45 – 69 years	23.96 (7.09)		0.285
	≥70 years	23.89 (7.25)	−0 .07	
Gender	Men	24.17 (7.03)		<0.001
	Women	23.75 (7.18)	−0.43	
Marital status	Married	24.27 (6.96)		<0.001
	Not married	22.98 (7.47)	−1.29	
Education level	No education	22.92 (7.20)		<0.001
	≥Primary level[b]	25.32 (6.82)	2.39	
Working status	Not working/ retired	24.05 (7.14)		<0.001
	Working	23.83 (7.09)	−0.22	
Socioeconomic position[c]	Low	23.27 (7.03)		<0.001
	High	24.39 (7.14)	1.12	
Place of residence	Urban	24.86 (7.04)		<0.001
	Rural	23.46 (7.11)	−1.40	
Religion	Hindu	23.90 (7.26)		0.009
	Minority religious groups[d]	24.06 (6.69)	0.17	
Social class	Others (incl. OBC)	24.24 (7.19)		<0.001
	Scheduled caste/ tribe	23.38 (6.93)	−0.86	
Housing type (*pucca* house)	No	22.96 (7.04)		<0.001
	Yes	24.77 (7.08)	1.80	
International poverty line	Above	24.16 (7.12)		<0.001
	At/below	22.86 (7.00)	−1.30	
Current excessive alcohol intake	No	23.99 (7.11)		<0.001
	Yes	23.32 (7.13)	−0.67	
Current use of tobacco (smoking/smokeless)	No	24.23 (7.16)		<0.001
	Yes	23.31 (6.98)	−0.92	
Physical activity	Active	23.52 (7.08)		<0.001
	Inactive	24.09 (7.12)	0.56	

[a]Student's t-test

[b]≥Primary level = primary + secondary + higher schooling

[c]MPCE quintiles categorized into low SEP (poorest and poor) and high SEP (middle, rich, and richest)

[d]Minority religious groups = Muslim + Christian + Others

Table S2: Unweighted regression coefficients and 95% confidence intervals for type of cooking fuel used with life satisfaction

	Life Satisfaction (overall score)			
	Model-1[a] **β (95% CI)**	**p-value**	**Model-2[b]** **β (95% CI)**	***P*-value**
Clean fuel	Reference		Reference	
Non-CF	–1.66 (–1.77, –1.54)	<0.001	–0.76 (–0.90, –0.63)	<0.001
Non-CF / separate kitchen	–1.12 (–1.25, –1.00)	<0.001	–0.50 (–0.65, –0.35)	<0.001
Non-CF / non-separate kitchen	–2.41 (–2.56, –2.26)	<0.001	–1.22 (–1.39, –1.04)	<0.001

[a]Unadjusted model

[b]Adjusted for the sociodemographic covariates: age, gender, socioeconomic position, marital status, education level, working status, place of residence, religion, social class, housing type, international poverty line, states, current excessive alcohol intake, current use of tobacco, and physical inactivity

Table S3: Descriptive statistics of study participants stratified by type of cooking fuel used after coarsened exact matching

Characteristics	Clean fuels, n = 11,260	Non-CF, n = 11,260	Clean fuels, n = 9,028	Non-CF in separate kitchen, n = 9,028	Clean fuels, n = 5,569	Non-CF in non-separate kitchen, n = 5,569	L1 statistics[a]	Test SMD[b]
Age								
45–69 years	9,492 (84.30)	9,492 (84.30)	7,652 (84.76)	7,652 (84.76)	4,707 (84.52)	4,707 (84.52)	0	<0.001
≥70 years	1,768 (15.70)	1,768 (15.70)	1,376 (15.24)	1,376 (15.24)	862 (15.48)	862 (15.48)		
Gender								
Men	4,794 (42.58)	4,794 (42.58)	3,828 (42.40)	3,828 (42.40)	2,341 (42.04)	2,341 (42.04)	0	<0.001
Women	6,466 (57.42)	6,466 (57.42)	5,200 (57.60)	5,200 (57.60)	3,228 (57.96)	3,228 (57.96)		
Marital status								
Married	8,742 (77.64)	8,742 (77.64)	7,150 (79.20)	7,150 (79.20)	4,238 (76.10)	4,238 (76.10)	0	<0.001
Not married	2,518 (22.36)	2,518 (22.36)	1,878 (20.80)	1,878 (20.80)	1,331 (23.90)	1,331 (23.90)		
Education level								
No education	6,049 (65.69)	6,049 (65.69)	4,753 (64.59)	4,753 (64.59)	3,647 (77.96)	3,647 (77.96)	0	<0.001
≥Primary	3,159 (34.31)	3,159 (34.31)	2,606 (35.41)	2,606 (35.41)	1,031 (22.04)	1,031 (22.04)		
Working status								
Not working	5,338 (47.41)	5,338 (47.41)	4,278 (47.39)	4,278 (47.39)	2,475 (44.44)	2,475 (44.44)	0	<0.001
Working	5,748 (51.05)	5,748 (51.05)	4,592 (50.86)	4,592 (50.86)	3,077 (55.25)	3,077 (55.25)		
Retired	174 (1.55)	174 (1.55)	158 (1.75)	158 (1.75)	17 (0.31)	17 (0.31)		
MPCE tertile								
1, Poorer	3,447 (30.61)	3,447 (30.61)	2,757 (30.54)	2,757 (30.54)	2,293 (41.17)	2,293 (41.17)	0	<0.001
2, Middle	4,303 (38.21)	4,303 (38.21)	3,465 (38.38)	3,465 (38.38)	2,071 (37.19)	2,071 (37.19)		
3, Richer	3,510 (31.17)	3,510 (31.17)	2,806 (31.08)	2,806 (31.08)	1,205 (21.64)	1,205 (21.64)		
Place of residence								
Rural	9,451 (83.93)	9,451 (83.93)	7,792 (86.31)	7,792 (86.31)	4,929 (88.51)	4,929 (88.51)	0	<0.001
Urban	1,809 (16.07)	1,809 (16.07)	1,236 (13.69)	1,236 (13.69)	640 (11.49)	640 (11.49)		
Religion								
Hindu	8,996 (79.89)	8,996 (79.89)	7,222 (80.00)	7,222 (80.00)	4,590 (82.42)	4,590 (82.42)	0	<0.001
Muslim	1,070 (9.50)	1,070 (9.50)	890 (9.86)	890 (9.86)	393 (7.06)	393 (7.06)		
Christian	765 (6.79)	765 (6.79)	615 (6.81)	615 (6.81)	414 (7.43)	414 (7.43)		
Others	429 (3.81)	429 (3.81)	301 (3.33)	301 (3.33)	172 (3.09)	172 (3.09)		

Social class								
Scheduled caste	2,002 (17.78)	2,002 (17.78)	1,494 (16.55)	1,494 (16.55)	1,278 (22.95)	1,278 (22.95)		
Scheduled tribe	1,523 (13.53)	1,523 (13.53)	1,263 (13.99)	1,263 (13.99)	874 (15.69)	874 (15.69)	0	<0.001
Other backward caste	5,023 (44.61)	5,023 (44.61)	4,071 (45.09)	4,071 (45.09)	2,496 (44.82)	2,496 (44.82)		
Others	2,712 (24.09)	2,712 (24.09)	2,200 (24.37)	2,200 (24.37)	921 (16.54)	921 (16.54)		
Housing type (*pucca* house)								
No	5,299 (46.06)	5,299 (46.06)	4,196 (46.48)	4,196 (46.48)	3,665 (65.81)	3,665 (65.81)	0	<0.001
Yes	5,961 (54.94)	5,961 (54.94)	4,832 (53.52)	4,832 (53.52)	1,904 (34.19)	1,904 (34.19)		
International poverty line								
Above	9,682 (85.99)	9,682 (85.99)	7,774 (86.11)	7,774 (86.11)	4,412 (79.22)	4,412 (79.22)	0	<0.001
At/below	1,578 (14.01)	1,578 (14.01)	1,254 (13.89)	1,254 (13.89)	1,157 (20.78)	1,157 (20.78)		
Current excessive alcohol								
Yes	564 (5.01)	564 (5.01)	435 (4.82)	435 (4.82)	276 (4.96)	276 (4.96)	0	<0.001
No	10,696 (94.99)	10,696 (94.99)	8,593 (95.18)	8,593 (95.18)	5,293 (95.04)	5,293 (95.04)		
Current use of tobacco[c]								
Yes	3,289 (29.21)	3,289 (29.21)	2,611 (28.92)	2,611 (28.92)	1,900 (34.12)	1,900 (34.12)	0	<0.001
No	9,974 (70.79)	7,974 (70.79)	6,417 (71.08)	6,417 (71.08)	3,669 (65.88)	3,669 (65.88)		
Physical inactivity								
Yes	8,583 (76.23)	8,583 (76.23)	6,787 (75.18)	6,787 (75.18)	4,136 (74.27)	4,136 (74.27)	0	<0.001
No	2,677 (23.77)	2,677 (23.77)	2,241 (24.82)	2,241 (24.82)	1,433 (25.73)	1,433 (25.73)		

Data presented as n (%).

BMI Body Mass Index, *SD* Standard Deviation, *IQR* Interquartile Range, *MPCE* Monthly Per Capita Expenditure, *SMD* Standardized Mean Difference.

Multivariate L1 distance after matching for each exposure groups – exposure group-1 (clean fuel vs. non-CF), exposure group-2 (clean fuels vs. non-CF in separate kitchen), and exposure group-3 (clean fuels vs. non-CF in non-separate kitchen) – is 0 (perfect balance across all covariates).

[a]Univariate L1 statistics – Value 0 indicating perfect balance of respective covariate between each exposure groups (clean fuels vs. non-CF; clean fuels vs. non-CF in separate kitchen; clean fuels vs. non-CF in non-separate kitchen).

[b]Standardized Mean Difference – For each covariate, the SMD was calculated as the difference in CEM-weighted proportions between each treatment and control groups divided by the pooled standard deviation. SMD <0.10 indicate good balance; SMD <0.001 indicate perfect balance.

[c]Current use of smoking/smokeless tobacco.

Table S4: Sub-group analysis – sample-weighted regression coefficients and 95% confidence intervals for type of cooking fuel used with life satisfaction (overall life satisfaction score), stratified by gender

Linear regression models	Men Non-CF, β (95% CI)	Women Non-CF, β (95% CI)	*P*-value[a]	Men Non-CF / separate kitchen, β (95% CI)	Women Non-CF / separate kitchen, β (95% CI)	*P*-value[a]	Men Non-CF / non-separate kitchen, β (95% CI)	Women Non-CF / non-separate kitchen, β (95% CI)	*P*-value[a]
Model 1: Unadjusted	–1.95 (–2.16, –1.74)	–2.00 (–2.20, –1.80)	0.747	–1.32 (–1.57, –1.07)	–1.26 (–1.49, –1.02)	0.719	–2.67 (–2.94, –2.39)	–2.81 (–3.07, –2.56)	0.440
[b]Model 2: Fully adjusted	–0.79 (–1.06, –0.51)	–0.98 (–1.23, –0.73)	0.018	–0.45 (–0.75, –0.16)	–0.54 (–0.81, –0.27)	0.281	–1.25 (–1.59, –0.92)	–1.56 (–1.87, –1.25)	0.007

[a]p-value of comparing coefficients between men and women in the full interaction model.

[b]Adjusted for the sociodemographic covariates: age, gender, socioeconomic position, marital status, education level, working status, place of residence, religion, social class, housing type, international poverty line, states, current excessive alcohol intake, current use of tobacco, and physical inactivity.

Table S5: Sub-group analysis – sample-weighted regression coefficients and 95% confidence intervals for type of cooking fuel used with life satisfaction

Linear regression models	Non-CF, β (95% CI)	Non-CF, β (95% CI)	*P*-value[a]	Non-CF / separate kitchen, β (95% CI)	Non-CF / separate kitchen, β (95% CI)	*P*-value[a]	Non-CF / non-separate kitchen, β (95% CI)	Non-CF / non-separate kitchen, β (95% CI)	*P*-value[a]
Age group	**45–69 years**	**≥70 years**		**45–69 years**	**≥70 years**		**45–69 years**	**≥70 years**	
Model 1: Unadjusted	–1.95 (–2.15, –1.75)	–2.00 (–2.21, –1.79)	0.718	–1.35 (–1.58, –1.11)	–1.21 (–1.46, –0.96)	0.427	–2.66 (–2.92, –2.39)	–2.83 (–3.10, –2.56)	0.373
[b]Model 2: Fully adjusted	–1.00 (–1.26, –0.74)	–0.74 (–1.00, –0.48)	0.560	–0.66 (–0.94, –0.38)	–0.30 (–0.59, –0.01)	0.168	–1.49 (–1.81, –1.16)	–1.30 (–1.62, –0.98	0.902
SEP	**High**	**Low**		**High**	**Low**		**High**	**Low**	
Model 1: Unadjusted	–1.86 (–2.06, –1.66)	–1.71 (–1.95, –1.47)	0.337	–1.35 (–1.58, –1.11)	–0.93 (–1.20, –0.66)	0.023	–2.65 (–2.94, –2.36)	–2.40 (–2.68, –2.12)	0.224
[b]Model 2: Fully adjusted	–0.92 (–1.17, –0.68)	–0.88 (–1.17, –0.59)	0.602	–0.68 (–0.94, –0.41)	–0.34 (–0.66, –0.02)	0.297	–1.37 (–1.71, –1.03)	–1.41 (–1.73, –1.08)	0.496
Residence	**Rural**	**Urban**		**Rural**	**Urban**		**Rural**	**Urban**	
Model 1: Unadjusted	–1.38 (–1.57, –1.20)	–2.87 (–3.28, –2.45)	<0.001	–0.71 (–0.92, –0.50)	–2.02 (–2.54, –1.50)	<0.001	–2.12 (–2.34, –1.90)	–3.97 (–4.60, –3.34)	<0.001
[b]Model 2: Fully adjusted	–0.93 (–1.14, –0.72)	–1.15 (–1.60, –0.71)	0.004	–0.57 (–0.80, –0.35)	–0.38 (–0.92, 0.17)	0.331	–1.42 (–1.68, –1.17)	–2.18 (–2.84, –1.53)	<0.001

[a]Unadjusted model.

[b]Adjusted for covariates: age, gender, socioeconomic position, marital status, education level, working status, place of residence, religion, social class, housing type, international poverty line, states, current excessive alcohol intake, current use of tobacco, and physical inactivity.

Table S6: Sensitivity analysis – sample-weighted regression coefficients and 95% confidence intervals for type of cooking fuel used with alternative life satisfaction measures

	Single-item life satisfaction		**Cantril Ladder**		**Life Satisfaction quintiles**	
	Model-1[a] β (95% CI)	**Model-2[b] β (95% CI)**	**Model-1[a] β (95% CI)**	**Model-2[b] β (95% CI)**	**Model-1[a] β (95% CI)**	**Model-2[b] β (95% CI)**
Clean fuel	Reference	Reference	Reference	Reference	Reference	Reference
Non-CF	–0.29*** (–0.31, –0.27)	–0.17*** (–0.19, –0.14)	–1.03*** (–1.07, –0.99)	–0.43*** (–0.47, –0.38)	–0.42*** (–0.44, –0.39)	–0.17*** (–0.20, –0.13)
Clean fuel	Reference	Reference	Reference	Reference	Reference	Reference
Non-CF / separate kitchen	–0.18*** (–0.21, –0.16)	–0.10*** (–0.12, –0.07)	–0.77*** (–0.82, –0.73)	–0.29*** (–0.35, –0.24)	–0.29*** (–0.33, –0.26)	–0.10*** (–0.14, –0.06)
Non-CF / non-separate kitchen	–0.41*** (–0.43, –0.38)	–0.26*** (–0.29, –0.23)	–1.32*** (–1.37, –1.27)	–0.61*** (–0.66, –0.55)	–0.55*** (–0.59, –0.52)	–0.25*** (–0.30, –0.21)

[a]Unadjusted model.

[b]Adjusted for covariates: age, gender, socioeconomic position, marital status, education level, working status, place of residence, religion, social class, housing type, international poverty line, states, current excessive alcohol intake, current use of tobacco, and physical inactivity.

***P<0.001

Text S1: Definition of Behavioral Covariates

Excessive alcohol consumption – Individuals responding 'yes' for at least two of the CAGE questions[1] was considered to consume excessive alcohol. The four CAGE questions are: "Have you ever felt the need to cut down your drinking?", "Have you ever felt annoyed by criticism of your drinking?", "Have you ever had guilty feelings about drinking?", "Have you ever taken a morning eye-opener?".

Current smoking and smokeless tobacco use – An individual was identified as currently "smoking" or using "smokeless tobacco" based on the questions "Do you currently smoke any tobacco products (cigarettes, bidis, cigars, hookah, cheroot, etc.)?" and "Do you currently consume any smokeless tobacco products such as chewing tobacco, gutka, or pan masala?"

Physical inactivity – Based on the ACC/AHA recommendation of engaging in 150 min of moderate intensity aerobic physical activity or at least 75 min of vigorous-intensity activity or an equivalent combination of both in a week, questions on frequency of moderate and vigorous physical activity were administered. Those who reported the frequency as "once a week", "one to three times a month" and "hardly ever" were identified as "physically inactive".[2]

Text S2: Multicollinearity assessment

Multicollinearity among the independent variables included in the regression models was assessed using Variance Inflation Factors (VIFs). VIF values were consistently low, ranging from 1.07 to 1.87, indicating absence of collinearity across all independent variables. Specifically, the VIF for polluting fuel use was 1.50; age, 1.21; gender, 1.64; marital status, 1.23; education level, 1.51; working status, 1.36; MPCE quintiles, 1.87; place of residence, 1.35; religion, 1.07; social class, 1.15; state/UT fixed effects, 1.08; housing type (pucca house), 1.34; international poverty line status, 1.69; current excessive alcohol intake, 1.10; current tobacco use (smoking or smokeless), 1.21; and physical activity, 1.12. All VIF values were well below the conventional threshold of 5, suggesting no evidence of problematic multicollinearity.

---

[1] Ewing, J. A., & Rose, B. A. (1970). Identifying the hidden alcoholic [W:] paper read at the 29th International Congress on alcoholism and drug dependence. Australia Butterworth, Sydney.

[2] Arnett, D. K., Blumenthal, R. S., Albert, M. A., Buroker, A. B., Goldberger, Z. D., Hahn, E. J., ... & Ziaeian, B. (2019). 2019 ACC/AHA guideline on the primary prevention of cardiovascular disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. Journal of the American College of cardiology, 74(10), e177-e232.