Cooking Fuel Types and the Health Effects: A Field Study in China

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Abstract

Recognizing the health effect induced by using solid fuels is a stimulus for speeding up the clean energy transition in rural China. This paper estimates the impact of cooking fuel choice on residents' health based on a Multinomial Logistic regression model. We conducted a field survey and collected data from ten villages in Northern China. The results indicate that fuel stacking is prevalent in the surveyed rural region, but a transition to cleaner fuels is underway. We find that rural residents' health status is significantly influenced by cooking fuel types. Respondents who used clean cooking fuels chronically have a 0.138 higher probability of positive evaluation and a 0.128 lower probability of negative evaluation of their health status, compared to those who use solid cooking fuel. Existing energy transition policies focus on outdoor air pollution reduction and associated public health benefits; while our results suggest that transition to clean energy in rural China can also bring significant indoor air pollution reduction and family health benefits.

Keywords: Solid fuels; Health effect; Energy transition; Healthy China

1. Introduction

Outdoor air pollution induced by industry and transportation activities is of great concern to the research community, yet relatively little attention has been paid to household air pollution (HAP). According to Zhang et al. (2022), long-term exposures to outdoor and household air pollution are both linked with a high occurrence of diseases like depression. World Health Organization indicates that the burden of attributable deaths due to HAP was 2.3 million in 2019, accounting for 6.6% of the global mortality (IHME, 2021). The burning of solid fuels (such as kerosene, firewood, coal) releases large quantities of environmental pollutants, including particulate matter, carbon monoxide, and nitrogen dioxide, which is a major source of indoor air pollution (Agbo et al., 2021; Balmes, 2019). Such pollutants also constitute an important portion of outdoor air pollution and even drive global warming to some extent, such as black carbon (Chafe et al., 2014; Downward et al., 2016). Moreover, exposure to indoor air pollution substantially increases the probability of chronic obstructive pulmonary disease, lung cancer, stroke, heart disease, and other non-communicable diseases (Pratiti et al., 2020).

Especially in developing countries, solid fuels constitute a large proportion of fuel choices for cooking and heating, exacerbating environmental degradation, poverty, and inequality (Wang et al., 2019). Solid cooking fuel is also an important source of indoor air pollution in rural China and is closely related to China's carbon actions. However, cooking has been the most overlooked area of the sustainable energy agenda (Wen et al., 2021). In China, more than 60% rural population lacked access to clean fuels and technologies for cooking in 2019 (WHO, 2021), and the cumulated number of deaths due to HAP reached 1 million in total (WHO, 2018). Since solid fuels are related to energy poverty and poverty alleviating in rural areas, speeding up the clean energy transition can benefit residents' health and well-being, which also play an important role in China's progress towards the "Healthy China 2030" policy goals and Sustainable Development Goals (SDGs) (He et al., 2018; Hou et al., 2021; Rosenthal et al., 2018). Besides, since China has pledged to achieve carbon neutrality by 2060 and peak emissions before 2030, and the residential/building sector accounts for about 20% of China's total energy consumption, speeding up the rural energy switching from solid fuel to clean fuels is an important component of realizing carbon neutrality in the residential sector (IEA, 2021). Compared with prominent outdoor air pollution, indoor air pollution has received relatively less attention in academics, social media, and environmental policy in China, which is a hidden hazard in rural areas (Aunan et al., 2019).

Much of the existing research focuses on the health effects of indoor air pollution caused by using solid fuels from an epidemiological or environmental perspective. These studies focus mainly on two aspects. One is concerned with personal exposure to high concentrations of various pollutants resulting from the combustion of solid fuels. Significantly higher levels of pollutant concentrations (such as polycyclic aromatic hydrocarbons, PM10) were found in kitchen air when traditional solid fuels were used compared to relatively clean fuels (Chen et al., 2017). The positive relationship between solid fuel use and higher concentrations of indoor pollutants, such as PM2.5, CO, CO_2, NO_2, SO_2, and volatile organic compounds (VOCs), has also been proven (Agbo et al., 2021; Du et al., 2018). Besides, several studies show that the degree of personal exposure to HAP is associated with household characteristics or microenvironments, such as roof type, ventilation conditions, kitchen materials, layout, and cooking behavior, et al., (Das et al., 2018; Fandino-Del-Rio et al., 2020; Pratiti et al., 2020).

Other studies are concerned with the positive relationship between indoor air pollution caused by solid fuel use and individual health from an exposure-response relationship or socioeconomics perspective. From the exposure-response perspective, researchers rely on measuring instruments (e.g., exposure monitors, blood pressure measurements) to record pollutant concentrations in specific locations and personal health responses (Young et al., 2019). Luo et al. (2021) indicate that exposure to indoor air pollution from solid fuel use had a significant effect on cognitive decline among middle-aged and older adults in China. Besides, exposure to indoor air pollution has been identified as a risk for several diseases, including acute respiratory infections and otitis media, chronic obstructive pulmonary disease (COPD), lung cancer, high blood pressure, asthma, and stroke, among others (Balmes, 2019; Burki, 2012; Lee et al., 2020). From the perspective of socioeconomics, one stream of literatures employs econometric methods to explore the relationship between solid fuel use and health status based on micro-survey data at the household level. Imelda (2020) confirms that clean cooking fuels can reduce infant mortality significantly relying on a fuel-switching program in Indonesia. In China, several studies use micro-survey data of CHARLS, CFPS, CHNS, and CGSS to find the relationship between solid fuel use and individual health. For example, Nie et al. (2016) find that cleaner fuels lead to better health among women; Liu et al. (2020) find that solid fuel users show a higher depression symptom among the elderly; Liu et al. (2020) indicate that the elderly cooking with clean fuels has higher ability to handle with daily activities. Ao et al. (2021) show that both indoor and outdoor air pollution contribute to worse mental health among the elderly. Luo et al. (2021) prove that solid fuel usage is associated with worse cognitive function. Tian et al. (2021) find obvious urban-rural health disparities among solid fuel users. Besides, solid fuel has heterogeneous influences on different groups, it is found that children, women, and cooking staff suffer more serious losses as those sub-groups have higher exposure levels compared to others (Aunan et al., 2019; Edwards and Langpap, 2012; Stabridis and van Gameren, 2018). Although large-sample and micro-survey datasets have the advantage of wide coverage, they lack rich information on cooking fuel choice, cooking behavior, and related energy consumption behavior.

This paper aims to estimate the relationship between cooking fuel choice and self-reported health status based on a residential energy consumption survey in Shandong Province and Hebei Province, the top two energy consumers and CO_2 emitters in China. We first describe the transition of cooking fuel choice, the morbidity of various diseases, and individual health; then a Multinomial logistic regression was used to model the association between cooking fuel choice and reported health status; finally, we also explore the interaction of fuel composition and gender to analyze the gender disparities and conducted robust tests.

This paper makes three contributions compared to previous studies. First, considering that the health effects of some pollutants cannot be immediately demonstrated, we used the interaction of primary cooking fuel in 2016 and 2011 to examine solid fuel's current and possible chronic effects. The influence of solid fuel use on health is a chronic, long-term process, and historical exposure may have led to the current disease patterns. Therefore, the revealed chronic health impact can provide more information to the literature. Second, considering the regional discrepancy in solid fuel use in China, this paper focused on two counties in Shandong and Hebei provinces. The two provinces are key areas of the "clean winter heating program" in northern China, which suffer heavily from solid fuel use. We designed a questionnaire survey and obtained 1,924 respondents from 717 households in 2016. The rich information enables us to conduct a detailed analysis on regional heterogeneity that is required for policymaking. Third, since rural individuals lack knowledge of acute and chronic diseases, we explore the relationship between solid fuel use and self-reported health status instead of specific diseases. Self-reported health has been widely used as a predicted indicator of individuals' chronic diseases and health outcomes, which can overcome the under-reported chronic diseases to some extent (Johnston et al., 2009).

The remainder of the paper is organized as follows: Section 2 provides an overview of the survey and data. Section 3 introduces the situation of cooking fuel use over the past 10 years in Qihe and Wuqiang counties, and respondents' health conditions in Qihe and Wuqiang counties revealed in this survey. Section 4 describes the empirical methodologies and variable definition. Section 5 quantitatively analyzes the health effects of cooking fuel use and reports some robust checks. Section 6 concludes this research.

2. Survey design

The data used in this paper was collected from a Residential Energy Consumption Survey (RECS) conducted by the Center for Energy and Environmental Policy Research (CEEP), Beijing Institute of Technology (BIT), in July and August 2016. Using a method of stratified random sampling, we chose six villages in Qihe county, Dezhou city, Shandong Province, and four villages in Wuqiang county, Hengshui city, Hebei Province. To ensure the data quality, all the questionnaires were completed face-to-face by the CEEP faculty members and graduate students. The survey details were described by Wu et al. (2017).

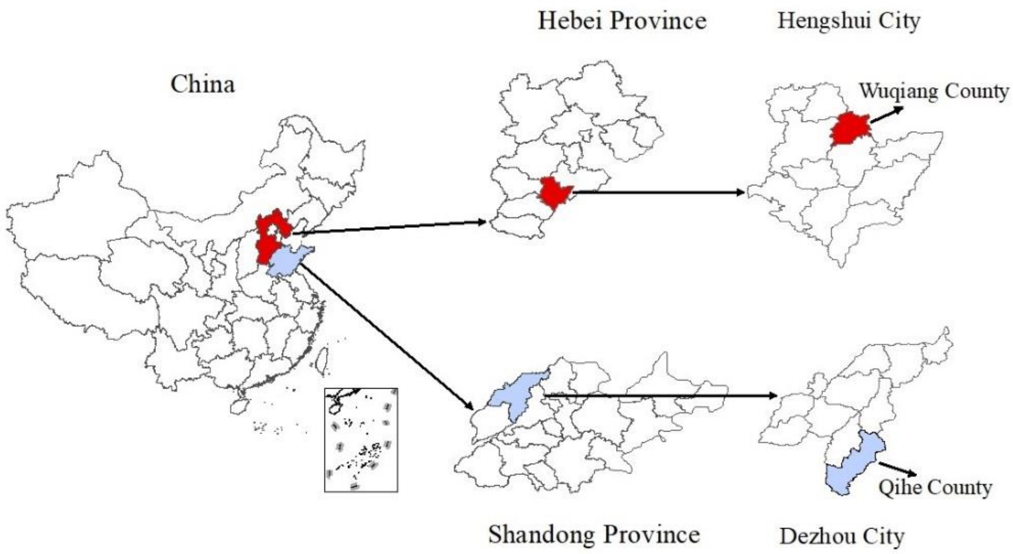

Figure 1. Survey areas

Note: This is a schematic map and does not indicate the exact boundaries.

This survey focused mainly on household energy consumption and its health effects. More specifically, the questionnaire included modules on demographic characteristics, cooking, heating, home appliances, other end-use energy consumption, and the health status of family members. After data collection and cleaning, we obtained a sample of 1,924 respondents from 717 households.

We chose the household head or the family member who was most familiar with the household situation to answer the survey. The respondents were asked which primary and secondary fuels they use for cooking. Eight choices were provided including firewood, straw or crop stalks, coal, marsh gas, LPG, natural gas, electricity, and others. The respondents were also asked which fuels from the eight choices they primarily and secondarily used for cooking 5 and 10 years ago. Herein, we omitted the "other" category because of its ambiguous nature. In addition, for the convenience of analysis, we used two methods to reclassify fuel types in this paper: method #1: biomass (firewood and straw or crop stalks), coal, gas (marsh gas, LPG, and natural gas), and electricity; method #2: solid fuel (firewood, straw or crop stalks, and coal) and clean fuel (marsh gas, natural gas, LPG, and electricity).

The questionnaire also included questions about people's health status. The respondents were asked, "How would you rate your health?" on a five-response scale from "very poor" to "very good." They were also asked to rate their family members' health status. As the respondent was the household head or the member most familiar with the household situation, we think their judgment or evaluation was credible. We considered that the respondents had a positive attitude toward their health status if their answer was "very good" or "good," had a negative attitude toward their health status if their answer was "very poor" or "poor," and had a neutral attitude toward their health if their answer was "fair." The respondents of this study were aged 18 or older.

3. Cooking fuel choice and health

3.1 Households using "stack" fuels for cooking

The energy ladder hypothesis insists that people will choose cleaner fuels when income increases, but energy stacking persists even when income increases. The respondents did not quit using a lower-level fuel entirely but used it as a backup, which means they use mixed fuel types (Zhu et al., 2019). According to our survey's data, 38.1%, 22.8%, and 7.6% of households used only one fuel for cooking in 2006, 2011, and 2016, respectively, while the majority use stack fuels for cooking. The fuel preferences of the households that used only one type of fuel are shown in Figure 2.

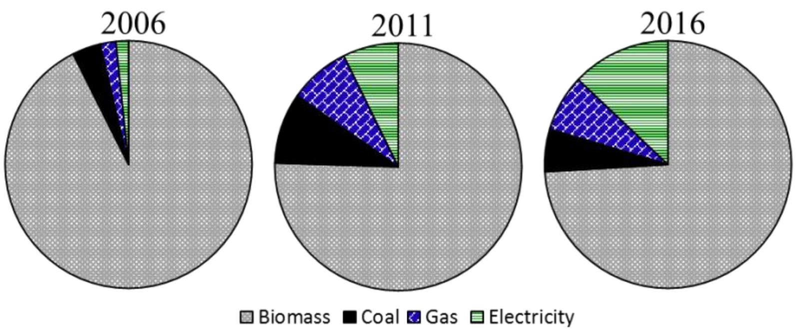

Figure 2. Fuel preferences in households using one cooking fuel type in 2006, 2011, and 2016

Most households choose biomass as the primary cooking fuel, but it has decreased over time, and households tend to choose progressively cleaner fuels over the past 10 years. The percentage of households using biomass as a primary fuel choice has decreased from 92.6% in 2006 to 74.1% in 2016, whereas the percentage of households using clean fuels (such as gas and electricity) has increased from 3.7% in 2006 to approximately 13% in 2016.

3.2 Cooking fuel stacking transition

Over the past 10 years, most households use at least two fuel types for cooking. Figure 3 illustrates the energy selection structure in those households. This figure reclassifies the cooking fuel choice according to method #2, i.e., solid fuels and clean fuels. The first character in the legend identifies the primary fuel choice, and the second character identifies the secondary fuel choice.

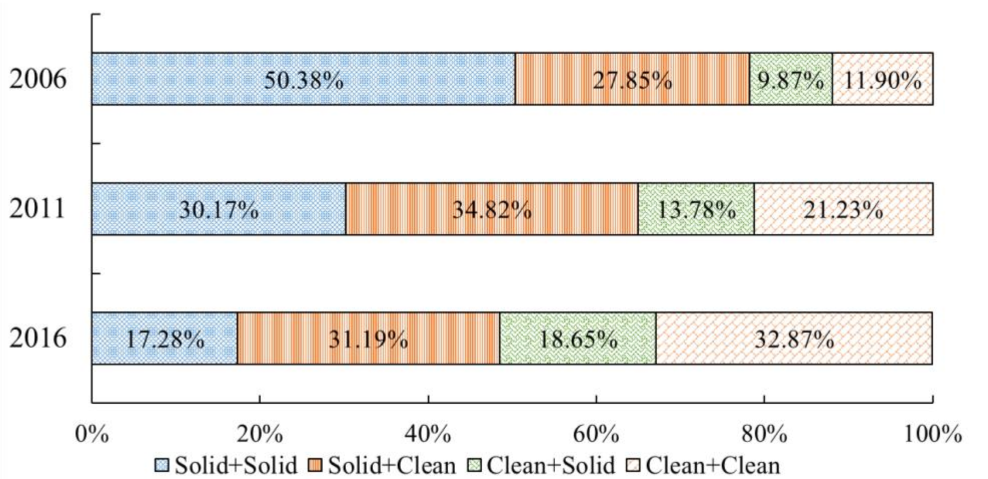

Figure 3. Population proportion using various fuel type compositions

Note: The first and second characters in the legend identify the primary and secondary fuel choices for cooking, respectively.

As Figure 3 shows, in 2006, the composition "Solid + Solid" was prevalent in rural areas of the two counties. Overall, 78.2% of the households used solid fuel as the primary cooking fuel. Among them, 27.9% of the households used clean fuel as the second choice. A total of 21.8% of the households chose clean fuel as the primary cooking fuel. Only 11.9% of the households were in the composition of "Clean + Clean" and used clean fuels exclusively for cooking. In 2011, the percentage of households choosing solid fuel as primary cooking fuel decreased, while the percentage of households choosing clean fuel as primary cooking fuel increased dramatically. In 2016, the fuel structure was rather different: the compositions "Clean + Clean" and "Clean + Solid" became more popular. More than half of the households chose clean fuels as primary cooking fuel, and the percentage of households using a primary solid fuel and a secondary clean fuel also increased to 31.2%. Overall, in the rural areas of the two counties, clean fuels have become more prevalent in recent years. Although there is a mixed-use of solid and clean fuels, rural residents are transitioning to cleaner fuels (Hou et al., 2017).

3.3 Respondents' health conditions

3.3.1 Reported health status under different cooking fuels

When asked about their health, one-quarter of the survey respondents said they had very good health, 22.6% said they had ordinary health, and 21.1% and 2.6% reported they had poor or very poor health, respectively. As mentioned in Section 2, individuals had positive attitudes toward their health if their answer was "very good" or "good," had negative attitudes toward their health if their answer was "very poor" or "poor," and had neutral attitudes toward their health if their answer was "ordinary." The 2006 data were disregarded because there were too many missing values. As shown in Figure 4, the respondents who chose solid fuels as primary cooking fuel were less likely to have good health than those who used clean fuels as primary cooking fuel in 2016. The situation is similar in 2011.

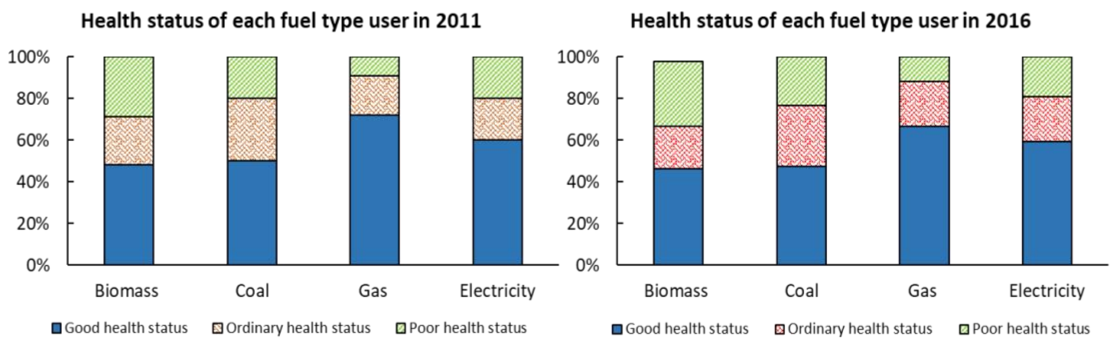

Figure 4. Respondents' reported health status in different primary fuel categories

Note: The health status was reported in 2016.

3.3.2 Incidence of various diseases under different fuel categories

Our questionnaire asked about the prevalence of related diseases based on the World Health Organization's list of major illnesses due to HAP. However, because we had a limited sample size and many diseases went untreated or were at least not properly diagnosed in rural areas of the two counties, this paper contains only a simple demonstration of the survey results. The total number of sick people in this survey was 473. As shown in Table 1, heart disease was the most prevalent, with 66.4% of the respondents that were suffering from it. Lung cancer had the lowest frequency, with only two respondents in our sample suffering from it., but the sum of all cases of illness was 639 and higher than the total number of respondents, which means that some respondents had not only one but multiple chronic diseases.

Table 1. Frequency of HAP-related diseases

Disease type	Frequency	Responses	Cases among sick respondents
Stroke	100	15.65%	21.14%
Heart disease	314	49.14%	66.38%
Pneumonia	19	2.97%	4.02%
chronic pulmonary disease	81	12.68%	17.12%
Lung cancer	2	0.31%	0.42%
Asthma	54	8.45%	11.42%
Cataract	57	8.92%	12.05%
lower respiratory infection	12	1.88%	2.54%
Total disease frequency	639	100%	
Total patients	473		135.1%

Note: Lung cancer and lower respiratory infections were omitted because of their low frequency.

Percent of responses is given by dividing the frequency of a certain disease by the total number of sick people. Percent of cases is given by dividing the frequency of a certain disease by the frequency of all diseases.

Table 2 demonstrates the morbidity of various diseases by different primary cooking fuel types in 2016 and 2011. For example, 5.14% of the respondents who used biomass as primary cooking fuel in 2016 suffered a stroke. Consistent with Table 1, heart disease was most prevalent. However, there is no evidence indicating that the morbidity of various diseases was lower among the respondents who chose clean fuels than those who used solid fuels. This may suggest that HAP is less relevant to fatal diseases than other minor yet chronic diseases.

Table 2. Disease statistics by primary cooking fuel types

%	Biomass		Coal		Gas		Electricity	
Year	2016	2011	2016	2011	2016	2011	2016	2011
Stroke	5.14	5.39	3.13	3.05	4.31	4.88	6.63	6.99
Heart disease	18.28	17.17	22.92	22.14	12.55	10.73	15.25	16.43
Pneumonia	0.96	1.10	1.04	3.05	1.57	0.00	0.92	0.70
Chronic pulmonary disease	3.94	4.11	5.21	6.11	4.71	2.93	4.47	3.85
Asthma	4.06	3.74	2.08	2.29	2.75	2.93	1.69	1.40
Cataract	4.66	4.02	1.04	0.76	1.18	1.46	2.00	1.75

All the values in Tables 1 and 2 may represent an underreporting of the true prevalence of those diseases because of underdiagnoses, limited health care resources, or the respondents' misunderstanding of their diagnosed diseases (Peabody et al., 2010). The health impacts of HAP might be underestimated if they are not accompanied by clinical symptoms.

4. Empirical methodologies

The combustion of solid fuels produces many harmful substances and has a serious impact on users' health. This section provides an empirical estimation of the health effects of fuel choices.

4.1 Multinomial Logistic Regression Model

Multinomial logistic regression was used to model the association between cooking fuel use and reported health status. The log odds of the outcomes were modeled as a linear combination of the predictor variables.

The direct output of this regression corresponds to the following equations (Nie et al., 2016):

$$\ln\left(\frac{P(RHS=1)}{P(RHS=0)}\right) = \beta_{10} + \beta_{1i}X_i\ , \quad (1)$$

and,

$$\ln\left(\frac{P(RHS=2)}{P(RHS=0)}\right) = \beta_{20} + \beta_{2i}X_i, \quad (2)$$

where X_i is a vector of the independent variables and β_i represents the corresponding coefficients. The left side of the equations means the log odds of the probability of choosing one outcome category over the probability of choosing the baseline category. However, this result cannot be easily understood, so we predicted probabilities to help readers understand the model. All the results shown in the following are all predicted probabilities.

According to the multinomial logistic model, the probability that respondent *i* chose category *j* is:

$$\mathrm{P}(i \text{ chooses } j\ ) = \frac{e^{x_i\beta_j}}{e^{x_i\beta_0}+e^{x_i\beta_1}+e^{x_i\beta_2}}, j = 0,1,2. \quad (3)$$

To identify the model, we constrained one of the β_is to zero. Setting β_0 at zero, we obtain

$$\mathrm{P(i\ chooses\ \ j)} = \begin{cases} \frac{1}{1+e^{x_i\beta_1}+e^{x_i\beta_2}}, \mathrm{j} = 0 \\ \frac{e^{x_i\beta_j}}{1+e^{x_i\beta_1}+e^{x_i\beta_2}}, \mathrm{j} = 1,2 \end{cases} \quad (4)$$

4.2 Variable definition

4.2.1 Dependent Variable.

We mainly estimated the influence of cooking fuel use on respondents' reported health status (denoted by *RHS*). The dependent variable is a discrete value, and the reported health status can be a useful and proper measure of overall health status (Halliday et al., 2021). In this paper, we study the influence of solid fuel use on the respondents' reported health status from a socioeconomic perspective. Reported health status was adopted due to three considerations. First, respondents in our survey had less knowledge about relevant acute and chronic diseases, consequently increasing the inaccuracy of our data when asked whether they had a specific disease. The socio-economic development of the surveyed rural areas is low and inadequate health care is prevalent. Partly because of low degrees of access-related health literacy, the respondents with low socioeconomic status perceived bodily symptoms as less serious or health-threatening (Samerski, 2019; van der Heide et al., 2018). Second, reported health status has been particularly attractive in large population-based surveys and is a valid omnibus health measure because of its ability to predict utilization and important health outcomes such as mortality (Bundgaard et al., 2020; DeSalvo et al., 2006). Third, self-reported health status has been proven to be significantly associated with multiple clinical measures and is a good overall predictor of diverse aspects of well-being (Goldman et al., 2004). In our questionnaire, reported health status was a single measure that asked the respondents to evaluate their own or a family member's overall health status.

4.2.2 Independent Variables

1) Cooking Fuel

The use of solid fuels in primitive stoves may release toxic smoke and pollute household air and thus may have negative effects on people's health (Liao et al., 2016). When the respondents were asked to evaluate their own or a family member's health status, they usually based their answers on whether they had complained about hard work, took medicine regularly, or had often been in a bad environment, among others. Families using solid fuel (such as firewood and/or crop stalks) need to collect the fuel in advance and transport (usually by humans) it to their houses. The physical exertion of this process may affect an individual's assessment of their health status. In addition, the use of inefficient cooking fuel means people must spend considerable time in smoke-filled kitchens, which may cause coughing, tears, throat discomfort, and other conditions. Long-term exposure may affect people's perception of their health and result in poor health evaluation. Therefore, primary cooking fuel is likely a critical factor that influences people's reported health. However, the impact of solid fuel use on health may not appear immediately and there may be a considerable lag time. Current physical discomfort may be caused by the fuel used now or by the fuel used a few years ago. Thus, the primary cooking fuel used 5 years before is also an independent variable. In addition, we added the interaction of primary fuel types in 2016 and 2011, which was reclassified according to method #2. Data from 2006 were not included in this analysis because there were too many missing values.

2) Household Income Per Capita

Household income per capita (denoted by *HIPC*) can influence people's health in various aspects. People with lower incomes have a higher likelihood of forgoing needed medical care and have poor medical services (Kim et al., 2017). When people have higher incomes, they can afford medical treatment for illnesses, improved access to medical care, and better living environment and sanitation. Therefore, the income effect is important as it will affect fuel choice and thus need to be controlled. However, the sign could be ambiguous: on the one hand, a higher income will lead to a better health condition; on the other hand, higher-income respondents are usually more conscious about health conditions and may lead to reporting more health problems.

3) Individual Risk Factors

People always provide a health status evaluation based on their current physical condition. Drinking and active smoking are proven health risk factors (Bockerman et al., 2018). Carson et al. (2021) show that adults exposed to secondhand smoke had a 42% increased yearly risk of hospitalization compared to those adults who were not exposed. Exercise also affects people's health assessment. Hypertension can influence their reported health status. Those with hypertension may be less likely to have a positive attitude toward their health status. In this work, whether a respondent is smoking, drinking, exercising regularly, or has hypertension (denoted by *smoke, drink, exercise, and hypertension,* respectively) are added to the model as control variables.

4) Demographic Factors

We controlled gender, age, and educational levels (denoted by *male, age, educ,* respectively) to control the heterogeneity of the respondents. Man and woman may have different health statuses at different ages. Highly educated respondents may make more accurate judgments about their own and their family's health status.

5) Others

We controlled the sleep time per day per person and house type (denoted by *sleep* and *house,* respectively) in the regression. A higher quality of sleep may be related to a higher probability of the respondents providing good health evaluations. Modern houses may have better ventilation. In any case, we included the variable of counties to control for unobserved fixed effects.

Table 3. Descriptive statistics of variables

Variable	N.	Min.	Max.	Average	Explanation
SRH	1496	1	3	1.81	1=”Good”, 2=”ordinary”, 3=”Poor”
HIPC	1497	150	74000	94 66	Household income per capita (*Yuan*)
Primary fuel in 2016	1476	1	4	2.37	1=“biomass”, 2=“coal”, 3=“gas”, 4=“electricity”
Primary fuel in 2011	1379	1	4	1.80	1=“biomass”, 2=“coal”, 3=“gas”, 4=“electricity”
Primary cooking fuel composition	1376	1	4	2.25	1= Solid fuel in 2016 + Solid fuel in 2011 2= Solid fuel in 2016 + Clean fuel in 2011 3= Clean fuel in 2016 + Solid fuel in 2011 4= Clean fuel in 2016 + Clean fuel in 2011
Male	1497	0	1	0.48	1=Male; 0=Female
Age	1497	18	95	54.37	Age of respondents in 2016
Educ	1497	0	16	5.78	Years of formal education attainment
Sleep	1497	0	16	8.01	Unit: Hour
Smoke	1491	0	1	0.29	Smoking or not. 1=Yes, 0=No
Drink	1489	0	1	0.30	Drinking or not. 1=Yes, 0=No
Exercise	1373	0	1	0.64	Exercise or not. 1=Yes, 0=No
House	1495	0	1	0.39	House type. 0=traditional house, 1=modern house
Hypertension	1429	0	1	0.31	Has hypertension or not. 1=Yes, 0=No

5 Results and discussions

5.1 Regression results

According to the results in Table 4, compared with respondents who used solid fuel, we found that respondents who used gas or electricity for cooking led to around 0.1 higher probability of positive evaluation of their health. Besides, residents who use clean fuels for a longer time report a more positive health status. Their attitudes toward health status were influenced not only by the cooking fuel used in the current period but also by those used in the past. Specifically, compared to residents who use solid fuels both in 2016 and 2011, residents using clean cooking fuels both in 2016 and 2011 have a 0.138 higher probability of positive evaluation and a 0.128 lower probability of negative evaluation of their health status, while residents using clean cooking fuels in 2016 but solid fuels in 2011 have a 0.067 higher probability of positive evaluation and a 0.112 lower probability of negative evaluation. This result is consistent with Tian et al. (2021) that solid fuels impair residents' health, while our results further consider the potential lagged health effects by including cooking fuel choice 5 years ago, and we found that longer time use of clean fuels led to a higher positive effect on respondents' health.

Second, per capita income has a significant influence on the respondents' positive evaluations; there is no evidence that per capita income influences the respondents' negative evaluations. For respondents whose household per capita income was 5,594 yuan, when their income increases by 10%, the probability of reporting a good health condition increase by 0.004. This result is comparable to Akanni et al. (2022) who explore income trajectories and self-rated health status in the UK and find that increased household income is associated with an increased likelihood of reporting excellent general health outcomes. Some studies also find that individuals who reported excellent health have higher household incomes than those likely to report a lower self-rated health category (Davillas et al., 2019).

Third, generally, younger residents, well-educated, with no hypertension, and high-income residents have positive reported health status. These results are basically in line with previous studies (Gupta et al., 2020). However, there is no evidence that the man and woman had significant differences in evaluating their health status in this survey sample. This finding is different from (Tian et al., 2021), who indicate that man has a higher probability to report good health status. This may be the different sample characteristics that they used a wider coverage of samples from urban and rural, while we focused on two specific counties.

Finally, various risk factors had different influences on the respondents' attitudes toward their health status. The possibility of negative evaluation on health status will increase by 0.248 if respondents have hypertension, while the possibility of positive evaluation will decrease by 0.162. There is no evidence that smoking had a significant influence on the respondents' health evaluations which could be because smoking is less significant compared to indoor air pollution. When people exercise regularly, their probability of negative evaluation decrease by 0.04, and there is no evidence that regular exercise influences the probability of the respondents' positive health evaluation. On the contrary, our results show that in the two counties studied, drinking alcohol decreased the probability of negative evaluation of their health, but there is no evidence that it increased their probability of positive evaluation of their health.

Overall, the respondents in Qihe county had a 0.081 higher probability of having a positive attitude regarding their own health and a 0.055 lower probability of having a negative attitude regarding their health compared to the respondents in Wuqiang county. This may relate to the different socioeconomic levels between the two counties.

Table 4. The marginal effects of primary cooking fuel on RHS in 2016 and 2011

	Reported health status					
	Good	Poor	Good	Poor	Good	Poor
Solid 2016 + Solid 2011 (base fuel composition)						
Clean 2016 + Solid 2011					0.067^{*}	-0.112^{***}
					(1.93)	(-3.53)
Clean 2016 + Clean 2011					0.138^{***}	-0.128^{***}
					(4.24)	(-4.38)
Biomass (base primary cooking fuel in 2016)						
Coal in 2016	-0.082	-0.074				
	(-1.43)	(-1.31)				
Gas in 2016	0.095^{**}	-0.180^{***}				
	(2.23)	(-5.16)				
Electricity in 2016	0.083^{***}	-0.098^{***}				
	(2.83)	(-3.61)				
Biomass (base primary cooking fuel in 2011)						
Coal in 2011			-0.058	-0.086^{*}		
			(-1.17)	(-1.84)		
Gas in 2011			0.114^{***}	-0.166^{***}		
			(2.48)	(-4.44)		
Electricity in 2011			0.104^{***}	-0.067^{**}		
			(2.80)	(-1.99)		
Ln (income per capita)	0.038^{***}	-0.013	0.041^{***}	-0.021^{*}	0.037^{***}	-0.013
	(2.89)	(-1.16)	(3.07)	(-1.80)	(2.77)	(-1.12)
Male	0.032	0.018	0.034	0.021	0.038	0.019
	(0.87)	(0.53)	(0.89)	(0.60)	(1.00)	(0.53)
Age	-0.007^{***}	0.006^{***}	-0.007^{***}	0.006^{***}	-0.007^{***}	0.006^{***}
	(-6.83)	(6.32)	(-7.14)	(6.31)	(-7.34)	(6.61)
Educ	0.011^{***}	-0.007^{*}	0.010^{***}	-0.007^{*}	0.008^{**}	-0.006^{*}
	(3.11)	(-1.86)	(2.50)	(-1.82)	(2.12)	(-1.68)
Sleep	0.016^{**}	-0.008	0.015^{**}	-0.007	0.015^{**}	-0.008
	(2.21)	(-1.26)	(2.03)	(-1.06)	(2.04)	(-1.25)
Smoke	-0.019	-0.020	-0.016	-0.016	0.017	-0.020
	(0.50)	(-0.59)	(0.41)	(-0.44)	(0.44)	(-0.54)
Drink	-0.009	-0.076^{**}	-0.015	-0.091^{***}	-0.016	-0.087^{**}
	(-0.25)	(-2.41)	(-0.40)	(-2.79)	(-0.42)	(-2.64)
Exercise	-0.032	-0.025	-0.009	-0.041	-0.012	-0.040^{**}

	Reported health status					
	Good	Poor	Good	Poor	Good	Poor
	(-1.19)	(-0.98)	(-0.31)	(-1.55)	(-0.41)	(-1.50)
Hypertension	-0.266***	0.173***	-0.246***	0.163***	-0.248***	0.162***
	(-8.74)	(5.97)	(-7.82)	(5.43)	(-7.92)	(5.44)
House	-0.037	0.009	0.036	0.007	-0.041	0.013
	(-1.42)	(0.36)	-1.33	(0.28)	(-1.51)	(0.52)
Qihe county	0.073***	-0.027	0.095***	-0.041	0.081***	-0.055**
	(2.57)	(-1.02)	(3.22)	(-1.49)	(2.94)	(-2.10)
No. of Obs.	1288	1288	1193	1193	1190	1190

Note: The marginal effects are shown in this table. In the fuel compositions, clean or solid represents the primary cooking fuel. "Solid 2016 + Clean 2011" is absent because no household chose solid fuels in 2016 but clean fuels in 2011. The t value is in parentheses; * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

5.2 Health effect of fuel choice by gender

Gender is an important factor that affects health (Kurata et al., 2020). Musango et al. (2020) find that gender is becoming more relevant in providing energy services to households in poor urban areas of Africa. The morbidity and mortality of many diseases vary greatly between men and women. In addition, men and women spend different amounts of time in the kitchen and cooking. Thus, the effects of solid fuels on health evaluations may be affected by gender. We used the interaction of fuel composition and gender to analyze the effects in Table 5.

As shown in Table 5, when using the same type of fuels, men is more likely to report a positive evaluation of their health status. Specifically, compared to men using solid fuels both in 2016 and 2011, men using clean fuels both in 2016 and 2011 have a 0.153 higher probability of positive evaluation while women of the same fuel choice have a 0.12 higher probability of positive evaluation. This result is much higher than the result of (Nie et al., 2016), who find that women using LPG for cooking have a 0.02 higher probability to reported excellent health status than those using wood/straw. This may be because we considered both current and possible chronic health effects of solid fuel, while other studies neglect the potential lagged effects. On the other hand, for men, using clean cooking fuel increased their probability of positive evaluation and decreased their probability of negative evaluation of their health status. Furthermore, the men were more likely to have a positive assessment of their health than the women when using the same combination of clean cooking fuel. Those differences may associate with the fact that men are usually householders and dominate in household practices and household decision makings, who spend less time in cooking than women (Musango., 2022). Similarly, previous research has proved that compared with clean fuel users, solid fuel users had a worse cognitive function, and these effects were stronger among female participants (Luo et al., 2021).

Table 5. The marginal effects of interactions between fuel composition and gender

	Reported health status	
Variables	Good	Poor
Male + Solid 2016 + Solid 2011 (Base)		
Male + Clean 2016 + Solid 2011	0.130***	-0.138***
	(2.58)	(-2.90)
Male + Clean 2016 + Clean 2011	0.153***	-0.129***
	(3.32)	(-2.96)
Female + Solid 2016 + Solid 2011	-0.003	-0.028
	(-0.06)	(-0.62)
Female + Clean 2016 + Solid 2011	0.009	-0.123**
	(0.16)	(-2.46)
Female + Clean 2016 + Clean 2011	0.120**	-0.155***
	(2.29)	(-3.37)
Ln (income per capita)	0.037***	-0.013
	(2.78)	(-1.12)
Age	-0.007***	0.006***
	(-7.35)	(6.59)
Educ	0.008**	-0.006*
	(2.06)	(-1.65)
Sleep	0.016**	0.008
	(2.06)	(-1.25)
Smoke	0.020	-0.020

Variables	Reported health status	
	Good	Poor
	(0.51)	(-0.55)
Drink	-0.017	-0.086***
	(-0.44)	(-2.63)
Exercise	0.012	-0.039
	(0.44)	(-1.48)
Hypertension	-0.247***	0.162***
	(-7.93)	(5.45)
House	-0.042	0.013
	(-1.53)	(0.52)
Qihe county	0.083***	-0.055**
	(2.92)	(-2.08)
No. of Obs.	1190	1190

Note: The marginal effects are shown in this table. "Solid 2016 + Clean 2011" is absent because no household chose solid fuels in 2016 but clean fuels in 2011. The t value is in parentheses; * p < 0.10, ** p < 0.05, and *** p < 0.01.

5.3 Robustness checks

Several studies have shown that cooking fuel type has a significant influence on the morbidity of HAP-related diseases. Potential biases may exist between the sick and healthy respondents. We analyzed the sick respondents and healthy respondents separately. The results are shown in Table 6.

Table 6. The marginal effects of cooking fuels on RHS among the sick and healthy respondents

Reported health status	Sick respondents		Healthy respondents	
	Good	Poor	Good	Poor
Solid 2016 + Solid 2011 (base fuel composition)				
Clean 2016 + Solid 2011	0.163***	-0.194***	0.028	-0.065**
	(3.24)	(-3.15)	(0.64)	(-2.10)
Clean 2016 + Clean 2016	0.174***	-0.212***	0.119***	-0.085***
	(3.79)	(-3.74)	(2.98)	(-2.98)
Ln (income per capita)	0.007	-0.029	0.045***	-0.005
	(0.38)	(-1.22)	(2.77)	(-0.47)
Male	0.068	0.001	0.004	0.049
	(1.35)	(0.02)	(0.08)	(1.48)
Age	-0.003*	0.005**	-0.005***	0.002**

Reported health status	Sick respondents		Healthy respondents	
	Good	Poor	Good	Poor
	(-1.84)	(2.35)	(-4.12)	(2.64)
Educ	0.010*	-0.007	0.009**	-0.007**
	(1.90)	(-1.08)	(1.85)	(-1.83)
Sleep	-0.004	0.002	0.018	-0.008
	(-0.35)	(0.15)	(1.79)	(-1.14)
Smoke	0.000	-0.085	0.054	-0.030
	(0.00)	(-1.13)	(1.14)	(-0.92)
Drink	-0.066*	-0.070	-0.003	-0.071**
	(-1.53)	(-1.07)	(-0.06)	(-2.39)
Exercise	0.010	-0.125**	-0.017	-0.010
	(0.26)	(-2.56)	(-0.49)	(-0.39)
Hypertension	-0.125***	0.227***	-0.233***	0.030
	(-3.47)	(4.69)	(-5.33)	(0.98)
House	-0.066*	0.045	-0.047	0.015
	(-1.82)	(0.92)	(-1.39)	(0.58)
Qihe county	0.121***	-0.118**	0.088***	-0.035
	(3.19)	(-2.36)	(2.48)	(-1.35)
No. of Obs.	386	386	804	804

Note: The marginal effects are shown in this table. “Solid 2016 + Clean 2011” is absent because no household chose solid fuels in 2016 but clean fuels in 2011. The t value is in parentheses; * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

As Table 6 shows, even the healthy respondents’ health status attitudes were influenced by the cooking fuel used in the current period and the past. Compared to the respondents who primarily used solid cooking fuel both in 2016 and 2011, those who used clean fuels had a significantly higher probability of positive evaluation and a significantly lower probability of negative evaluation of their health. More specifically, compared to the composition “primarily solid cooking fuel in 2016 and 2011,” the respondents who chose the composition “primarily clean cooking fuel both in 2016 and 2011” had a 0.119 higher probability of positive evaluation of their health. Similarly, compared to the composition “primarily solid cooking fuel in 2016 and 2011,” the respondents who chose the compositions “primarily clean cooking fuel in 2016 and primarily solid cooking fuel in 2011" and "primarily clean cooking fuel both in 2016 and 2011" had 0.065 and 0.085 lower probability, respectively, of negative evaluation of their health.

Cooking and heating are two of the main sources of rural energy consumption (Tao et al., 2018). Solid heating fuels, like solid cooking fuels, may also have generated household air pollution and affected the respondents' reported health status. The following analysis tested whether the respondents' reported health statuses were influenced by heating fuels.

Table 7. The marginal effects of heating fuels

	Only heating fuel		Both cooking and heating fuel	
Reported health status	Good	Poor	Good	Poor
Solid 2016 + Solid 2011 (base cooking fuel composition)				
Clean 2016 + Solid 2011			0.066*	-0.115***
			(1.87)	(-3.62)
Clean 2016+ Clean 2011			0.138***	-0.132***
			(4.23)	(-4.49)
Solid fuels (base heating fuel)				
Clean fuels	0.018	0.029	0.012	0.033
	(0.64)	(1.13)	(0.40)	(1.24)
Ln (income per capita)	0.044***	-0.025**	0.037***	-0.016
	(3.41)	(-2.10)	(2.73)	(-1.30)
Male	0.031	0.018	0.037	0.018
	(0.84)	(0.53)	(0.98)	(0.52)
Age	-0.007***	0.006***	-0.007***	0.006***
	(-6.81)	(5.89)	(-7.35)	(6.61)
Educ	0.014***	-0.010***	0.008**	-0.006*
	(3.66)	(-2.76)	(2.12)	(-1.69)
Sleep	-0.014**	-0.008	0.016**	-0.007
	(-1.99)	(-1.31)	(2.06)	(-1.16)
Smoke	0.009	-0.017	0.018	-0.022
	(0.24)	(-0.49)	(0.46)	(-0.61)
Drink	-0.005*	-0.072	-0.016	-0.084**
	(-0.12)	(-2.26)	(-0.42)	(-2.56)
Exercise	0.021	-0.028**	-0.012	-0.038

Reported health status	Only heating fuel		Both cooking and heating fuel	
	Good	Poor	Good	Poor
	(0.76)	(-1.11)	(-0.41)	(-1.42)
Hypertension	-0.265***	0.165***	-0.248***	0.161***
	(-8.73)	(5.67)	(-7.93)	(5.42)
House	-0.035	0.005	-0.042	0.012
	(-1.33)	(0.21)	(-1.53)	(0.46)
Qihe county	0.075**	-0.036	0.089***	-0.043
	(2.54)	(-1.33)	(2.87)	(-1.53)
Observation	1309	1309	1190	1190

Note: The marginal effects are shown in this table. Both cooking and heating fuels were reclassified using method #2. "Solid 2016 + Clean 2011" is absent because no household chose solid fuels in 2016 but clean fuels in 2011. The t value is in parentheses; * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Table 7 shows the effects of heating fuel on reported health status. No evidence shows that heating fuel significantly influenced reported health status whereas cooking fuels always have a significant influence on reported health status. These results are consistent with those in Table 4. This may be associated with rural households' short heating periods and the majority rely on coal for heating.

6. Conclusion and Implications

6.1 Conclusions

Solid fuels constitute a large proportion of fuel choices for cooking and heating in rural China, posing a large risk to residents' health and well-being. This paper investigated the influence of cooking fuel transition on residents' self-reported health status based on a residential energy consumption survey in two typical energy consumption and carbon emission provinces of China, Shandong, and Hebei. Based on the data advantage, we describe the cooking fuel transition and individual health in detail, and employ a Multinomial logistic regression to model the association between cooking fuel choice and reported health status. Considering that rural residents lack knowledge about acute and chronic diseases, self-reported health status instead of specific disease is used as the dependent variable. Besides, considering the lagged effect of indoor pollution, the interaction of primary cooking fuel in 2016 and 2011 is used to explore solid fuel's current and potentially chronic effects. The main findings of this study are summarized as follows:

(1) Although clean energy transition is underway over time, solid fuels remain a large share of rural households cooking fuel choice. There is still a large space for promoting clean energy use in rural China. cooking energy is in transition to clean fuels from 2006 to 2016, there are about 67% of households use solid fuel for cooking and 48% use it as primary cooking fuel.

(2) Solid cooking fuel does pose a negative impact on residents' self-reported health status. Compared with respondents who used solid fuel, we found that respondents who used gas or electricity for cooking led to around 0.1 higher probability of positive evaluation of their health. From a long-term perspective, compared with respondents who used solid cooking fuels in both 2016 and 2011, respondents who used a combination of clean and solid cooking fuels had a lower 0.12 probability of negative evaluation of their health status. Besides, if respondents used clean cooking fuels in 2016 and 2011, respondents had a 0.138 higher probability of positive evaluation and a 0.128 lower probability of negative evaluation of their health status compared to solid cooking fuel users.

(3) Even using the same type of fuel, men and women have different subjective feelings about their health status. Men were more likely to report positive health status than women when they chose clean fuels in 2016 and 2011. The reason is that most cooking activities are undertaken by women, and they spend much time in a smoky kitchen. Besides, income and age significantly affect respondents' positive attitudes toward their health, but there is no evidence that low income leads to participants'

negative attitudes toward their health status. Older respondents are more likely to perceive themselves as in poor health. Compared to respondents in Wuqiang county of Hebei province, respondents in Qihe county of Shandong province have a 0.08 higher probability of positive evaluation of their health and a 0.06 lower probability of negative evaluation.

6.2 Implications

In China's ambitions for rural revitalization and carbon neutrality, speeding up the rural energy switching from solid fuels to clean fuels is an urgent task for the government to deal with problems caused by household air pollution and energy poverty in rural areas, and some policy implications are proposed based on the results. First, considering the income level and energy preferences in rural areas, popularizing photovoltaic poverty alleviation projects in regions rich in solar energy resources, diversifying natural gas resources, and strengthening infrastructure development are useful ways to increase residents' income, and promoting renewable energy usage. Besides, there are lots of opportunities to explore and expand the applications of biomass fuels, instead of burning for cooking, such as animal feed and crop fertilizer. The ongoing new rural revitalization program should also promote clean cooking fuels in rural households, such as subsidies for purchasing energy-efficiency equipment, and installations of rooftop solar energy.

Second, although promoting clean energy transition has great benefits, some actions may be hindered by investments cost. However, Stringer and Joanis. (2022) find that each province can benefit more than costs from energy transition in Canada under five different scenarios. In China, Niu et al. (2021) find that the construction of biogas projects for cooking fuel in rural China has multiple environmental and social benefits, and even economic benefits. Zhao et al. (2021) indicate that the benefit of "clean heating renovation" surpasses cost by 1.51 and 3.06 based on two methods. Overall, the clean energy transition can bring large benefits than costs when an appropriate policy is designed.

Third, the government should pay attention to disseminating the health and environmental impacts of solid fuel use in rural areas. Interventions, such as improving residents' environmental and health awareness, increasing health care resources, and encouraging rural residents, especially the elderly, to take regular medical examinations, could help to improve rural residents' health and welfare. For example, the rural community could disseminate the negative impacts of solid fuels periodically to improve residents' cognitions.

Besides, since women spend more time in the kitchen and are more likely to make poor evaluations of their health status, the government should help women learn more skills to reduce indoor air pollution, like ventilating the room regularly, using dry firewood, or anthracite coal if necessary. Women also should be trained in more skills to improve productivity and time utilization, which will improve their opportunities for more marketable jobs. This also contributes to the promotion of gender equality.

Finally, a full understanding of exposures, influencing mechanisms, and health effects can be difficult to obtain based on household observational studies. Although a field study has the advantage of collecting detailed information, there are some limitations in our study. Respondents may have different health evaluation criteria, and each respondent's health standards may greatly differ from others. Even self-reported health status is a reasonable indicator of residents' health when lacking accurate diagnostic information. Low rates of medical treatment could lead to a lower estimated result of health impact. Besides, the use of dummy variables for cooking fuel instead of quantities may also underestimate the magnitude of solid fuel, more detailed information to quantify solid fuels is needed in future studies. Other omitted variables of exposure time, and house ventilation conditions could also result in a lower bound of our estimate.

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