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Cooking Fuel Type and Its Health Effects: A Field Study in China

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Abstract

This paper estimates the impacts of cooking fuel choice on residential health. We conducted a fieldwork and collected the data from ten villages in Northern China. The multinomial Logistic regression is used to address the multiple fuel types. The results indicate that cooking fuel stacking is prevalent in the surveyed rural villages, but a transition to cleaner fuels is underway, and the residents' health status was significantly influenced by cooking fuel types. Respondents who used clean cooking fuels had a 0.138 higher probability of having a positive evaluation and a 0.128 lower probability of having a negative evaluation of their health status, compared to those who used solid cooking fuel. The main driver of energy transition in rural households should be indoor air production reduction and family health benefits, while not just outdoor air pollution reduction or relevant public health benefits.

Keywords: Healthy China; Solid cooking fuels; Cooking fuel; Indoor air pollution; energy ladder; energy transition;

1. Introduction

Outdoor air pollution induced by industrial and transportation activities is of great concern to the research community, yet relatively little attention has been paid to household air pollution (HAP) caused by the combustion of cooking and heating fuels such as coal and firewood. According to (Zhang et al., 2022), long term exposures to outdoor and indoor pollution are both linked with a high occurrence of diseases like depression. World Health Organization indicates that the burden of the attributable deaths due to HAP was 2.3 million in 2019, accounting for 6.6% of the global mortality (IHME, 2021). HAP is produced mainly from the combustion of solid fuels that generate many harmful substances, including particulate matter, carbon monoxide, and nitrogen dioxide, among others (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). Exposure to HAP substantially increases the probability of chronic obstructive pulmonary disease, lung cancer, stroke, heart disease, and other non-communicable diseases (Pratiti et al., 2020).

Solid cooking fuel is an important source of HAP in rural China and its usage is closely related to China's carbon actions. 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). Solid fuel usage is related to energy poverty and poverty alleviating in rural areas, while clean and sustainable energy significantly benefits residents' health, the progress towards the "Healthy China 2030" policy goals, and Sustainable Development Goals (SDGs) (He et al., 2018; 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 model fuels is an important component of realizing carbon neutrality in the residential sector (IEA, 2021). The fuel choice in rural China is also important because the continuous and robust growth of rural economy and consumption upgrading may lead to energy consumption and emissions (Shi, 2021; Zhang et al., 2020).

Compared with prominent ambient air pollution, household 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). Although promoting the energy transition can benefit residents' health, mitigate pollution, promote human development, the investments required for such a transition are often quite costly. In Canada, (Stringer and Joanis., 2022) calculate the costs for five different scenarios and taking into account the savings incurred by lower fossil fuel consumption post-transition, and find that each province can benefit from the energy transition. The province which produces electricity using fossil fuels benefit more. Much of the existing research focuses on the health effects of HAP 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 such as wood and peat were used compared to relatively clean fuels such as electricity and liquefied petroleum gas (LPG) (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 were concerned with the positive relationship between HAP caused by solid fuel use and individual health from an exposure-response relationship perspective 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) indicates 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 literature 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) confirmed 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 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 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 of solid fuel usage in China, this paper focused on two counties in Shandong and Hebei. They are key provinces of the “clean winter heating program” in the north of China, which suffer heavily from solid fuel usage. 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 policy making. 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 resources. Section 3 introduces the situation of cooking fuel use over the past 10 years in Qihe and Wuqiang counties, and 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 the 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).

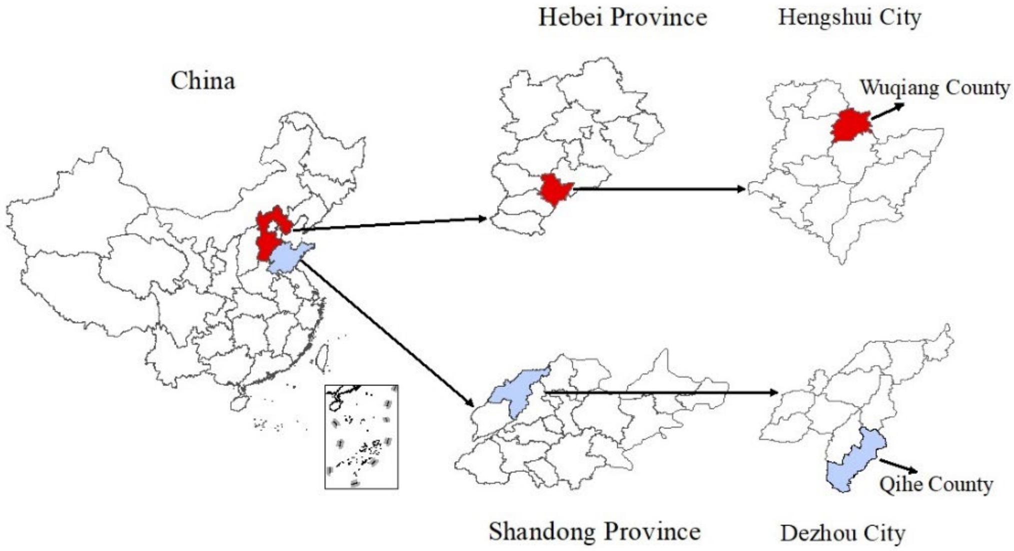

Figure 1. Survey areas

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 head of the household 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 currently use for cooking. The eight choices provided included firewood, straw or crop stalks, coal, marsh gas, LPG, natural gas, electricity, and others (to be specified). 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 head of the household or the member most familiar with the household situation, we trust their judgment or evaluation was credible. We considered that the subjects 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 subjects 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 their income increases, but energy stacking persists even when their income increases. The respondents did not quit using a lower-level fuel entirely, but used it as a backup, which means they used 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.

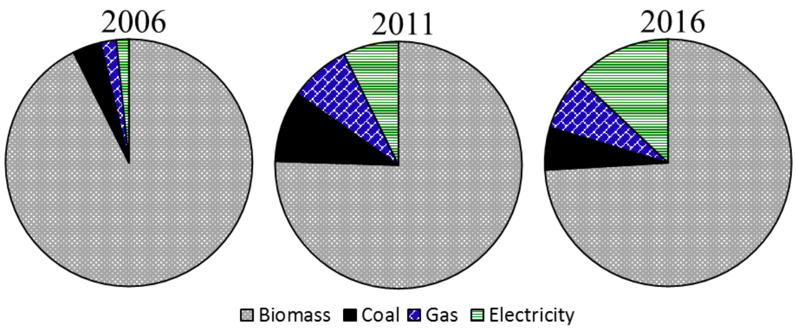

Figure 2. Fuel preferences in households using one cooking fuel type in 2006, 2011, and 2016

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

3.2 Cooking fuel stacking transition

Over the past 10 years, most households used at least two fuel types for cooking. Figure 3 illustrates the energy selection structure in those households. This figure reclassified 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.

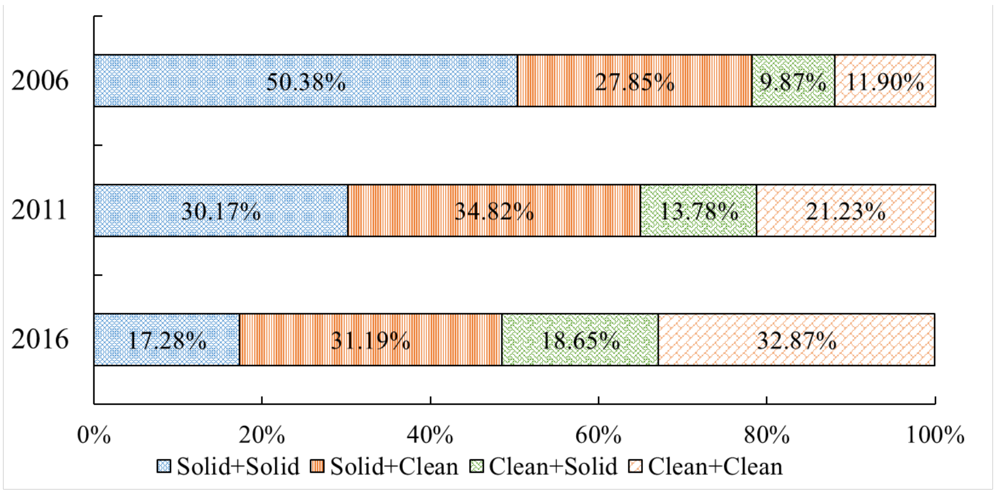

Figure 3. Population proportion using various fuel type compositions

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 their primary cooking fuel. Among them, 27.9% of the households used clean fuel as their secondary choice. A total of 21.8% of the households chose clean fuel as their primary cooking fuel. Only 11.9% of the households conformed to the composition "Clean + Clean" and used clean fuels exclusively for cooking. In 2011, the percentage of households choosing solid fuel as their primary cooking fuel decreased, while the percentage of households choosing clean fuel as their 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 such as gas and electricity as their 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 was 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 their primary cooking fuel were less likely to have good health than those who used clean fuels as their primary cooking fuel in 2016. This was very similar even when we considered primary cooking fuel in 2011.

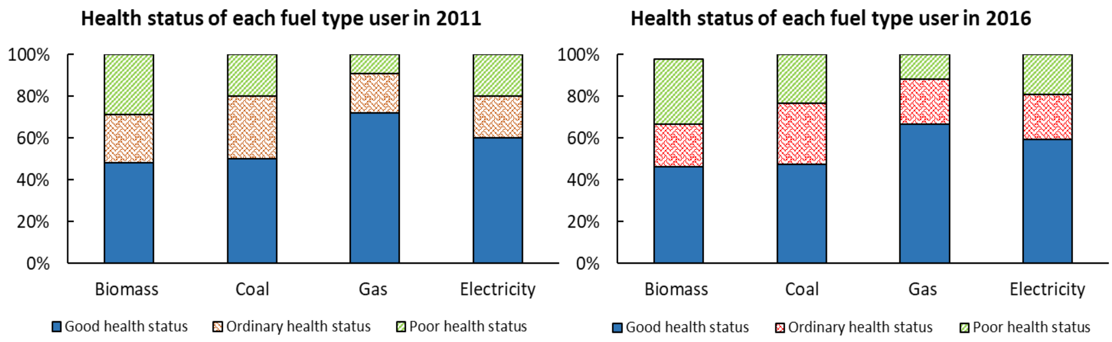

Figure 4. Respondents’ reported health status in different primary fuel categories

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 sick 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 of the 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%

Disease type	Frequency	Responses	Cases among sick respondents
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 their primary cooking fuel in 2016 suffered a stroke. Consistent with Table 1, heart disease was most prevalent. However, there was no evidence indicating that the morbidity of various diseases was lower among the respondents who chose clean fuels than among 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 these 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 such as biomass and coal produce many harmful substances and has a serious impact on the users' health. This section provides an empirical estimation of the influence of fuel choices on the respondents' reported health conditions.

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):

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

and,

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

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 parts are all predicted probabilities.

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

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

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

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

4.2 Variable definition

4.2.1 Dependent Variable.

We mainly estimated the influence of cooking fuel use on the respondents' reported health status (denoted by *RHS*). The dependent variable is a multiple discrete variable, 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, these individuals had less knowledge about relevant acute and chronic diseases and consequently increased the inaccuracy of our data when asked if 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 rate 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 could be due to the fuel type presently being used or the type that was 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 (donated 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 of 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 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, exercise regularly, has hypertension (denoted by *smoke, drink, exercise, and hypertension respectively*) are added in the model as control variables.

4) Demographic Factors

We controlled gender (denoted by *male*), age (denoted by *age*), and educational levels (denoted by *educ*) to control the heterogeneity of the study respondents. Males and females 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 (denoted by *sleep*) and house type (denoted by *house*) 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 county to control for unobserved fixed effects.

Table 3. Descriptive statistics of independent variables

Variable	Obs.	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

From Table 4, we can obtain the following results: First, as shown in the last two columns, the respondents who usually used solid fuel had lower levels of reported health status. Their attitudes toward their health status were influenced not only by the cooking fuel used in the current period but also by those used in the past. When using clean cooking fuels in 2016 and 2011, the respondent had a 0.138 higher probability of having a positive evaluation and a 0.128 lower probability of having a negative evaluation of their own health status compared to respondents who used solid cooking fuel in 2016 and 2011. Similarly, if a respondent used clean cooking fuels in 2016 but solid fuels in 2011, he/she had a 0.067 higher probability of having a positive evaluation and a 0.112 lower probability of having a negative evaluation of his/her own health status compared to respondents who used solid cooking fuel in 2016 and 2011. This finding is similarly to (Tian et al., 2021) that residents in rural areas more rely on solid fuels and the use of solid fuels for cooking significantly impairs residents' health statuses.

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

Third, there was no evidence that the male and female respondents had significant differences in evaluating their health status in this survey sample. With an increase in age, the respondents were less likely to have positive assessments regarding their health status. Those with higher educational levels may also have had a higher probability of having a positive assessment regarding their health and a lower probability of having a negative attitude. This could be explained that high educational people may seek timely medical treatment to prevent deterioration over time.

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 0.248 if he or she is in hypertension, while the possibility of positive evaluation will decrease 0.162. There was no evidence that smoking had a significant influence on the respondents' health evaluations which could be become that compared HAP, smoking is less significant. When people exercise regularly, their probability of having a negative evaluation decrease by 0.04, and there was no evidence that regular exercise influenced the probability of the respondents having a positive health evaluation. On the contrary, our results show that in the two counties studied, drinking alcohol decreased the probability of the respondents having a negative evaluation of their own health, but there was no evidence that it increased their probability of having a positive evaluation of their own 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 own health compared to the respondents in Wuqiang County.

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**
	(-1.19)	(-0.98)	(-0.31)	(-1.55)	(-0.41)	(-1.50)

	Reported health status					
	Good	Poor	Good	Poor	Good	Poor
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) found that in poor urban areas in Africa, gender is becoming more relevant in providing energy services to households. 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 have been affected by gender. We used the interaction of fuel composition and gender to analyze the effects in Table 5.

As shown in Table 5, in the group of clean cooking fuels in 2016, there were significant differences between the male and female respondents when evaluating their health. Specifically, women who chose clean fuels in 2016 and 2011 had a 0.12 higher probability of having a positive evaluation and a 0.155 lower probability of having a negative evaluation compared to the men who chose solid fuels in both 2016 and 2011. On the other hand, for men, using clean cooking fuel increased their probability of having a positive evaluation and decreased their probability of having a 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. However, when solid fuels were used in both 2016 and 2011, there was no significant difference between male and female reported health status. This result may associate with the fact that the gender of household head aways male and they are dominated in every household practice and household decision making (Musango., 2022).

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
	(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***

Variables	Reported health status	
	Good	Poor
	(-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**
	(-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

Reported health status	Sick respondents		Healthy respondents	
	Good	Poor	Good	Poor
	(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 in 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 having a positive evaluation and a significantly lower probability of having a 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 0.119 higher probabilities of having a 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 probabilities, respectively, of having a 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, similar to 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
	(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

Reported health status	Only heating fuel		Both cooking and heating fuel	
	Good	Poor	Good	Poor
	(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 showed 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.

In addition to the possible missing variable problem and the sample selection bias mentioned above, the potential self-selection problem may also affect the results. Our data are not collected from a random trial and we cannot determine which residents in the sample use solid fuels for cooking while the rest use clean fuels. On the other hand, if a resident answers that he uses solid fuel when in fact he uses clean fuel, his health status becomes difficult to ascertain. What's more, some unobserved difference between residents who are dependent on solid fuels and clean fuel for cooking may also affect residents' health, leading to a self-selection problem. According to (Tian et al., 2021), this problem may overestimate the health effects of cooking fuel choice.

6. Conclusion and Implications

6.1 Conclusions

Based on the data collected from field survey in two typical provinces in north of China, this study investigated the influence of cooking fuel transformation on residential health. Since rural individuals lack knowledge about acute and chronic diseases, self-reported health status instead of specific disease was used as dependent variable. Besides, the interaction of primary cooking fuel in 2016 and 2011 is used to explore solid fuel's current and potential chronic effects, which considering the lag effect of indoor pollution. The main findings of this study are summarized as follows:

(1) There is still much room for development in the use of clean energy in rural areas. Nowadays, even the primary cooking energy are transforming to clean fuels over time, there are still about 48% residents use solid fuels as their primary fuel.

(2) Household cooking fuel usage can influence the health of residents, both physically and psychologically. The respondent's reported health status was influenced by cooking fuel types in both 2016 and 2011. If a respondent used clean cooking fuels in 2016 and 2011, he/she had a 0.138 higher probability of having a positive evaluation and a 0.128 lower probability of having a negative evaluation of his/her own health status compared to those who used solid cooking fuels in 2016 and 2011.

(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 men spend less time in smoky kitchen. Besides, Income and age significantly influenced the respondents' positive attitudes toward their health, but there was no evidence that a low average household income caused the participants to have negative attitudes toward their health status. The older respondents are, the more likely they are to perceive themselves as in poor health. Compared to the respondents in Wuqiang County in Hebei Province, the respondents in Qihe County in Shandong Province had a 0.08 higher probability of having a positive evaluation of their own health and a 0.06 lower probability of having a negative evaluation.

6.2 Implications

Based on the above conclusions, some policy implications can be proposed for rural China. First, as solid fuels such as firewood and straw are still widely used in rural China, promoting the utilization of clean fuel is top priority to promote rural energy development and construct new rural areas. For example, developing small hydropower and wind energy, using straw to make biogas first and then use biogas as cooking fuel, or returning straw to oil as fertilizer, making forage, or planting eatable fungi. Inexpensive energy equipment or clean fuel subsidies can also effectively accelerate the spread of clean fuels, improve the life quality of farmers and benefit new rural revitalization.

Second, the government's attention should be paid to disseminate the health and environmental impacts of polluting energy use in rural areas. Using clean fuels can help rural residents stay away from the smoky kitchen, saving a lot of physical strength and time, and reducing symptoms like coughs and headaches. Indoor air pollution is not easy to detected compared to outdoor air pollution, but both indoor and outdoor air pollution have adverse effect on residents' health. However, people spend much more time indoors, helping rural residents understand the necessary for an energy transition is important. Interventions such as improving residents' dietary habits and daily routines, strengthening their health awareness, increasing health care resources, and encouraging rural residents, especially the elderly, to undergo regular medical examinations can also significantly reduce indoor air pollution and improve rural residents' health and welfare.

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

Finally, we acknowledge the following limitations of this paper: A full understanding of exposures, influencing mechanisms, and health effects can be difficult to obtain using multi-household observational studies, where thorough exposure assessments or experimental controls are impractical. Respondents may have different health evaluation criteria. One respondent's health standards may greatly differ from others. In this regard, respondents might have different perceptions about when medical treatment is needed. In addition, low rates of medical treatment in rural areas and fuel transition from solid to halfway clean can also cause a lower estimated result of the health impact.

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