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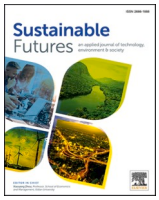

Impact of clean energy use on the health of rural residents in China: The mediating role of leisure activities and household cleanliness

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ABSTRACT

Against the backdrop of global sustainable development goals and Healthy China Initiative, investigating the health impacts of clean energy adoption in rural areas is critical for improving rural well-being and advancing sustainable social development. Using data from 6535 China Family Panel Studies, this study employs a multiple ordered probit model and mediation effect model to examine the health effects of clean energy use. Descriptive statistics reveal that 62.3 % of rural residents report good, very good, or excellent health, while 61.6 % use clean energy. Despite these encouraging trends, both health outcomes and clean energy adoption rates still leave room for improvement. Empirical results demonstrate that clean energy use significantly improves rural health outcomes by reducing asthma incidence, physical discomfort, and depressive symptoms. Notably, the health benefits are more pronounced among women, low-income households, and residents in central-western regions. Mechanistic analysis identifies two indirect pathways: clean energy adoption improves health outcomes through increased leisure activities and enhanced household cleanliness. Consequently, the government needs to enhance the production and promotion of clean energy, implement awareness campaigns for it, foster a conducive atmosphere for its utilization, and bolster the establishment of public cultural and recreational facilities in rural regions.

1. Introduction

In the context of increasing global climate change and environmental degradation, sustainable development has become a global imperative for humanity [1]. Health, as a cornerstone of human capital, not only underpins individual overall development but also forms the foundation for sustainable socioeconomic progress [2]. United Nations' Sustainable Development Goal 3 (SDG 3) explicitly articulates the global commitment to health and well-being, with its core objective being "to ensure healthy lives and promote well-being for all at all ages". In 2019, China promulgated the Healthy China 2030 initiative—a comprehensive policy framework designed to advance health equity, prioritize public health as a strategic pillar of national development, and strengthen health promotion systems. According to the Health Literacy Monitoring of Chinese Residents, the health literacy level of Chinese residents reached 27.78 % in 2022, representing a 2.38-percentage-point increase from 2021 and indicating a steady upward trend. Notwithstanding national progress, a significant urban-rural health literacy gap persists, with urban residents achieving a 31.94 % health literacy rate—8.16 percentage points higher than their rural counterparts. This persistent gap highlights systemic inequalities and constitutes a major bottleneck in achieving universal health coverage. China, as a major agricultural nation, faces critical challenges where farmers' health directly impacts food security, rural vitalization, and sustainable socioeconomic development. Given this strategic importance, China's central government has promulgated the Guiding Opinions on Promoting Healthy Village

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Construction, aiming to enhance rural health outcomes and achieve equitable development.

Rural areas lag significantly behind urban regions in infrastructure development [3], household income [4], and energy access [5], contributing to adverse rural health outcomes. Specifically, limited medical resources exacerbate healthcare accessibility challenges; low-income populations face inadequate nutrition and medication affordability issues; reliance on traditional biomass fuels persists, with limited clean energy adoption. These interconnected factors create a multidimensional health burden for rural residents. In developing countries like China, poor and rural households rely primarily on solid fuels (e.g., firewood, coal) [6], resulting in low clean energy adoption rates. Combustion of solid fuels significantly increases the prevalence of respiratory diseases [7] and elevates healthcare costs [8]. According to the World Health Statistics 2024, household and ambient air pollution caused 6.7 million global deaths in 2019.

As the world's largest carbon emitter and energy consumer [9], China faces critical challenges in balancing energy security and environmental sustainability. Energy serves as both a fundamental livelihood resource and a critical production input. Clean energy promotion, as a cornerstone of sustainable energy systems, plays a pivotal role in reducing carbon intensity and advancing ecological sustainability [10,11]. In recent years, China's rural clean energy transition has accelerated due to government policy support [12,13]. By 2017, rural households had reduced biomass and coal consumption for cooking/heating by 45 % and 12 % respectively compared to 2012, while natural gas use more than doubled [13]. This shift has led to significant reductions in harmful emissions (e.g., SO_2, NOx) and improvements in ecological sustainability [14]. Therefore, understanding how clean energy adoption influences rural health outcomes and the underlying mechanisms is critical for achieving China's Healthy China Initiative goals.

Existing research has extensively documented determinants of population health, primarily through two analytical dimensions. First, scholars have examined intrinsic determinants encompassing individual and household characteristics. Educational level [15], marital status [16], and household income [17] demonstrate significant positive associations with health status. Second, extrinsic environmental factors have been investigated. Deteriorating ecological conditions, including climate variability [18] and air pollution [19], have been shown to adversely affect population health outcomes.

Previous research has identified residential leisure activities [20,21] and household cleanliness [22–24] as significant health determinants. In addition to these factors, clean energy transition represents a critical health influencer [25], contributing to air pollution reduction [26] and population health enhancement [27]. Rural energy consumption patterns significantly influence resident well-being [28]. Clean energy adoption improves rural health outcomes [29–31], primarily by reducing chronic disease incidence [32] and mental health conditions [33]. Studies show clean energy enhances elderly health through reduced indoor air pollution exposure and improved sleep quality [34]. Conversely, traditional energy use increases depression risk via indoor air pollution [35]. However, healthy diets and social engagement can mitigate these adverse health effects [36].

In summary, first, existing studies have primarily explored the direct health impacts of clean energy adoption in rural areas but lack mechanistic analysis, with a narrow focus on mediating variables such as air quality, sleep quality, and social activities. While prior research has explored the health effects of leisure engagement and household cleanliness, it overlooks their potential mediating roles in the clean energy-health relationship. Second, current literature emphasizes subjective health ratings, neglecting the effects of clean energy adoption on common physical and mental health conditions. Building upon these considerations, this study utilizes data from the 2018 China Family Panel Studies and employs both the multivariate ordered Probit model and the mediating effect model to systematically examine the health impacts of clean energy use among rural residents. Specifically, it investigates the underlying mechanisms, analyzes effects on common physiological and psychological disorders, and further explores heterogeneous health impacts under varying conditions.

This study offers two key contributions to the existing literature. First, it advances the analysis of mechanisms linking clean energy use to health outcomes by investigating the mediating roles of leisure activities and household cleanliness. Second, it broadens health outcome measures to include both physiological and psychological disorders (e.g., asthma and depression).

China's case study has had significant global implications. First, in terms of carbon emission reduction, China's extensive adoption of clean energy has substantially reduced greenhouse gas emissions, making notable contributions to global climate change mitigation and carbon reduction target attainment. Chinese decarbonization initiatives also play a pivotal role in achieving global carbon neutrality goals. Second, regarding demonstration effects, the successful experience and models of China's clean energy development offer a valuable reference for other nations. Chinese carbon reduction policies and clean energy strategies have stimulated global interest in clean energy research and development as well as industrial investment, thereby accelerating the worldwide proliferation of clean energy technologies.

The subsequent sections of this study are organised as follows: Section 2 delineates the theoretical framework and posits research hypotheses. Section 3 delineates the study methodology and data sources. Section 4 delineates the analysis of empirical results. Section 5 examines the findings within their contextual framework. Section 6 ends the analysis and proposes avenues for future investigation.

2. Theoretical analysis and research hypotheses

2.1. Impact of clean energy use on the health status of rural residents

Sustainable development theory posits that enhancing human well-being and promoting public health serve as the core objectives of societal progress. Therefore, promoting the adoption of clean energy inherently aligns with the tenets of sustainable development. Previous studies have established that the adoption of clean energy technologies in rural areas is significantly associated with improvements in health outcomes [37]. Specifically, inefficient combustion of traditional solid fuels—common in rural households—releases harmful chemicals into the air, contributing to indoor air pollution and increasing risks of lung infections, strokes, and cardiovascular and respiratory diseases [38]. Prolonged exposure to such environments imposes serious long-term health burdens on rural residents. In contrast, clean energy technologies can effectively mitigate indoor air pollution due to their high combustion efficiency, low emissions, and energy utilization optimization [39]. This dual improvement in indoor and outdoor environmental quality has been linked to reduced prevalence of chronic illnesses and lower incidence of depression [40]. Additionally, access to clean energy provides other health-related benefits. Rural residents often expend significant labor to acquire traditional solid fuels—such as gathering firewood and transporting coal—which increases their physical exertion and elevates risks of accidental injuries [41]. Shifting to clean energy technologies reduces labor intensity and streamlines energy acquisition and utilization for rural households, enhancing both convenience and overall life satisfaction [42]. This reduction in labor demands also alleviates psychological stress, further contributing to the health improvement of rural populations. Based on these insights, this study formulates the subsequent hypothesis.

H1. The adoption of clean energy is significantly associated with improvements in rural residents' health.

2.2. Clean energy use, leisure activities, and health status of rural residents

Leisure activities represent a critical dimension of human lifestyles,

exerting profound implications for health outcomes. Empirical evidence indicates that regular engagement in leisure activities contributes to health maintenance through multiple pathways. Specifically, physical leisure activities enhance cardiovascular fitness, improve musculoskeletal function, and reduce risks of chronic conditions such as diabetes and cardiovascular illnesses [21]. Meanwhile, cognitive and social leisure activities alleviate psychological distress, promote emotional well-being, and significantly reduce the incidence of depressive symptoms [43]. However, the productive and domestic labor demands of rural residents significantly constrain their leisure time allocation. For instance, in domestic energy procurement processes, the collection of traditional solid fuels such as firewood and crop residues consumes substantial time and physical effort [44], consequently diminishing opportunities for leisure activities participation. Conversely, clean energy adoption eliminates these labor-intensive processes, thereby enabling rural residents to reallocate saved time toward leisure activities [41]. Furthermore, clean energy utilization enhances rural environmental quality, creating more conducive conditions for outdoor recreational activities and consequently increasing participation motivation [45,46]. Building on these findings, this study formulates the subsequent hypothesis.

H2. The adoption of clean energy can significantly improve rural residents' health by promoting their participation in leisure activities.

2.3. Clean energy use, household cleanliness, and the health of rural residents

Household cleanliness constitutes a critical determinant of health outcomes [23]. A sanitary living environment enhances rural residents' physical comfort and psychological well-being, thereby generating positive health impacts. First, improved domestic hygiene reduces microbial proliferation and pathogen transmission, while optimizing indoor air quality to decrease risks of respiratory conditions such as asthma [24]. Second, orderly household arrangements minimize accident risks. Cluttered spaces elevate injury probabilities during routine activities (e.g., mobility and object handling), whereas systematic spatial organization mitigates such hazards and improves home safety [47]. Third, well-maintained domestic environments foster perceptions of security and contentment, reducing negative emotional states like anxiety and stress, which supports mental health preservation in rural populations [48]. Crucially, clean energy adoption demonstrates significant correlations with enhanced household sanitation levels [49,50]. In comparison to conventional energy sources, the adoption of clean energy technologies significantly reduces airborne pollutant emissions, thus decreasing the accumulation of contaminants (e.g., dust and particulate matter) in residential environments [51]. Moreover, the extensive implementation of clean energy not only enhances rural residents' environmental consciousness and energy-efficient behaviors but also promotes healthier lifestyle practices. This dual transformation is expected to encourage greater prioritization of household hygiene and proactive engagement in domestic cleaning routines [52]. Building on these findings, this study formulates the subsequent hypothesis.

H3. The adoption of clean energy can significantly improve rural residents' health by enhancing household cleanliness.

Therefore, the theoretical framework illustrated in Fig. 1 integrates the study's theoretical foundations and research hypotheses.

3. Research and data methodology

3.1. Data source

This study utilized data from the Chinese Family Panel Studies (CFPS), conducted by the Institute of Social Science Survey in 2018. The survey project intends to capture social, economic, demographic, educational, and health shifts in China by analyzing data from examined samples at the individual, family, and community levels. This is a countrywide, large-scale, multidisciplinary social tracking survey project using multi-stage equal-probability sampling. The project uses multi-stage equal probability sampling and combines computer-assisted survey technology to conduct interviews to improve research efficiency and data reliability. The research area involves 25 provinces (municipalities and districts), and the sample capacity reaches 16,000 households. The questionnaire consists of five parts: individual self-answer questionnaires, questionnaires on behalf of the children's parents, questionnaires on behalf of individuals, questionnaires for family members, and questionnaires on the household economy. According to the needs of this study, the data in the questionnaire related to individuals and families were screened, irrelevant and missing values were eliminated, and extreme values were eliminated. We finally selected 6535 samples of rural residents for the study.

3.2. Variable selection

3.2.1. Explained variables

The explained variable in this study is rural residents' health status. Grounded in health cognition theory, individuals' subjective health evaluations serve as the cognitive foundation for health behavior decisions, integrating multidimensional factors including physiological functioning, psychological states, and social adaptability into a comprehensive evaluation [53]. Researchers widely employ self-rated health measures due to their validity in capturing both subjective and objective health dimensions [29,54]. This subjective assessment uniquely incorporates personal health information unavailable through objective metrics while demonstrating strong correlations with clinical indicators (e.g., morbidity and mortality rates) and enhanced data accessibility. Accordingly, this study operationalizes rural residents' health status using standardized self-rated health measures.

3.2.2. Core explanatory variables

The core explanatory variable in this study is household clean energy adoption. Clean energy utilization primarily encompasses two key domains: cooking and space heating. Cooking energy consumption dominates rural energy expenditure and critically impacts residents' well-being [28]. The energy ladder theory postulates that energy sources

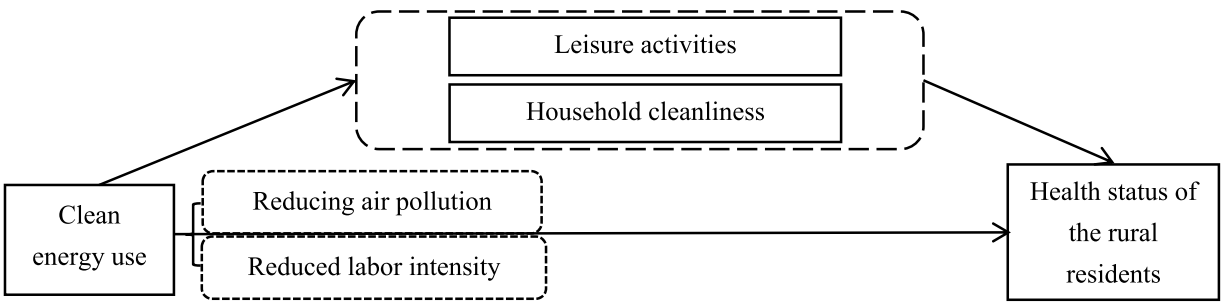

Fig. 1. Theoretical analysis framework.

vary in quality and utilization efficiency, with clean energy typically exhibiting superior energy quality and lower environmental externalities [25,49]. Given data availability constraints and building upon prior research [29,55], we operationalize rural residents' energy transition through cooking fuel choices. Households using firewood or coal are categorized as traditional energy consumers, whereas those adopting liquefied petroleum gas, natural gas, solar energy, biogas, or electricity are classified as clean energy adopters.

3.2.3. Mediating variables

The mediating variables in this study are leisure activities and household cleanliness. Leisure activities include daily consumption, social participation and recreational pursuits. These activities are essential for individual relaxation and leisure and significantly affect physical and mental health. According to the questionnaire content and thorough review of the literature [21,43], the study measures rural residents' leisure activities in terms of film and television (hours/week), exercise (hours/week), and reading (books/year). The entropy method was further utilised to derive a composite level of the three indexes to characterise participation in rural residents' leisure activities. Based on Kelly's leisure classification theory [56], these three types of activities correspond to three core dimensions: passive leisure, physical activity, and cognitive engagement. Among them, film and television, as a typical representative of passive leisure, reflect the individual's demand for entertainment and information through the media; exercise belongs to physical activity-based leisure, reflecting the function of health maintenance and social interaction; and reading constitutes cognitive participatory leisure, involving knowledge accumulation and spiritual development.

Household cleanliness reflects the living environment and quality of life of rural residents. This study selected the self-assessment level of rural residents' home cleanliness to characterise the degree of household cleanliness. According to cognitive theory, the individual's subjective evaluation of household cleanliness is based on the comprehensive cognition of daily life [57,58]. In daily life, people will unconsciously observe and evaluate the home environment. This evaluation is an individual's intuitive feeling and judgement of household cleanliness. This kind of subjective evaluation is often highly correlated with the actual situation because individuals are most frequently exposed to the home environment in daily life and are most familiar with it. Their evaluation can reflect the real situation of household cleanliness.

3.2.4. Control variables

Given the multidimensional determinants of rural residents' health outcomes, this study integrates individual and household characteristics as control variables, building upon prior studies [29,59]. The individual characteristics include gender, age, education level, political status, marital status, and medical insurance status; family characteristics include family population size and family economic status. At the same time, the regional variables are controlled. The chosen variables are presented in Table 1.

Table 1 delineates the statistical definitions and descriptive statistics of the variables. The mean value of the health status of the rural residents is 2.779, signalling that the interviewees' general health status is relatively good. Nevertheless, there is still far more scope for enhancement. 61.6 % of the overall sample comprised rural residents utilising clean energy, indicating that the respondent group has a high rate of clean energy use but has room for improvement. Among the mediating variables, the mean values of leisure activities participation and household cleanliness are 1.781 and 4.937, respectively, indicating that rural residents' participation in leisure activities is low and their household cleanliness is average. Among the control variables, there are more male respondents, the mean age is about 49 years old, there are more people with primary and middle school education, but there are fewer residents with party membership, and most of the residents are married and have medical insurance; the family size has an average of around four individuals, while the average family economic status is forty-six thousand, seven hundred yuan.

Table 2 presents the mean differences of study variables. Results show that clean energy adopters report an average health score 0.159 units higher than non-adopters. Cross-tabulation analysis reveals that 4073 rural residents (62.3 % of the total sample) are categorized as good, very good, or excellent health. Among clean energy users, 1559 (64.3 %) report good health, 519 (21.6 %) very good health, and 513 (21.3 %) excellent health. Conversely, in the non-adopter group, 883 (59.1 %) report good health, 285 (19.1 %) very good health, and 314 (21.1 %) excellent health. These descriptive findings suggest a positive association between clean energy adoption and rural health outcomes.

Furthermore, the levels of leisure activities and household cleanliness among clean energy users are respectively 0.002 and 0.360 units higher than those among non-users, indicating potential effects of clean energy usage on rural living conditions. Regarding mediating variables, leisure activities and household cleanliness were dichotomized into low and high groups based on the sample mean. The results demonstrate that residents in the high leisure activity group and high household cleanliness group showed 0.006 and 0.160 units higher health scores, respectively, compared to those in the low groups, providing empirical evidence for the mediating role of these factors in health outcomes.

Table 1
Descriptive statistics for each variable.

Variable type	Variable name	Variable Definition and Assignment	Average value	Standard deviation
Explained variable	Health status of the rural residents	Poor = 1; Fair = 2; Good = 3; Very good = 4; Excellent = 5	2.779	1.272
Core explanatory variable	Clean energy use	Yes = 1; No = 0	0.616	0.486
Intermediary variable	Leisure activities	The combined value of the three indicators	0.021	0.033
	Household cleanliness	1~7	4.937	1.496
Individual characteristic	Gender of head of household	Male = 1; Female = 0	0.510	0.500
	Age of head of household	Actual age of respondents (years)	52.525	13.372
	Educational level of the head of household	Illiterate = 1; Elementary school = 2; Middle school = 3; High school/secondary school = 4; College and above = 5	2.196	1.039
	The political profile of the head of household	Party member = 1; Non-member = 0	0.005	0.073
	Marital status of head of household	Marriage = 1; Other = 0	0.859	0.349
	Health insurance status of the head of household	Have health insurance? Yes = 1; No = 0	0.937	0.244
Family characteristics	Household size	Number of persons in the household (persons)	3.963	1.930
	Family economic income status	Your household's total income during the past year (10,000Yuan)	4.670	5.673
Regional characteristics	Regional distribution	Eastern region = 1; Central region = 2; Western region = 3	1.940	0.843

Note: Yuan is the Chinese currency unit, and in 2023, 1 Yuan equals 0.14191 USD.

Table 2
Analysis of differences in the means of the variables.

Variable name	Clean energy use		Gender of head of household		Family income status		Regional distribution	
	No	Yes	Female	Male	Low-income group	High-income group	Central-West	East
Health status of the rural population	2.681	2.840	2.663	2.890	2.678	2.955	2.769	2.794
Clean energy use	0.000	1.000	0.656	0.578	0.524	0.779	0.558	0.708
Leisure activities	0.020	0.022	0.019	0.024	0.021	0.021	0.020	0.023
Household cleanliness	4.715	5.075	5.027	4.851	4.772	5.228	4.854	5.070

To explore data heterogeneity, subgroup analyses were conducted based on gender, household income, and regional distribution. Household income was split at the sample mean into low-income and high-income groups, while regions were categorized as Central-Western and eastern according to economic development levels (Table 2). Results showed that male residents had health scores 0.227 units higher than females, high-income residents scored 0.277 standard deviation units higher than low-income counterparts, and Eastern residents had scores 0.025 standard deviation units higher than Central-Western residents.

Further, clean energy use increased male residents' health levels by 0.121 units, though this effect was 0.124 units smaller than that observed in females. In the high-income group, clean energy adoption improved health levels by 0.055 units, 0.058 units less than the improvement observed in low-income households. Eastern residents experienced a 0.182-unit health improvement following clean energy adoption, 0.035 units higher than that observed in Central-Western residents. These data form the basis for subsequent heterogeneity analysis.

3.3. Model construction

3.3.1. Ordered probit model

The explained variable in this study is rural residents' health status, which is an ordinal variable. Given this, drawing on Hou et al.'s research [32], this study employs a multiple ordered probit model. The regression equation is:

$$Health = \lambda_1 + \alpha_1 CEU + \beta_1 C + \delta_1 \quad (1)$$

In the formula (1), *Health* reflects the health status of rural residents. *CEU* stands for clean energy use. *C* represents the control variables. λ_1 is the constant term. α_1 and β_1 are the coefficients to be estimated. δ_1 is the error term.

3.3.2. Mediation effect model

To further examine whether leisure activities and household cleanliness mediate the relationship between clean energy use and rural health, this study employs the mediation analysis framework proposed by Wen et al. [60]. The mediating effect model is constructed as follows:

$$Health = \lambda_1 + \alpha_1 CEU + \beta_1 C + \delta_1 \quad (2)$$

$$M = \lambda_2 + \alpha_2 CEU + \beta_2 C + \delta_2 \quad (3)$$

$$Health = \lambda_3 + \alpha_3 CEU + \varphi M + \beta_3 C + \delta_3 \quad (4)$$

In the formula: *M* is the mediation variable and *C* is the control variable. λ_2 and λ_3 are constant term. α_2, α_3, β_2, β_3, and φ are the coefficients to be estimated. δ_2 and δ_3 are error terms. If the coefficients to be estimated in the equation, α_1, α_2, α_3, and φ, are significant, and also if α_2 is of the same sign as α_3, this evidence suggests the existence of a mediating influence.

4. Analysis of empirical results

4.1. Impact of clean energy use on the health status of rural residents

To enhance regression analysis accuracy, this study logarithmically transformed the household economic income variable and assessed multicollinearity using variance inflation factors (VIF). The analysis revealed a maximum VIF of 1.34 and a mean VIF of 1.16, both well below the critical threshold of 10, indicating no significant multicollinearity issues. Stata 17 software was used to estimate the impact of clean energy adoption on rural residents' health outcomes via a multivariate ordered probit model. Regression coefficients are presented in Table 3.

Model 1 shows that the coefficient for clean energy use is positive and statistically significant at the 5 % level, providing evidence that clean energy adoption significantly enhances the health of rural residents, thereby providing support for Hypothesis 1.

Significant health determinants include gender, age, and household economic status. Male rural residents exhibit significantly better health status than females, consistent with prior research showing that while females generally have longer lifespans, males often report better health outcomes [30]. Age negatively affects health: as individuals age, physiological functions decline, metabolism slows, and immunity weakens, increasing susceptibility to diseases. Household economic status is also a key health determinant, as wealthier households can afford better nutrition and healthcare services [4].

4.2. Robustness tests

To verify the reliability of the benchmark regression outcomes, this study employs explained variable replacement and alternative model specifications to conduct robustness checks.

4.2.1. Replacement of explained variables

In this study, "How would you rate your current health status relative to one year prior?" was employed as a proxy measure for the explained variable in robustness checks. Regression analysis using the alternative measure shows that clean energy use is positively associated with rural residents' health at the 1 % significance level (Table 3). This corroborates the stability of the principal research outcomes.

4.2.2. Replacement of the baseline regression model

This study re-estimated the model using the ordinary least squares (OLS) method instead of the ordered probit model. Regression results show that clean energy adoption remained statistically significant at the 10 % level with a positive coefficient (Table 3), and these robustness findings align with the benchmark regression results.

4.2.3. Placebo test

While the robustness test supports the reliability of the baseline regression findings, it does not fully account for potential randomness or unobservable factors. To address this, we adopted the placebo test methodology proposed by Meng et al. [61], which involves generating 1000 randomly assigned experimental groups to estimate the distribution of coefficients capturing the influence of clean energy use on health through sham experiments. As shown in Fig. 2, the placebo test results indicate that the estimated coefficients cluster around zero and follow a normal distribution, thereby validating the reliability of the model specification. Furthermore, the observed coefficients (denoted by vertical dashed lines) are substantially larger than the counterfactual estimates, providing additional evidence that clean energy adoption

Table 3
Benchmark regression results and robustness test results of clean energy use on the health status of the rural residents.

Variable name	Model 1		Model 2		Model 3	
	Coefficient	Standard error of robustness	Coefficient	Standard error of robustness	Coefficient	Standard error of robustness
Clean energy use	0.059**	0.029	0.105***	0.032	0.065*	0.034
Gender of head of household	0.251***	0.027	0.124***	0.029	0.288***	0.031
Age of head of household	−0.017***	0.001	−0.013***	0.001	−0.020***	0.001
Educational level of the head of household	0.003	0.014	0.017	0.015	0.003	0.016
The political profile of the head of household	0.130	0.151	−0.117	0.179	0.162	0.177
Marital status of head of household	0.067	0.041	0.003	0.048	0.069	0.047
Health insurance status of the head of household	−0.018	0.055	−0.035	0.061	−0.021	0.063
Household size	0.002	0.008	−0.006	0.008	0.002	0.009
Family economic income status	0.037***	0.010	0.009	0.012	0.042***	0.012
Regional distribution	Controlled		Controlled		Controlled	
Pseudo R^2	0.023		0.016		—	
Obs	6535		6535		6535	
_Cons	—	—	—	—	3.287***	0.167
R-squared	—		—		0.066	

Note: Model 1 shows the results of the baseline regression; Model 2 shows the results of the robustness test with replacement of the explanatory variables; Model 3 shows the results of the robustness test with replacement model. *, **, *** denote significance at the 10 %, 5 %, and 1 % levels, respectively.

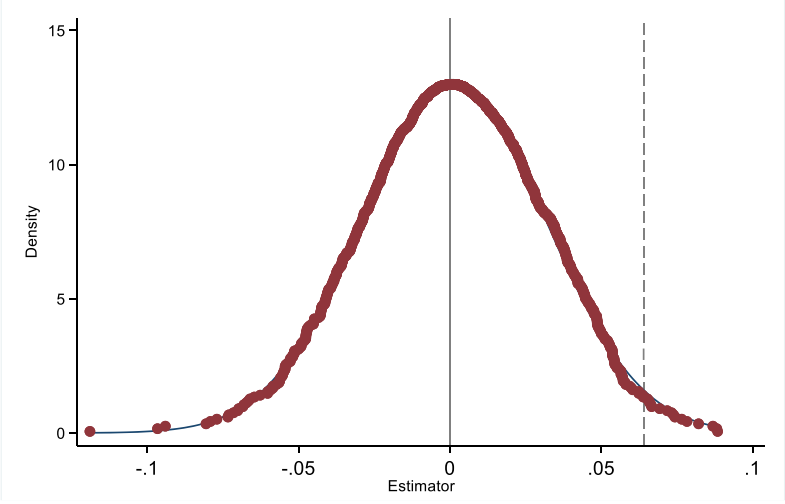

Fig. 2. Placebo test results.

significantly improves rural residents' health.

4.3. Endogeneity test analysis

The previous benchmark regression verified that using clean energy may greatly enhance the health status of rural residents. Still, the potential endogeneity problem between the two was neglected, which may result in inaccuracies in the benchmark regression results. Consequently, this study will further explore the endogeneity issue to improve the dependability and precision of the research analysis.

4.3.1. Self-selection bias

Rural residents' clean energy adoption is influenced by multiple factors, including self-selection, which may lead to endogeneity bias. To tackle this, this study utilizes the propensity score matching (PSM) method—a widely recognized approach to mitigate endogeneity and self-selection issues. Table 4 presents estimation results from three classical matching algorithms: nearest neighbor matching, kernel matching, and radius matching. All PSM estimates reveal that clean energy adopters exhibit better physical health outcomes. These findings ralign with the benchmark regression results, thereby confirming the reliability of the research findings.

Table 4
PSM estimates clean energy use on health status of the rural residents.

Matching method	Health status of the rural residents				
	Treated	Controls	ATT	Standard error	T-value
Nearest neighbor matching	2.840	2.758	0.082*	0.043	1.91
Kernel matching	2.840	2.753	0.087**	0.038	2.29
Radius matching	2.840	2.753	0.087**	0.039	2.25

Note: * and ** denote significance at the 10 % and 5 % levels, respectively.

4.3.2. Mutual causation

Given the potential endogeneity arising from reciprocal causality, this study utilizes the instrumental variable (IV) methodology proposed by Zhang et al. [59], using the clean energy adoption rate of other rural residents in the same district/county as an IV. In terms of relevance, group effect theory posits that individual behavior is shaped by peer actions within the same community [62], implying that the clean energy adoption rate of neighboring residents significantly affects one's own adoption likelihood. Regarding exogeneity, the adoption decisions of others do not directly influence an individual's health outcomes,

satisfying the exclusion restriction.

Table 5 presents the two-stage least squares (2SLS) estimation results. The Hausman test rejects the null hypothesis at the 1 % significance level, confirming endogeneity in clean energy adoption. In the first stage, the instrumental variable demonstrates a statistically significant beneficial effect on rural clean energy adoption. The first-stage F-statistic of 438.34 exceeds the conventional threshold of 10, rejecting the weak instruments hypothesis and confirming the instruments' strong correlation with the endogenous variable. The second-stage results maintain a statistically significant positive effect of clean energy use on health outcomes, corroborating the baseline estimates. These findings demonstrate that after addressing endogeneity through instrumental variables, clean energy adoption remains robustly associated with improved health status among rural residents.

4.4. Extensibility analysis

Rural residents' health comprises two primary dimensions: physical and mental health. To examine the differential impacts of clean energy use, this study analyzed both aspects. Physical health was operationalized as the presence of asthma or frequent illness. For mental health assessment, this study utilized the Center for Epidemiologic Studies Depression Scale (CES-D) as proposed by Yin et al. [34]. The CES-D measures depressive symptoms based on the frequency of eight emotions/behaviors reported over the past week: feeling depressed, difficulty concentrating, poor sleep, positive mood, loneliness, life satisfaction, sadness, and inability to continue activities. Negative emotions (e.g., depression, loneliness) were assigned positive scores, while positive emotions (e.g., positive mood, life satisfaction) received negative scores. Total CES-D scores were calculated, with elevated values signifying more severe depressive symptoms and worse mental health. These results align with prior findings by Ma et al. [63].

Regarding physical health, clean energy use reduces asthma incidence and physical discomfort. For mental health, clean energy adoption significantly improves psychological well-being and lowers depression risk. Combustion of conventional fuels releases substantial amounts of air pollutants. These pollutants irritate the respiratory tract, leading to the onset and exacerbation of respiratory diseases, such as asthma, while triggering symptoms like headaches, fatigue, and coughing. Clean energy adoption mitigates these pollutant emissions, thereby reducing respiratory irritation and disease incidence.

Chronic exposure to high-pollution environments has been linked to psychological distress, including depression and anxiety. The adoption of clean energy improves environmental quality, enabling residents to inhabit cleaner and healthier environments. This environmental improvement contributes to better mental health outcomes and reduced depression incidence.

Table 5
2SLS regression results of clean energy use health status of the rural residents.

Variable name	Model 4: Clean Energy Use		Model 5: Health status of the rural population	
	Coefficient	Standard error of robustness	Coefficient	Standard error of robustness
District and county clean energy utilization rates for other rural residents	0.862***	0.019	—	—
Clean energy use	—	—	0.279***	0.068
Control variable	Controlled		Controlled	
Hausmann test p-value	0.000			
Phase I F-value	438.34			
Obs	6535			

Note: *** denotes significance at the 1 % level.

4.5. Heterogeneity analysis

While using clean energy can enhance the health of rural residents, its impact may vary depending on individual characteristics, resource endowment, and regional economic development. Prior mean difference analysis has indicated that the health advantages of using clean energy are more significant among women, low-income households, and eastern residents. Therefore, this study stratified the samples by gender, household economic status, and region to derive more detailed conclusions.

4.5.1. Analysis of gender heterogeneity

This study divided the samples into female and male groups. Table 6, Table 7 shows that the impact of clean energy use on women's health is more significant than that on men's health. Under the traditional "men manage external affairs, women manage domestic affairs" marriage pattern, women tend to take on more household responsibilities. Therefore, clean energy adoption in these activities significantly reduces harmful gas emissions and indoor air pollution, directly benefiting women's health.

Furthermore, influenced by gender bias and feudal traditions, rural women may not prioritize their health or lack awareness of seeking medical care. However, improvements in household hygiene from clean energy adoption could encourage women to prioritize their health and adopt more active lifestyles. This is supported by evidence showing that female residents experienced a 0.124-unit greater improvement in health outcomes from clean energy use compared to male residents.

4.5.2. Heterogeneity in household economic income status

This study categorized the sample into low-income and high-income groups based on average household income. Clean energy use positively affects the health status of rural residents in the low-income group at the 10 % significance level. However, no significant effects were observed among high-income residents (Table 7). These results confirm that low-income households using clean energy report 0.058 higher health scores compared to their high-income counterparts. This discrepancy can be ascribed to high-income households' greater access to clean energy and diversified health improvement strategies, whereas low-income residents typically encounter substandard living conditions, restricted energy access, and financial constraints. Therefore, the health advantages of clean energy use are more evident among low-income populations.

4.5.3. Regional heterogeneity

The study divided the sample into two subsamples: one in the Central-West and the other in the East. The findings in Table 7 demonstrate that the health advantages of using clean energy are more significant for rural residents in the Central-West than in the East. This finding contradicts the earlier result, which showed that residents in the East experienced a 0.035-unit higher health benefit from using clean energy than those in the Central-West.

An underlying factor contributing to this disparity is the traditional dependence of Central-West areas on solid fuels. Using these fuels causes severe indoor air pollution, which significantly impacts health. Thus, when residents in these areas switch to cleaner energy alternatives, the reduction in pollutant emissions is more substantial, leading to more pronounced health benefits [64].

Additionally, the East generally has higher levels of economic and social development, along with better healthcare and infrastructure. Rural residents in the East may already enjoy relatively better living conditions, so the marginal health benefits of clean energy use are relatively smaller.

4.6. Analysis of impact mechanisms

In this study, the mediated effect model was further utilized to test the mechanism of action. The findings are displayed in Table 8.

Table 6
Regression results of clean energy use on physical and mental health of rural residents.

Variable name	Model 6: Asthma		Model 7: Physical discomfort		Model 8: Depression	
	Coefficient	Standard error of robustness	Coefficient	Standard error of robustness	Coefficient	Standard error of robustness
Clean energy use	−0.131*	0.069	−0.134***	0.035	−0.437***	0.114
Control variable	Controlled		Controlled		Controlled	
_Cons	−3.081***	0.352	−0.432**	0.179	12.086***	0.608
Pseudo R^2	0.068		0.044		—	
R-squared	—		—		0.102	
Obs	6535		6535		6535	

Note: *, **, *** denote significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 7
Results of the analysis of gender, household economic income status, and regional heterogeneity of the health status of the rural residents.

Variable name	Model 9: Health status of the rural residents		Model 10: Health status of the rural residents		Model 11: Health status of the rural residents	
	Female	Male	Low-income group	High-income group	Central-West	East
Clean energy use	0.092**, (0.044)	0.031, (0.040)	0.076*, (0.043)	0.042, (0.040)	0.089**, (0.036)	0.036, (0.051)
Control variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Pseudo R^2	0.026	0.016	0.012	0.022	0.022	0.024
Obs	3200	3335	2603	3932	4007	2528

Note: ** and ***denote significance at the 10 % and 5 %, respectively.

Table 8
Results of the mediation effect test.

Variable name	Model 12 Health status of the rural residents	Model 13 Leisure activity	Model 14 Health status of the rural residents	Model 15 Household cleanliness	Model 16 Health status of the rural residents
Clean energy use	0.059**, (0.029)	0.002*, (0.001)	0.058**, (0.029)	0.155***, (0.028)	0.054*, (0.029)
Leisure activities	—	—	0.943**, (0.380)	—	—
Household cleanliness	—	—	—	—	0.022**, (0.009)
Control variable	Controlled	Controlled	Controlled	Controlled	Controlled
_Cons	—	0.006, (0.005)	—	—	—
Pseudo R^2	0.023	—	0.023	0.014	0.023
R-squared	—	0.016	—	0.274	—
Obs	6535				

Note: *, **, *** denote significance at the 10 %, 5 %, and 1 % levels, respectively.

Evidence from Model 12 demonstrates that using clean energy can significantly enhance the health status of rural residents. Model 13 shows that clean energy use encourages rural residents to engage in leisure activities, while Model 14 reveals that both clean energy use and leisure activities improve rural residents' health status. These results indicate that clean energy use directly benefits health and indirectly enhances health outcomes through increased participation in leisure activities. Specifically, leisure activities exert a significant mediating influence, accounting for 3.2 % of the total effect. This finding supports Hypothesis 2.

Combining the regression results of Models 12, 15, and 16, the utilization of clean energy significantly enhances the health and household cleanliness of rural residents. The simultaneous regression analysis of clean energy utilization and household cleanliness on health outcomes in rural inhabitants shows that both variables achieve statistical significance with positive coefficients, suggesting that household cleanliness mediates the association between clean energy use and health improvements. The mediating effect accounts for 5.8 % of the total effect. This finding supports Hypothesis 3.

5. Discussion

The health of rural residents is closely linked to their quality of life and family well-being [65], serving as the foundation for rural economic development and social harmony and stability [66]. As a critical strategy to advance the UN 2030 Agenda for Sustainable Development, clean energy transition exhibits threefold policy synergies in improving health equity (SDG 3), ensuring affordable energy (SDG 7), and narrowing regional disparities (SDG 10). This study investigates the influence of clean energy adoption on the health outcomes of rural households from a family life perspective, uncovering the critical significance of energy transformation in enhancing public health and fostering sustainable development.

Clean energy use positively impacts rural residents' health, aligning with prior studies [29,31,55]. From the quantitative results, the health level of residents who use clean energy is 0.159 units higher on average than that of residents who do not use clean energy. This is substantially consistent with the mean difference analysis results of Zhu et al. [55]. Distinct from previous research, this study not only focuses on individuals' subjective self-evaluation of overall physical health but also investigates the tangible effects of clean energy adoption on improving physical and psychological health. Efficient combustion of clean energy significantly reduces toxic substance emissions, thereby lowering the incidence of respiratory diseases [67]. Furthermore, reduced fuel collection frequency alleviates risks of physical fatigue and accidental injuries associated with long-term labor, further enhancing health outcomes [68].

The impact of clean energy use on the improvement of women's health is more obvious. This is contrary to the conclusions of Zhu et al. [55] but consistent with the results of Liu et al. [69]. As women are more responsible for domestic tasks, they are more affected by pollutants from traditional energy use, while clean energy effectively reduces exposure

to pollutants and therefore enhancing women's health [31]. The health benefits of clean energy use are more significant among low - income earners. This aligns with the conclusions of Zhao et al. [70]. Low - income people tend to live in poorer environments, have a high dependence on traditional energy sources, and are more jeopardized by their pollution; clean energy can effectively enhance the quality of the environment in which they live, so the health benefits are more pronounced. The health benefits of clean energy use by rural residents in the Central-West regions are more pronounced. In rural parts of the Central-West regions, the reliance on conventional energy sources is significant, and the pollutants generated provide a considerable risk to residents' health. The use of clean energy can greatly reduce pollutant emissions, so the health benefits are more significant [12,71].

In previous studies on the mechanisms underlying the influence of clean energy use on rural residents' health, research has primarily focused on variables such as air pollution, sleep quality, and social activities [34–36]. This study concludes that leisure activities and household cleanliness play a mediating role between clean energy adoption and health outcomes in rural households. The high efficiency of clean energy decreases the time residents spend on traditional fuel collection, allowing them to dedicate more leisure time to physical exercise, cultural entertainment, and other activities that help alleviate stress and improve physical fitness. Meanwhile, clean energy adoption decreases pollutant emissions, enhances household cleanliness, and reduces residents' exposure to harmful pollutants, thereby lowering disease risks.

In summary, this study overcomes the limitations of traditional subjective health assessments by refining health outcomes into specific physiological and psychological conditions such as asthma and depression. It confirms that clean energy adoption significantly decreases the prevalence of respiratory ailments and mental health issues, offering a multi-dimensional perspective for health research. Furthermore, this study finds that the health advantages of clean energy are especially significant for women, low-income households, and residents in Central-West regions, revealing the complex interplay between energy transition and socio-economic and gender disparities while providing an empirical basis for targeted policy design. Additionally, by introducing 'leisure activities' and 'household cleanliness' as mediating variables, this research demonstrates that clean energy indirectly improves health by promoting leisure engagement and enhancing household environmental hygiene, thereby addressing gaps in existing literature on internal mechanisms.

6. Conclusions and future prospects

6.1. Conclusions

Using data from the China Family Panel Studies, this study applies the multivariate ordered probit model and mediating effect test to examine the influence of clean energy adoption on rural residents' health. The following conclusions are drawn: First, baseline regression results reveal that clean energy use substantially enhances rural residents' health, and these findings remain robust after accounting for endogeneity and conducting robustness checks. Second, extended analyses show that clean energy adoption reduces the incidence of chronic diseases and mental health issues, particularly asthma and depression, while alleviating physical discomfort. Third, heterogeneity analysis indicates that the health advantages of clean energy use are more significant among females, economically disadvantaged households, and residents in the Midwest. Fourth, mechanism analysis reveals that leisure activities and household cleanliness partially mediate the influence of clean energy use on health, with mediating effects of 3.2 % and 5.8 %, respectively.

6.2. Theoretical implications

This study transcends the single-dimensional limitations of traditional health assessment frameworks by decomposing health outcomes into specific physiological and psychological conditions (e.g., asthma and depression). It systematically demonstrates the multifaceted health value of clean energy adoption in reducing disease burdens, thereby providing empirical evidence for constructing composite evaluation index systems in environmental health research. The analysis further reveals heterogeneous health benefits, with more pronounced effects observed among female populations, low-income households, and residents in central and western regions. This finding aligns with the core principles of gender theory and environmental justice theory, offering a theoretical foundation for designing differentiated policies tailored to socioeconomic disparities. Additionally, the study uncovers the mediating mechanisms through which clean energy indirectly improves health: increasing participation in leisure activities and enhancing household cleanliness. These contributions extend the theoretical explanatory framework of environment-behavior interactions in health behavior theory, bridging gaps between energy policy and public health outcomes.

6.3. Practical implications

Promoting Clean Energy Use: To curb chronic diseases and mental illnesses, it is crucial to actively promote clean energy adoption and raise public awareness of its health benefits. The government should leverage diverse channels, including traditional media and new media platforms, to expand the reach of clean energy promotion. Encouraging collaborations with clean energy enterprises and social organizations can facilitate the implementation of multifaceted promotional campaigns, thereby enhancing the market influence and social acceptance of clean energy. Furthermore, cross-sector partnerships with medical, educational, and environmental sectors can strengthen the dissemination of the health-related benefits of clean energy.

Implement Targeted Measures: Given the heterogeneous impacts of clean energy on rural residents, tailored policies should be designed to foster an enabling environment and strengthen policy support. Rural female populations exhibit more pronounced health challenges than their male counterparts. Strategies include promoting environmental conservation awareness through education and training, as well as encouraging a balanced division of household labor to alleviate women's burdens. Consumer subsidies for clean energy and related appliances should be increased, with specific measures such as direct subsidies, tax incentives, and low-interest loans to reduce costs—especially for economically disadvantaged rural households. Additionally, investments in clean energy infrastructure in central and western regions should be scaled up to expand coverage and attract enterprises and investment to the sector.

Encouraging Leisure Activities and Household Cleanliness: Clean energy adoption can improve health outcomes by promoting leisure engagement and household cleanliness. Public cultural and recreational facilities in rural areas should be upgraded through increased investment to provide residents with diverse leisure options. Creating an enabling environment for active participation in cultural and recreational activities is crucial. Incorporating household cleanliness into local traditions and organizing cleaning initiatives during festivals or celebrations can foster collective awareness and encourage participation. Implementing recognition and reward systems for "clean home demonstration households" can further motivate residents to maintain high standards of household sanitation.

6.4. Limitations and future research

While this study yields practical implications, several limitations warrant attention. First, cross-sectional studies fail to capture temporal variations in how clean energy utilization interacts with personal health trajectories. Future research should explore this relationship using panel data to capture temporal effects. Second, although the subjective self-

assessment reflects farmers' health perceptions to some extent, it is susceptible to bias from personal emotions and psychological states, potentially compromising the accuracy of health status measurement. Third, with the rapid advancement of digital technologies, their synergy with energy transformation and health management has grown increasingly significant. Applications of technologies such as the Internet of Things and artificial intelligence can monitor real-time dynamic correlations between energy use patterns and residents' health indicators, offering a novel perspective for evaluating the health impacts of clean energy policies. Future studies may investigate how digital tools can optimize energy intervention designs and evaluations to maximize energy-health synergies.

CRediT authorship contribution statement

Wenmei Liao: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Chao Chen:** Writing – original draft, Visualization, Investigation. **Xunpeng Shi:** Writing – review & editing. **Feng Ye:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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