BMC Public Health

RESEARCH

Open Access

Impact of environmental regulation, energy technology innovation on population health

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Abstract

Background Environmental regulations and energy technology innovation play crucial roles in promoting environmental construction, enhancing ecological environment quality, and improving residents' health and well - being.

Method This study integrated the 2017, 2018, and 2021 Chinese General Social Survey (CGSS) data with urban macro - data. Empirical tests were conducted using the Ologit model, followed by robustness and heterogeneity tests, to explore the impact of environmental regulations and energy technology innovation on residents' health.

Result Empirical research findings indicate that, first, environmental regulations and energy technology innovation contribute to improving residents' self - rated health and mental health. Second, after introducing the interaction term between environmental regulation and energy technology innovation, it was discovered that energy technology innovation negatively moderates the promoting effect of environmental regulation on residents' health, suggesting a substitution effect between the two. Finally, heterogeneity analysis reveals that environmental regulations and energy technology innovation exhibit significant age - related, gender - based, and urban - rural heterogeneity in their impacts on residents' health.

Conclusion This study recommends that residents actively engage in environmental supervision, the government further strengthens environmental supervision, and enterprises continue to pursue energy technology innovation to enhance the positive impact of environmental regulation and energy technology innovation on residents' health.

Keywords Environmental regulation, Energy technology innovation, Self-assessed health, Mental health

Presentation of the issue

The rapid development of the Chinese economy has significantly improved people's quality of life [1]. However, it has also given rise to increasingly severe environmental pollution problems [2], and the conflict between economic development and environmental pollution has become more prominent [3]. On one hand, rapid economic growth has effectively enhanced residents' health levels, with the average life expectancy of Chinese residents increasing remarkably. On the other hand, various types of environmental pollution resulting from industrialization can significantly undermine the health of Chinese residents [4, 5]. According to the World Health Organization's health statistics report, environmental pollution has a negative impact on residents' health. For instance, Lee PureunHaneul's research found that air pollution can trigger various respiratory diseases [6]; Migliaccio Silvia discovered that environmental pollutants increase the likelihood of cardiovascular and cerebrovascular diseases [7]; Denise determined

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through a literature review that various environmental pollutants have been proven to be carcinogenic to adults [8]. Moreover, environmental pollution can directly affect residents' lifespan. Jan believed that environmental pollution can reduce residents' life expectancy [9], and Meo's research showed that air pollutants can increase residents' mortality rate [10]. Further analysis indicates that due to the spatial spillover effects of environmental pollution [11], it not only affects the health of local residents but also poses a threat to the health of residents in surrounding cities. Precisely because of the negative externalities of environmental pollution on residents' health, environmental regulation has become an inevitable choice in social development. As the main drivers of social development, both the government and enterprises are expected to play key roles in environmental regulation.

To address the negative impact of environmental pollution, the Chinese government has implemented a variety of environmental regulatory measures. Specifically, the Chinese government has successively issued multiple environmental policies, such as the Action Plan for Air Pollution Prevention and Control, the Action Plan for Water Pollution Prevention and Control, and the Action Plan for Soil Pollution Control, achieving remarkable results. Simultaneously, through financial means like energy - conservation and environmental - protection expenditures and investment in industrial pollution control, the Chinese government has also made significant progress in environmental protection and pollution control. According to the 2023 China Ecological Environment Status Bulletin, China's ecological environment has been continuously improving. From the enterprise perspective, as the main source of industrial pollution, environmental regulation is essential for enterprises. To achieve sustainable development between environmental protection and economic growth, energy technology innovation is a necessary choice for enterprises [12]. On one hand, through energy technology innovation or technological progress, enterprises have enhanced the utilization of renewable energy [13] and natural resources [14]. The improvement in enterprises' green productivity helps reduce industrial pollution emissions, thereby promoting the harmonious development of the ecological environment [15]. On the other hand, energy technology innovation can also influence the efficiency of government environmental regulations. When the level of energy technology innovation is high, enterprises can more efficiently develop and adopt clean - energy technologies, reduce pollution - control costs, and respond more effectively to government environmental regulations, further improving environmental quality. However, when the level of energy technology innovation is low, it not only fails to improve the efficiency of government environmental regulations but also leads to limited environmental improvement due to the low - level technology.

In current research, scholars have explored the impact of environmental pollution on residents' health from diverse perspectives. Nonetheless, there is still a lack of a research framework that combines environmental regulation and energy technology innovation, especially in terms of micro - level data analysis and the exploration of heterogeneity among different groups. Against this backdrop, a question that requires further consideration is whether environmental regulation and energy technology innovation have actually improved the health of the population. Based on the above background and analysis, this study aims to investigate the impact of environmental regulation and energy technology innovation on the health level of the population from the perspectives of sociology, management, and economics. By using the data from the 2017, 2018, and 2021 Chinese General Social Survey (CGSS), and with data sourced from the China Statistical Yearbook, and the State Intellectual Property Office, this study employs the Ologit model to empirically test the impact of environmental regulation and energy technology innovation on residents' health. Compared with existing studies, the possible marginal contributions of this paper are as follows:

Firstly, most existing literature focuses on the impact of either environmental regulations or energy technology innovation on residents' health separately, lacking a comprehensive research framework that combines the two. There is also a shortage of micro - level data analysis and exploration of heterogeneity among different groups. Moreover, existing literature rarely delves into the interaction between environmental regulation and energy technology innovation, especially how energy technology innovation moderates the impact of environmental regulation on residents' health. This study fills these research gaps by integrating environmental regulations, energy technology innovation, and resident health into a multidimensional research framework, providing a more comprehensive perspective.

Secondly, this study matches provincial - level macro - data on environmental regulation and energy technology innovation with residents' micro - data to explore their impact on residents' health. This provides micro - level evidence for the government to formulate environmental protection policies, which is of practical significance.

Thirdly, this study examines heterogeneity from multiple perspectives. It not only analyzes the overall impact of environmental regulations and energy technology innovation on residents' health but also further explores the differences in these impacts among different groups, such as age, gender, and urban - rural areas. This in - depth analysis offers a more targeted basis for policy - making.

The remaining part of this study is structured as follows: The second part presents a theoretical analysis of the impact of environmental regulation and energy technology innovation on population health and formulates the hypotheses of this study based on the theoretical analysis. The third section describes the data sources, variable definitions, and model design. The fourth section presents the basic regression empirical results, robustness test results, and heterogeneity test results of this study and discusses them based on the test results. The fifth section conducts a comprehensive discussion in light of the research results. The sixth section puts forward feasible recommendations and points out the limitations of this study in response to the research findings.

Theoretical analysis and research hypothesis

Environmental regulation and population health

The increasingly prominent environmental problems [16] in China have become a major threat to the sustainable development of the Chinese economy and the physical and mental health of its residents [17]. Existing research has shown that environmental pollution has a negative impact on both the physical and mental health of residents. To counteract the negative effects of environmental pollution on residents' physical and mental health, the Chinese government has implemented various environmental regulatory measures [18]. So, does environmental regulation affect residents' health? The theory of environmental exposure and health posits that residents' health is closely related to various exposure factors in the environment. These factors can enter the human body through air, water, soil, food, and other pathways, leading to various health problems. From the perspective of the environmental exposure and health theory, this study analyzes the direct and indirect impacts of environmental regulations on residents' health. Firstly, analyze the direct impact of environmental regulations on residents' health. Environmental regulation is an important means for the government to reduce environmental pollution, protect the ecological environment, and promote sustainable development by formulating and implementing a series of policies, regulations, and measures. The fundamental purpose is to reduce environmental pollution [19]. By doing so, it helps improve the physical and mental health of residents. For example, existing research has found that high concentrations of PM2.5, nitrogen dioxide, and sulfur dioxide can not only cause various acute or chronic diseases [20], but also increase the risk of death for residents [21]. Furthermore, as the level of air pollution rises, it will also suppress the mental health level of residents [22]. Evidently, air pollution can have a detrimental effect on residents' health. Through implementing environmental regulations such as policy constraints [23], increasing urban green spaces [24], and increasing environmental protection expenditures [25], air pollutants can be effectively controlled and reduced, which is beneficial for improving residents' health [26]. Meanwhile, from the perspective of water pollution, it not only threatens drinking - water safety [27], but toxic substances in water pollution may also negatively impact residents' health through the food chain [28]. Therefore, through environmental regulations, such as the government increasing efforts in wastewater treatment, the quality of the water - source environment can be improved [29], thus avoiding the negative impact of water pollution on residents' health. In addition, the government can also avoid the impact of soil pollution on residents' health through environmental regulations [30]. New pollutants also include noise pollution, which not only causes hypertension [31] and heart disease in residents [32], but also affects their mental health by disturbing their sleep [33]. The government can effectively address the impact of noise pollution on residents' health through environmental regulation measures such as investment in noise - pollution control, thereby alleviating the effects of various pollutants on residents' physical and mental health.

Secondly, considering the indirect impact of environmental pollution on residents' health, on one hand, the inhibitory effect of environmental pollution on residents' health leads to an increase in residents' health expenditure [34, 35]. The reduction in disposable funds also has a negative impact on residents' mental health. On the other hand, environmental pollution inevitably reduces residents' sense of well - being, thus suppressing their mental health [36]. At the same time, with the improvement of residents' awareness of pollution prevention [37], residents will strengthen their pollution avoidance behavior [38], and increase expenditures on necessary defensive items such as masks and air purifiers to mitigate the impact of pollution exposure on their health [39]. Through environmental regulations, reducing the level of environmental pollution can save residents from these additional expenses. Residents can then invest this portion of funds in health - related aspects, promoting the improvement of their own health levels.

In summary, the theory of environmental exposure and health suggests that various exposure factors can affect residents' physical and mental health, and environmental regulations can reduce these exposure factors in the ecological environment, thereby helping to mitigate the impact of environmental pollution on residents' health. Based on this, this study proposes the following two research hypotheses:

H1a: Environmental regulation contributes to the self-assessed health of the population.

H1b: Environmental regulation contributes to the mental health of the population.

Energy technology innovation and population health

Energy technology innovation refers to the process of improving energy efficiency, reducing energy consumption and environmental pollution, and promoting the development of the energy system towards a cleaner, more efficient, and sustainable direction through the research and application of new technologies, processes, materials, and other means. Do energy technology innovations affect the health of the population? The answer is affirmative [40]. On one hand, industrial production inevitably generates industrial pollution, including waste gas, waste water, waste residue, and noise. Under the requirements of the government's environmental protection policy [41], and to achieve sustainable economic development in the new era, energy technology innovation [42] has become a necessary path for enterprises. Enterprises' green production through energy technology innovation [43] not only improves resource utilization [44], but also reduces pollutant emissions [45], which enhances the overall environmental level of society. The improvement in the environment has a positive impact on the physical and mental health of residents. On the other hand, due to the spatial spillover effect of green technology [46], at the social level, the use of green energy technology to handle production waste [47] and municipal waste [48] can help reduce pollutant emissions, thus lowering the likelihood of environmental pollution and having a positive effect on residents' health. From this perspective, energy technology innovation is beneficial for improving the health of the population. Moreover, energy technology innovation requires enterprises to increase the number of professional and skilled workers. The increase in labor demand [49] and changes in the economic level [50] have a positive impact on the labor market, and disposable funds also affect residents' health expenditure and health investment [51].

In summary, energy technology innovations can influence the health of the population from both direct and indirect perspectives. Based on this, this study proposes the following two research hypotheses:

H2a: Energy technology innovations can help improve the self-assessed health of the population.

H2b: Energy technology innovations can help improve the mental health of the population.

The interaction between environmental regulations and energy technology innovation on residents' health

There may be a complex interactive relationship between environmental regulations and energy technology innovation. This interaction is not only reflected in the driving effect of environmental regulation on energy technology innovation but also in the enhancing effect of energy technology innovation on environmental regulation. In addition, the synergistic effect between the two has a significant impact on residents' health.

Firstly, environmental regulations promote energy technology innovation in enterprises through policy constraints and fiscal incentives. Strict environmental policies increase the cost of pollution control for enterprises, forcing them to adopt cleaner production technologies and reduce pollution emissions. For example, the Chinese government has implemented environmental policies such as the Action Plan for Air Pollution Prevention and Control, the Action Plan for Water Pollution Prevention and Control, and the Action Plan for Soil Pollution Control to encourage enterprises to adopt clean - energy technologies and reduce industrial pollution emissions. Environmental regulations not only drive technological innovation by increasing enterprises' environmental protection costs but also encourage them to engage in green technology innovation through incentives such as financial subsidies and tax incentives. This policy - driven technological innovation not only helps reduce environmental pollution but also enhances the competitiveness of enterprises.

Secondly, energy technology innovation can improve the efficiency of environmental regulation enforcement. By developing and applying clean - energy technologies, companies can more efficiently reduce pollutant emissions, thereby lowering the cost of implementing environmental regulations. For example, the application of renewable - energy technologies can reduce the use of fossil fuels, lowering air - pollutant emissions and enhancing the effectiveness of environmental regulations. Moreover, energy technology innovation can also promote the improvement of environmental quality across society through technology spillover effects. For instance, the promotion of clean - energy technology not only reduces industrial pollution but also decreases pollutant emissions in urban waste treatment, further improving environmental quality.

Finally, there may be synergies between environmental regulations and energy technology innovation. Environmental regulations provide policy support and market demand for energy technology innovation, while energy technology innovation offers technical guarantees and solutions for environmental regulations. This synergistic effect jointly promotes the improvement of environmental quality and the enhancement of residents' health. For example, environmental regulations promote energy technology innovation in enterprises through policy constraints and fiscal incentives, and energy technology innovation enhances the effectiveness of environmental regulations by improving pollution - control efficiency and reducing the implementation cost of environmental regulations. This synergistic effect not only helps reduce

environmental pollution but also improves the health level of residents.

Based on the above analysis, this study proposes the following hypothesis:

H3: Innovation in energy technology can have a positive impact on the health of residents through environmental regulations. Specifically, energy technology innovation may regulate the impact of environmental regulations on residents' health through substitution effects (i.e., as the level of energy technology innovation increases, the government reduces environmental governance investment) or complementary effects (i.e., energy technology innovation improves the efficiency of environmental regulation enforcement).

Research design

Data sources

The data on individual residents used in the empirical analysis of this study are derived from the Chinese General Social Survey (CGSS). As the earliest nationwide, comprehensive, and continuous academic survey project in China, the CGSS is implemented by the China Survey and Data Center of Renmin University of China. It adopts stratified sampling and multi - stage random sampling methods to ensure the representativeness of the sample nationwide. In the stratified sampling, the CGSS stratifies based on China's administrative divisions (provinces, cities, counties), ensuring that each province has corresponding sample coverage. In the second step, it uses multi - stage random sampling. Within each layer, the CGSS randomly selects cities or counties first, then randomly selects communities within each city or county, and finally randomly selects households and individuals within the communities. Through this sampling method, the CGSS data can cover 28 provinces in China, including both urban and rural areas, ensuring the representativeness of the sample in terms of geographical distribution, population characteristics, and other aspects. In this study, the micro - data of residents from the 2017, 2018, and 2021 CGSS were systematically collected. The environmental regulation data used in the empirical analysis are sourced from the China Statistical Yearbook, and the energy technology innovation data come from the State Intellectual Property Office of China. After data summarization, these data are respectively matched with the residential micro - data. The data - matching steps are as follows:

To match macro - data with micro - data, this study uses provincial identifiers for matching. The specific steps are as follows:

Data cleaning: First, the CGSS data were cleaned to remove missing variables and samples that refused to answer. Then, based on the province information in the CGSS data, the residents' health data were matched with the environmental regulations and energy technology innovation data of each province.

Variable definition: In the matching process, environmental regulation (ER) is measured by the completed investment in environmental pollution control in each province. Energy technology innovation (ETI) is measured by the number of renewable - energy authorized patents in each province. To eliminate dimensional differences, logarithmic processing was performed on environmental regulations and energy technology innovation data.

Matching process: By using the province information in the CGSS data, the health data of each resident were matched with the environmental regulations and energy technology innovation data of their province. For example, if a resident lives in Beijing, their health data will be matched with the completed investment in environmental pollution control and the number of authorized patents for renewable energy in Beijing.

Post - matching Data Processing: After the matching is completed, the data is further standardized to ensure that all variables can be compared on the same scale. For instance, logarithmic transformation of the environmental regulation and energy technology innovation data is carried out to reduce the skewness of the data distribution.

This study selected data from the 2017, 2018, and 2021 CGSS, mainly for the following reasons. Firstly, the data from these years have good representativeness and continuity, which can accurately reflect the changing trends of China's social environment, economic conditions, and residents' health in recent years. Secondly, 2017 and 2018 were periods when China intensively introduced a large number of environmental regulation and energy technology innovation policies. Selecting data from these years helps to more effectively capture the impact of policy implementation on residents' health. Thirdly, the 2021 data is the latest available data, which can reflect the latest trends of social and environmental changes.

In addition, this study fully considers the time - lag effect of environmental regulation and energy technology innovation on residents' health. The effects of environmental policies and technologies usually take some time to emerge. Therefore, selecting multi - period data helps to comprehensively capture the cumulative effects of policies and technological innovations. Meanwhile, with the release of more data in the future, the complexity of the time - lag effect will be further explored.

Data validity analysis

In this study, since self - assessment data of health and mental health based on the subjective consciousness of respondents are used, a brief analysis is conducted to ensure the validity and reliability of the data:

Firstly, the self - assessment indicators of health and mental health are widely used in existing research and are generally considered to have high validity. For example, self - assessment of health through a five - level scale (ranging from "very unhealthy" to "very healthy") can effectively reflect an individual's overall health status. Mental health, measured by the frequency of depression or frustration (ranging from "always feeling depressed" to "never feeling depressed"), can also effectively reflect an individual's psychological state.

Secondly, as the earliest national, comprehensive, and continuous academic survey project in China, the CGSS data uses a stratified multi - stage random sampling method, which greatly ensures the representativeness and reliability of the data. The survey process of the CGSS is rigorous, and the questionnaire design is scientific, which can effectively reduce the bias of self - reported data.

In conclusion, the use of residents' self - assessment data of health and mental health is reasonable and valid.

Description of variables

Dependent variables

The explanatory variables in this study are residents' self - assessed health (SHealth) and residents' mental health (MHealth). In the CGSS data, the question regarding residents' self - assessed health (SHealth) is stated as follows: What do you think is your current physical health condition? Referring to the method of Li Zhiguang [52], this study assigns scores based on residents' responses to this question. Residents who answer "very healthy" are assigned 5 points, "relatively healthy" 4 points, "average" 3 points, "unhealthy" 2 points, and "very unhealthy" 1 point. The question about residents' mental health (MHealth) is described as: In the past four weeks, how often have you felt depressed or down? According to residents' responses to this question, those who answer "never feeling depressed or down" are assigned 5 points, "rarely feeling depressed or down" 4 points, "sometimes feeling depressed or down" 3 points, "often feeling depressed or down" 2 points, and "always feeling depressed or down" 1 point. The higher the score, the higher the level of residents' self - assessed health or mental health.

Independent variables

The independent variables of this study are environmental regulation (ER) and energy technology innovation (ETI). Among them, environmental regulation (ER) is measured by the completed investment in environmental pollution control in each province, which can reflect the strength of government environmental regulation. The completed investment in environmental pollution control refers to the financial investment of each province in environmental pollution control, covering aspects such as air pollution control, water pollution control, and soil pollution control. The reasons for choosing this indicator are as follows:

Comprehensiveness: The completed investment in environmental pollution control covers pollution control investments in multiple aspects such as air, water, and soil, which can comprehensively reflect the efforts of each province in environmental regulation.

Quantifiability: This indicator is quantifiable and can directly reflect the financial investment of each province in environmental regulation, facilitating cross - provincial comparison and analysis.

Policy relevance: The completed investment in environmental pollution control is closely related to the government's environmental protection policies and can reflect the effectiveness of policy implementation. For example, the Chinese government has implemented policies such as the "Action Plan for Air Pollution Prevention and Control" to encourage provinces to increase investment in environmental pollution control, thereby improving environmental quality.

Energy technology innovation (ETI) is measured by the number of renewable energy authorized patents in each province, and the data is from the National Intellectual Property Administration of China. The number of renewable energy authorized patents refers to the number of patents obtained by each province in the field of renewable energy technology, including patents for clean energy technologies such as solar energy, wind energy, and hydropower. The reasons for choosing this indicator are as follows:

Innovation: The number of renewable energy authorized patents can directly reflect the level of activity of each province in energy technology innovation and is an important indicator for measuring energy technology innovation.

Clean energy orientation: This indicator focuses on clean energy technologies and can reflect the efforts of various provinces in reducing the use of fossil fuels and promoting clean energy.

Policy relevance: The number of renewable energy authorized patents is closely related to the government's energy policies and can reflect the effectiveness of policy implementation. For example, the Chinese government has promoted clean energy technology innovation in various provinces through policies such as the Renewable Energy Law to reduce environmental pollution.

In the empirical test, logarithmic transformation is applied to environmental regulation (ER) and energy technology innovation (ETI) respectively.

Control variables

The factors affecting residents' health are becoming increasingly diverse. In this study, the individual

micro - characteristics, social factors, and some macro - factors of residents are incorporated into the research framework.

1. Personal Micro - characteristics
   Gender: Gender is an important factor affecting residents' health. To explore the impact of gender on residents' health, this study uses gender as a control variable.
   Age: Age is a key factor affecting residents' health. As residents age, their health status usually declines, so age is used as a control variable.
   Education level (Edu): The education level may be closely related to residents' health. Residents with a higher education level may pay more attention to health.
   Marriage status: Marital status has a significant impact on residents' health.
   Registered residence (Hr): Registered residence is an important factor affecting residents' health. There are development differences between urban and rural areas, so residents with different registered residences may have different health levels.
   Internet usage frequency (Internet). With the development of digital technology, residents can obtain a large amount of medical knowledge through the Internet. To explore whether the frequency of Internet use affects residents' health, it is used as a control variable in this study.
2. Characteristics of social factors
   Family Economic Status (FES): Family economic status is an important factor affecting residents' health.
   Socializing with neighbors (SWN): Social activities with neighbors have a significant impact on residents' health. Good neighborly relationships can provide social support, reduce loneliness, and thus help improve mental health. Therefore, it is used as a control variable.
   Socializing with friends (SWF): Social activities with friends also have a significant impact on residents' health.
   Social trust (ST) and social equity (SE): Both social trust and social equity may be important factors affecting residents' health, so they are added as control variables.
3. Macro - factor variables
   Urbanization rate (City): The urbanization rate is an important factor affecting residents' health. Urbanization usually comes with better medical resources and infrastructure, but it may also bring higher living pressures and environmental risks, resulting in complex impacts on residents' health.
   Per capita GDP of residents (Pgdp): The per capita GDP of residents is an important factor affecting their health. A high per capita GDP usually means better economic conditions and medical resources, which helps to improve the health level of residents.

Urban Medical Resource Level (MRL): The level of urban medical resources is an important factor affecting residents' health. A high level of medical resources usually means better medical services, which helps to improve the health level of residents.

In this study, after excluding samples with missing variables and those that refused to answer, the CGSS data for 2017, 2018, and 2021 are organized and matched with the corresponding macro - data, and the macro - data is logarithmically transformed. This study covers 28 provinces in China, with a total of 31,308 samples, among which 14,627 are male samples, accounting for 46.72%, and 16,681 are female samples, accounting for 53.28%, making the study sample representative.

The descriptive statistics of the samples are shown in Table 1. It can be seen from the table that among the 31,308 samples, the average value of residents' self - assessed health is 3.497, which is higher than the "average health" level but still some distance away from the "relatively healthy" level. The average value of residents' mental health is 3.862, indicating a relatively high level of mental health. At the same time, from the average, maximum, and minimum values of environmental regulation, it can be seen that there is a large gap in environmental pollution control investment among different provinces in China. The maximum value of energy regulation is 6.654, and the minimum value is 0.123, with a difference of more than 50 times. From the maximum, minimum, average, and variance of the energy technology innovation variable, it can also be seen that there is a large gap in the degree of emphasis on energy technology innovation among different provinces. The maximum value of energy technology innovation is 14.978, and the minimum value is 7.658, with a difference of nearly two times. The reasons for the above - mentioned problems may stem from differences in economic development levels, policy implementation, and industrial structures among provinces. Economically developed provinces usually have more financial resources for environmental governance, while provinces with a high proportion of industry face greater pollution pressure and require more investment in governance. These disparities directly affect residents' health. Provinces with higher investment have better environmental quality and higher levels of residents' health, while provinces with lower investment may face greater environmental pollution and health risks. Secondly, the gap in energy technology innovation data (such as the nearly two - fold difference between the

Table 1 Descriptive statistics of variables

Variable	Variable Description	Mean	Std. Dev.	Min	Max.
SHealth	Self-assessed health of the population (very healthy = 5, relatively healthy = 4, average = 3, relatively unhealthy = 2, very unhealthy = 1)	3.497	1.089	1	5
MHealth	Mental health of the population (never depressed or frustrated = 5, rarely depressed or frustrated = 4, sometimes depressed or frustrated = 3, often depressed or frustrated = 2, always depressed or frustrated = 1)	3.862	1.006	1	5
ER	Investment completion in environmental pollution control	1.941	1.481	0.123	6.654
ETI	Number of renewable energy patents authorized by province	12.241	1.542	7.658	14.978
SEX	Sex (male = 1, female = 0)	0.467	0.499	0	1
Age	(a person's) age	51.591	16.829	18	118
EDU	Level of education (illiterate/semi-illiterate = 0, elementary school = 6, junior high school = 9, senior high school/secondary/technical/vocational = 12, college = 15, undergraduate degree = 16, postgraduate degree = 19)	9.036	4.82	0	19
Marriage	Marital status (married or cohabiting = 1, divorced or single or widowed = 0)	0.766	0.424	0	1
Hr	Household status of the population (urban = 1, rural = 0)	0.444	0.497	0	1
Internet	Frequency of Internet use (never = 1, rarely = 2, sometimes = 3, often = 4, very often = 5 points)	2.966	1.704	1	5
FES	Family economic status (well below average = 1 point, below average = 2, average = 3, above average = 4, well above average = 5)	2.568	0.748	1	5
SWN	Socializing with neighbors (almost every day = 7, 1 or 2 times a week = 6, a few times a month = 5, about 1 time a month = 4, a few times a year = 3, 1 time a year or less = 2, never = 1)	3.874	2.21	1	7
SWF	Socializing with friends (almost every day = 7, 1 or 2 times a week = 6, a few times a month = 5, about 1 time a month = 4, a few times a year = 3, 1 time a year or less = 2, never = 1)	3.933	1.888	1	7
ST	Trust of the population in society (very trusting = 5, more trusting = 4, can't say trusting distrusting = 3, more distrusting = 2, very distrusting = 1)	3.544	1.011	1	5
SE	Social equity (very fair = 5, more fair = 4, not fair but not unfair = 3, more unfair = 2, very unfair = 1)	3.224	1.034	1	5
City	urbanization level (of a city)	65.312	11.864	46.29	89.13
Pgdp	GDP per inhabitant	4.837	0.193	4.464	5.279
MRL	Measuring the level of urban medical resources by the number of health technicians per 1,000 population in each province	7.37	1.663	5.01	13.2

maximum and minimum number of renewable energy authorized patents) may be due to differences in scientific research investment, industrial structures, and policy support among provinces. Provinces with high research investment and developed clean energy industries (such as Jiangsu and Guangdong) have outstanding performance in technological innovation, while economically underdeveloped provinces are relatively lagging behind. This gap also affects residents' health. Provinces with high levels of technological innovation improve environmental quality by reducing pollutant emissions, thereby enhancing residents' health levels, while provinces with low levels of technological innovation may face greater environmental pressure and health risks.

Modeling

To test the research hypotheses of this study, a benchmark model was constructed with reference to the studies of I.M. Fei [53] and M. Sun [54]:

$$\mathrm{Health_i} = \mathrm{aER_i} + \mathrm{bETI_i} + \mathrm{cER_i{*}ETI_i} + \alpha\,\mathrm{A_i} + \beta\,\mathrm{B_i} + \gamma\,\mathrm{D_i} + \epsilon_{\,\mathrm{i}} \quad (1)$$

In this model, Health represents the dependent variable, which reflects residents' self - assessed health and mental health. It is measured using residents' self - rated physical and mental health responses from the questionnaire. ER is one of the core explanatory variables, denoting environmental regulation, and ETI is the second core explanatory variable, representing energy technology innovation. The term ER×ETI represents the interaction term between environmental regulation and energy technology innovation. A, B, and D are the control variables in this study. Specifically, A represents the micro - individual characteristics of residents, B represents social factors, and D represents the level of urbanization, per capita GDP, and the level of healthcare resources in the province where the residents live. ε is the error term of the model. The coefficients a, b, c, α, β, and γ represent the regression coefficients of the corresponding variables. If a regression coefficient is positive and passes the significance level test, it indicates that the variable can positively promote residents' self - rated health and mental health. Conversely, if the regression coefficient is negative and passes the significance level test, it means the variable can negatively inhibit residents' self - rated health and mental health.

Particular attention should be paid to the regression coefficient of the interaction term ER×ETI. A positive

regression coefficient for ER×ETI that passes the significance level test implies that as the level of energy technology innovation improves, the promoting effect of environmental regulation on residents' health is strengthened, indicating a complementary effect between energy technology innovation and environmental regulation. Conversely, a negative regression coefficient for ER×ETI that passes the significance level test suggests that as the level of energy technology innovation increases, the promoting effect of environmental regulation on residents' health weakens, demonstrating a substitution effect between the two.

In the selection of the estimation method, this study chose to use the Ologit model for empirical analysis. The main reason is that both SHealth and MHealth, as dependent variables, are ordered categorical variables. The Ologit model can effectively handle the orderliness of dependent variables, capture nonlinear relationships, and provide more accurate estimation results. Compared with linear regression models, the Ologit model is more suitable for analyzing ordered categorical data, as it can avoid the potential impact of measurement errors in the dependent variable on the results. Meanwhile, compared with the oprobit model, the results of the Ologit model are easier to interpret, especially when calculating the odds ratio, which is more intuitive. Additionally, the Ologit model performs more robustly in handling extreme values. Therefore, in the empirical research, the Ologit model is employed for regression testing and analysis.

Empirical results and analysis

Analysis of the results of the empirical tests of the benchmark regression

To further explore the impact of environmental regulation and energy technology innovation on residents' health, this study employed the Ologit model in the basic test. Independent variables, interaction terms, and control variables were introduced in batches, and the results of the benchmark regression empirical test are presented in Table 2. Table 2 shows the benchmark regression results of environmental regulation and energy technology innovation on residents' self - assessed health and mental health, respectively. The impacts of environmental regulation and energy technology innovation on residents' health will be discussed in the following sub - points based on the regression test results.

Firstly, as can be seen from Model 1 and Model 7, without the involvement of other variables in the regression test, environmental regulation significantly promotes residents' self - assessed health and mental health. The regression coefficients are 0.094 and 0.113, respectively, indicating that environmental regulation has a more pronounced promotional effect on residents' mental health than on self - assessed health. Further analysis shows that the impact of environmental regulation on residents' health can be estimated by multiplying the ER regression coefficient by the standard deviation of ER. A one - standard - deviation change in the ER index (1.481) leads to an impact of 0.139 ($1.481 \times 0.094 = 0.139$) on residents' self - assessed health and 0.167 ($1.481 \times 0.113 = 0.167$) on their mental health. This means that if environmental regulation (ER) increases by one standard deviation, the probability of residents' self - assessed health and mental health increasing by one level is 13.9% and 16.7%, respectively. For example, the self - assessed health level might rise from "very unhealthy" to "relatively unhealthy".

Secondly, according to the benchmark regression results of Model 2 and Model 8, energy technology innovation significantly promotes residents' self - rated health and mental health in the absence of other variables. The regression coefficients are 0.070 and 0.092, respectively. Further analysis reveals that for every one - standard - deviation increase in energy technology innovation, the impacts on residents' self - rated health and mental health are 10.8% and 14.2%, respectively. Continuing to analyze the benchmark regression results of Model 3 and Model 9, after introducing energy technology innovation, the regression coefficients of environmental regulation decrease to 0.079 and 0.086, respectively. However, both still pass the 1% significance level test, indicating that environmental regulation still has a significant impact on residents' self - rated health and mental health. At the same time, although the regression coefficient of energy technology innovation also decreases, its promoting effect on residents' self - rated health and mental health remains significant, with regression coefficients of 0.023 and 0.041, respectively.

Thirdly, the interaction term between environmental regulation and energy technology innovation was analyzed. From the regression test results of Model 4 - Model 6 and Model 10 - Model 12, it can be observed that the regression coefficients of the interaction term are negative and pass the significance level test. However, the regression coefficients of environmental regulation and energy technology innovation are still positive and pass the 1% significance level test. This indicates that the positive effects of environmental regulation and energy technology innovation on population health are somewhat resilient. This result implies that the interaction term has an inhibitory effect on residents' health and also proves that energy technology innovation negatively moderates the positive effect of environmental regulation on residents' health. The reason for the negative regression coefficient of the interaction term can be explained by the theory of diminishing returns. In the initial stage of strengthening environmental regulations and energy technology innovation, significant environmental

Table 2 Benchmark regression test results

variant	SHealth						MHealth					
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**	**Model 9**	**Model 10**	**Model 11**	**Model 12**
ER	0.094***		0.079***	0.599***	0.393***	0.325***	0.113***		0.086***	0.841***	0.660***	0.793***
	(13.66)		(9.00)	(6.89)	(4.50)	(3.68)	(15.98)		(9.52)	(9.67)	(7.53)	(8.95)
ETI		0.070***	0.023***	0.097***	0.076***	0.039***		0.092***	0.041***	0.102***	0.092***	0.083***
		(10.66)	(2.73)	(8.24)	(6.44)	(2.80)		(13.80)	(4.86)	(8.77)	(7.85)	(6.08)
ER*ETI				-0.040***	-0.025***	-0.018***				-0.057***	-0.044***	-0.058***
				(-6.43)	(-4.01)	(-2.78)				(9.09)	(-7.00)	(-8.89)
SEX				0.196***	0.211***	0.207***				0.208***	0.213***	0.227***
				(9.31)	(9.95)	(9.73)				(9.92)	(10.04)	(10.67)
Age				-0.039***	-0.034***	-0.034***				-0.008	0.003***	0.003
				(-51.05)	(-38.43)	(-37.37)				(-1.13)	(3.05)	(0.36)
EDU				0.047***	0.017***	0.019***				0.051***	0.025***	0.021***
				(16.12)	(5.52)	(6.19)				(17.93)	(8.24)	(6.76)
Marriage				0.091***	0.051**	0.049**				0.243***	0.221***	0.233***
				(3.69)	(2.04)	(1.95)				(9.94)	(8.93)	(9.40)
Hr				0.121***	0.002	0.013				0.267***	0.166***	0.094***
				(5.00)	(0.07)	(0.51)				(11.10)	(6.69)	(3.67)
FES					0.452***	0.445***					0.359***	0.367***
					(29.85)	(29.30)					(23.77)	(24.15)
Internet					0.119***	0.121***					0.103***	0.082***
					(13.39)	(13.43)					(11.58)	(9.04)
SWN					0.007	0.005					-0.015***	-0.005
					(1.27)	(0.80)					(-2.62)	(-0.87)
SWF					0.077***	0.076*** (11.47)					0.030***	0.029***
					(11.69)						(4.54)	(4.44)
ST					0.03***	0.030***					0.101***	0.100***
					(2.73)	(2.67)					(9.05)	(8.96)
SE					0.141***	0.141***					0.194***	0.193***
					(12.95)	(12.90)					(17.67)	(17.59)
City						-0.008***						0.014***
						(-3.95)						(7.00)
Pgdp						0.746***						0.086
						(4.95)						(0.57)
MRL						-0.053***						0.019
						(-4.72)						(1.64)
N	31,308	31,308	31,308	31,308	31,308	31,308	31,308	31,308	31,308	31,308	31,308	31,308
Pseudo R^2	0.002	0.0013	0.002	0.064	0.084	0.084	0.003	0.0023	0.003	0.018	0.036	0.039

improvements and health benefits may occur. However, with further intensification of regulations and deepening of technological innovation, marginal benefits may decline. Additionally, technology spillover effects may lead to a weakening of the effectiveness of environmental regulations. As companies can reduce pollution emissions more efficiently through technological innovation, the marginal effect of environmental regulations is reduced. From this perspective, it can be concluded that there is a substitution effect between environmental regulation and energy technology innovation regarding residents' health.

Finally, the control variables in the baseline regression test results were analyzed.

Regarding the micro - variables of the population, gender affects the physical and mental health of the population [55]. The regression results indicate that the health level of men is higher than that of women. A possible reason is that modern women not only bear the pressure of work but may also be responsible for caring for children and parents. The combined pressure from multiple aspects may lead to a lower health level among female residents compared to men. From the regression coefficient of age, it is clear that age has a more significant inhibitory effect on residents' physical health. This is understandable because as residents age, their physical fitness generally declines, thus affecting their physical health. Hou's study also found a similar inhibitory effect of age on residents' health [56]. Then, considering the number of years of education of residents [57], an increase in education years significantly contributes to residents' self - assessed health and mental health. A possible explanation is that higher education can lead to higher income and also raise awareness of the importance of health investment, thereby improving residents' health. From the regression coefficients of marital status, it can be seen that being married or cohabiting can promote residents' physical and mental health. This is reasonable because residents with partners can receive better care when they are ill and experience less loneliness due to companionship, which in turn improves their physical and mental well - being. Analyzing the effect of household registration on health, the results clearly show that household registration has a greater impact on mental health. Perhaps compared to rural areas, cities and towns have better infrastructure and more recreational facilities, which provide urban residents with more opportunities to relieve psychological stress, making them more psychologically healthy.

From the social factor variables, it can be seen that FES has a positive effect on both the self - assessed health and mental health of the population. This may be because as the population's disposable funds increase, they are better able to afford healthcare services, hire private dietitians, and engage in exercise, thus contributing to the improvement of their health level. Similar findings were reported by Eric [58]. The positive regression coefficient of the Internet use frequency suggests that Internet use promotes the health of the population [59]. A possible reason is that residents can improve their self - assessed health and mental health by obtaining specialized healthcare knowledge through the Internet and reducing stress and loneliness through various online recreational activities [60]. The positive regression coefficients of SWF, ST, and SE indicate that social support can improve residents' health [61].

From the regression coefficient analysis of macro factors, the level of urbanization has a suppressive effect on residents' self-rated health, possibly due to the fact that urbanization is usually accompanied by an acceleration in work pace and an increase in living costs, which puts greater economic and work pressure on residents [62]. During the process of urbanization, the increase in industrial activities and traffic flow has led to air pollution and noise pollution [63], further increasing the health risks for residents. This has affected self-rated health. The level of urbanization has a promoting effect on residents' mental health, possibly due to the abundant entertainment facilities and leisure activities in cities providing residents with more opportunities for stress relief and relaxation [64]. At the same time, community services and diverse social networks in cities provide residents with more social support, reducing feelings of loneliness and psychological pressure.Wang's study found that urbanization will increase the number of visits to the doctor by residents [65]. Analyzing the effect of GDP per capita on health, the coefficients were analyzed and found that GDP per capita has a significant effect on self-assessed health, which is understandable, as an increase in income allows for the purchase of more healthcare services, which in turn promotes health [59]. Finally, the regression coefficient of the level of medical resources shows that the impact of medical resource level on residents' mental health is not significant, but it has a suppressive effect on residents' self-rated health. The possible reason is that the increase in medical resources may attract a large number of non local residents to seek medical treatment, leading to greater competition for medical resources among local residents and thus affecting the quality of medical service [66]. At the same time, the increase in medical resources may be accompanied by an increase in work pressure for doctors and rising medical costs, leading to greater economic pressure for residents. Moreover, the increase in medical resources may benefit more high-income groups or urban residents, while low-income groups or rural residents may not have equal access to these resources, leading to increased health inequality. Based on the above possible reasons, medical

resources can have a suppressive effect on residents' self-rated health.

In summary, there are numerous factors influencing the self - assessed health and mental health of the population. Both environmental regulation and energy technology innovation in this study can improve the self - assessed health and mental health of the population, verifying the correctness of H1a, H1b, H2a, H2b, and H3, respectively.

Robustness tests

To reinforce the reliability of the benchmark regression findings, this study conducted additional robustness tests. Drawing on the approach of Dongyang Li [67], two distinct methods were utilized for assessment: index deletion and the replacement of econometric models.

The first method involved reducing the indicators. Specifically, the self - assessment scales for health and mental health were simplified from a five - level to a four - level scale. In the case of self - assessed health, "very healthy" and "relatively healthy" were consolidated into a single category labeled "relatively healthy". For mental health, the ratings of "never depressed or frustrated" and "rarely depressed or frustrated" were combined into "rarely depressed or frustrated". This adjustment was implemented to examine whether the research results were sensitive to the variable measurement methods.

The second method entailed replacing the econometric model. Here, the Oprobit model was employed in place of the Ologit model. This substitution aimed to test the sensitivity of the results to the distribution assumptions of the model. Both of these methods were designed to mitigate the potential influence of extreme values and distribution - related assumptions inherent in the baseline model, thereby strengthening the robustness of the research conclusions.

The regression results obtained from the indicator - censoring method are presented in Table 3. Similarly, the outcomes of the empirical test using the Oprobit model are also shown in Table 3. As can be observed from the regression results in Table 3, regardless of whether the deletion - index method or the Oprobit model was used for the empirical analysis, environmental regulations and energy technology innovation exhibited a significant positive impact on residents' self - rated health and mental health ($p < 0.01$). Specifically, under the reduced - index method, the regression coefficient for environmental regulation was 0.222, and under the Oprobit model, it was 0.220. For energy technology innovation, the regression coefficients were 0.033 and 0.025, respectively, under the two methods. Additionally, the pseudo R^2 values of the model were 0.103 and 0.085 for the reduced - index method and the Oprobit model, respectively. These values indicated that the model had a good goodness - of - fit. These statistical indicators further corroborated the robustness and significance of the research conclusions. This implies that the research results were not unduly affected by the variable measurement methods or the model distribution assumptions, demonstrating a high degree of robustness. Moreover, the results from the reduction of indicators and the Oprobit model further validated the reliability of the baseline model, suggesting that the research conclusions were less sensitive to potential model limitations.

Heterogeneity test

The results of both the baseline regression and the robustness tests indicate that, for the overall sample, environmental regulation and energy technology innovation can positively enhance the health of the population. However, the survey sample encompasses a diverse range of individual characteristics. It remains to be determined whether the impacts of environmental regulation and energy technology innovation vary for residents with different individual characteristics. Thus, further tests are necessary. In this heterogeneity test, age - based, gender - based, and urban - rural heterogeneity tests will be conducted to explore the differential health effects of environmental regulation and energy technology innovation on residents with distinct characteristics.

This study undertakes heterogeneity analysis from the perspectives of age, gender, and urban - rural areas for the following reasons. Firstly, residents of different age groups have varying health needs and concerns. An age - heterogeneity analysis can reveal the differences in how environmental regulations and energy technology

Table 3 Robustness test

variant	Robustness test for indicator censoring		Robustness Tests for Oprobit Models	
	SHealth	MHealth	SHealth	MHealth
ER	0.222**	0.481***	0.220***	0.441***
	(2.25)	(4.71)	(4.32)	(8.54)
ETI	0.033**	0.101***	0.025***	0.047***
	(2.14)	(6.43)	(3.21)	(5.91)
control variable	containment	containment	containment	containment
N	31,308	31,308	31,308	31,308
Pseudo R2	0.103	0.052	0.085	0.039

innovation affect the health of residents across different age brackets. Secondly, there are significant disparities in social roles and health - related behaviors between males and females. A gender - heterogeneity analysis can uncover the differences in the impacts of policies and technological innovations on the health of residents of different genders. Finally, urban and rural residents face different environmental issues and have varying degrees of access to resources. A heterogeneity analysis between urban and rural areas can shed light on the differences in the effects of environmental regulation and energy technology innovation on the health of residents in different regions. By conducting heterogeneity analysis from these three perspectives, this study can comprehensively consider multiple aspects of residents' socio - economic characteristics, living environments, and personal behaviors, providing a more targeted basis for policy - making.

Tests for age heterogeneity

To investigate the impact of environmental regulation and energy technology innovation on residents of different age groups, in this section, the sample of residents is divided into adolescent samples (45 years old and below), middle - aged samples (46–60 years old), and elderly samples (61 years old and above). The results of the age - heterogeneity test are presented in Table 4.

From the regression results in Table 4, it is evident that environmental regulations can promote the self - rated health and psychological well - being of adolescents, middle - aged, and elderly residents. Among them, the regression coefficient of self - rated health for elderly residents is the highest, with a value of 0.419, passing the 1% significance level test. Next are middle - aged residents, with a regression coefficient of 0.395, passing the 5% significance level test. For teenagers, the regression coefficient is 0.323, also passing the 5% significance level test. This indicates that the positive effect of environmental regulation on the self - assessed health of elderly residents is particularly significant. This finding can be explained by the life - cycle theory and the health - behavior theory. According to the life - cycle theory, elderly residents are more vulnerable to environmental pollution due to their decreased physical function. Therefore, environmental regulations have a more pronounced impact on their health. Additionally, the health - behavior theory suggests that adolescents are less sensitive to environmental changes due to their stage of development. Thus, environmental regulations have a relatively weaker impact on their health. A possible reason for this is that as age increases, the likelihood of acute and chronic diseases induced by environmental pollution also rises. Consequently, as the intensity of environmental regulation increases, its effect on the self - assessed health of elderly residents becomes more prominent.

When it comes to the effect of environmental regulation on residents' mental health, as can be gleaned from the regression coefficients, environmental regulation has the most significant effect on the mental health of adolescents, followed by middle - aged residents, and then elderly residents. A possible explanation is that as the level of environmental pollution decreases, it provides more opportunities for teenagers to engage in outdoor activities and travel. This reduces their psychological stress and thus improves their mental health. In contrast, middle - aged residents have relatively fewer opportunities for outings or travel due to work commitments and physical conditions.

Next, let's analyze the impact of energy technology innovation on residents' self - assessed health and mental health. From the regression results in Table 4, it can be seen that energy technology innovation has a significant effect on the mental health of young residents, as well as on the self - assessed health and mental health of middle - aged and elderly residents. This is because energy technology innovation reduces the level of urban pollution, lowering the likelihood of residents falling ill due to environmental pollution. The improved environmental quality also increases the likelihood of residents going out for activities and traveling. However, energy technology innovation has no significant impact on the self - rated health of adolescents. This may be because adolescents are in the prime of their physical fitness, with an overall good health condition and low sensitivity to environmental changes. Therefore, the environmental improvement brought about by energy technology innovation has a relatively minor impact on their health.

Table 4 Age heterogeneity test

variant	adolescents		middle-aged		Elderly residents	
	SHealth	MHealth	SHealth	MHealth	SHealth	MHealth
ER	0.323**	0.874***	0.395**	0.858***	0.419***	0.817***
	(2.29)	(6.25)	(2.45)	(5.27)	(2.59)	(4.96)
ETI	0.029	0.072***	0.057**	0.107***	0.052**	0.101***
	(1.33)	(3.30)	(2.26)	(4.28)	(2.05)	(3.94)
control variable	containment	containment	containment	containment	containment	containment
N	11,313	11,313	9515	9515	10,480	10,480
Pseudo R2	0.038	0.022	0.045	0.047	0.039	0.054

The above analysis shows that there are age - related differences in the impact of environmental regulation and energy technology innovation on the health of the population.

This discovery has important policy implications. For elderly residents, the government should prioritize strengthening air and noise pollution control to reduce their risk of chronic diseases. Additionally, the government can enhance their health level by providing more outdoor activity spaces, such as increasing urban green spaces and improving community environments. For teenagers, the government should increase outdoor activity areas and green infrastructure to promote their mental health and physical development.

Tests for gender heterogeneity

The resident samples were grouped according to gender, and the regression results are presented in Table 5. From the regression results in Table 5, it can be observed that environmental regulations have a more significant promoting effect on men's self - rated health, with a regression coefficient of 0.411, passing the 1% significance level test. The promotion effect of environmental regulations on women's mental health is more pronounced, with a regression coefficient of 0.824, also passing the 1% significance level test. This finding can be explained by gender - role theory and differences in occupational exposure.

Environmental regulations have a significant impact on men's self - rated health, possibly because men are more likely to be engaged in high - polluting industries. The implementation of environmental regulations directly reduces their occupational exposure risks, thereby significantly improving their self - rated health. Moreover, men usually shoulder more economic responsibilities in their social roles. Environmental regulations can indirectly alleviate their economic pressure by improving environmental quality, further enhancing their self - rated health. In contrast, environmental regulations have a better effect on women's mental health. This is mainly because women assume more caregiving responsibilities within the family. Environmental regulations reduce the health risks of family members by improving environmental quality, thereby alleviating women's psychological pressure. Additionally, women are generally more sensitive to environmental issues. The implementation of environmental regulations, such as increasing green spaces and reducing noise, directly improves their living environment, thus enhancing their mental health.

Analyzing the impact of energy technology innovation on residents' health, it can be seen from the regression results that energy technology innovation has a more significant promoting effect on men's self - rated health, with a regression coefficient of 0.049, passing the 5% significance level test. The promotion effect of energy technology innovation on women's mental health is more significant, with a regression coefficient of 0.113, passing the 1% significance level test. A possible reason is that due to the different division of labor in society, energy technology innovation reduces environmental pollution, lowering the occupational exposure risks for men at work and significantly improving their self - rated health. Moreover, energy technology innovation often brings an increase in high - skilled positions, and men are more likely to benefit from these positions, obtaining higher economic income and thus improving their self - rated health. In contrast, energy technology innovation has a better effect on women's mental health. Mainly because women take on more caregiving responsibilities in the family. Energy technology innovation reduces the health risks of family members by improving environmental quality, thereby alleviating women's psychological pressure. Also, women are more sensitive to environmental issues. The implementation of energy technology innovation, such as reducing pollution and increasing the use of clean energy, directly improves their living environment, thus enhancing their mental health.

This discovery has important policy implications. For men, the government should strengthen occupational health protection and environmental supervision, especially in high - polluting industries such as manufacturing and construction. This can promote the adoption of clean - production technologies, reduce pollutant emissions, and improve the working environment. For women, the government should strengthen community environmental governance and mental - health support. For example, by increasing community green spaces and

Table 5 Gender heterogeneity test

variant	Male population		Female population	
	SHealth	MHealth	SHealth	MHealth
ER	0.411***	0.763***	0.260**	0.824***
	(3.16)	(5.82)	(2.15)	(6.83)
ETI	0.049**	0.049**	0.032*	0.113***
	(2.44)	(2.45)	(1.69)	(6.02)
control variable	containment	containment	containment	containment
N	14,627	14,627	16,681	16,681
Pseudo R2	0.079	0.035	0.088	0.039

Table 6 Tests for urban-rural heterogeneity

variant	municipalities		countryside	
	SHealth	MHealth	SHealth	MHealth
ER	−0.051 (−0.38)	0.620***	0.425***	0.884***
		(4.55)	(3.46)	(7.21)
ETI	0.008	0.052***	0.058***	0.093***
	(0.40)	(2.47)	(3.05)	(4.94)
control variable	containment	containment	containment	containment
N	13,913	13,913	17,395	17,395
Pseudo R2	0.076	0.027	0.089	0.041

reducing noise pollution, the government can improve women's mental - health level.

Tests for urban-rural heterogeneity

In this section, the sample of residents is divided into urban and rural samples based on their household registration, and the regression results are shown in Table 6. From the regression results in Table 6, it can be seen that environmental regulation has a promoting effect on the mental health of urban residents, as well as on the physical and mental health of rural residents. Energy technology innovation can also promote the psychological health of urban residents, the physical health of rural residents, and their mental health. Moreover, by comparing the regression coefficients, it is evident that environmental regulation and energy technology innovation have a stronger impact on the physical and mental health of rural residents.

This finding can be explained by the environmental - justice theory and the resource - accessibility theory. According to the environmental - justice theory, rural areas typically face higher environmental - pollution risks, such as soil and water pollution. Therefore, environmental regulations have a more significant impact on the health of rural residents. The resource - accessibility theory suggests that urban residents usually have greater access to medical resources and environmental - governance resources. As a result, the impact of environmental regulations on the health of urban residents may be relatively weaker. Thus, with the improvement of the level of environmental regulation in rural areas and the level of energy - technology innovation, the environmental quality in rural areas will be enhanced, and the health of rural residents can be more significantly affected.

Meanwhile, from Table 6, it can be noted that the regression coefficient of environmental regulation on the self - rated health of urban residents is negative, indicating that environmental regulation may have a potential negative impact on the self - rated health of urban residents. The possible reasons are as follows. Firstly, the implementation of environmental regulation may increase the economic costs of enterprises and residents in the short term. This can lead to higher living costs and employment pressure for urban residents, which in turn affects their self - rated health. At the same time, urban residents have high expectations for health and quality of life. Environmental regulations may not fully meet their expectations in the short term, resulting in a decrease in self - rated health scores. From the above analysis, it can be seen that there are urban - rural differences in the impact of environmental regulation and energy technology innovation on residents' health.

This discovery has important policy implications. For rural areas, the government should increase investment in water and soil pollution control to ensure that rural residents have access to clean drinking water and safe food. Additionally, the government can encourage rural areas to adopt clean - energy technologies and reduce industrial pollution through financial subsidies and policy support. For urban areas, the government should strengthen the control of air and noise pollution. By increasing urban green spaces and improving community environments, the government can improve the mental - health level of urban residents.

Conclusion and discussion

Conclusion

Environmental pollution is an inescapable consequence of economic development, and the health problems it causes for the population are becoming increasingly prominent. Whether environmental regulation and energy technology innovation, as the primary means of environmental pollution management, can promote residents' self - assessed health and mental health is the focus of this study. In this research, CGSS data were combined with data from the China Statistical Yearbook and patent data, and the Ologit model was utilized to conduct benchmark regression tests. The study's findings are as follows:

Firstly, strengthening the intensity of environmental regulation is conducive to promoting residents' self - assessed health and mental health. For each one - standard - deviation increase in the strength of environmental regulation (ER), the probabilities of residents' self - assessed health and mental health rising by one level are 13.9% and 16.7%, respectively. It is worth noting that

there is significant heterogeneity in the impact of environmental regulation on residents' health. Environmental regulations have the most pronounced effect on the self - assessed health of elderly residents and the mental health of adolescents. They have a stronger impact on the self - assessed health of men compared to women and a greater impact on the mental health of women than on men. Moreover, they have a more significant impact on the self - assessed health and mental health of rural residents than on those of urban residents. This finding holds great significance in the field of public health. It indicates that by strengthening environmental regulation, the negative impacts of air pollution, water pollution, and noise pollution on residents' health can be effectively mitigated, thereby reducing the incidence of chronic diseases such as respiratory and cardiovascular diseases. Additionally, improving environmental quality can enhance residents' mental health and alleviate psychological stress and anxiety caused by environmental pollution.

Secondly, enhancing the level of energy technology innovation is beneficial for promoting residents' self - assessed health and mental health. For every one - standard - deviation increase in energy technology innovation, the impacts on residents' self - assessed health and mental health are 10.8% and 14.2%, respectively. There are also differences in the health - promoting effects of energy technology innovation among residents with different characteristics. The impact of energy technology innovation on the self - assessed health and mental health of middle - aged residents is the most significant, followed by elderly residents, while its impact on the self - assessed health of adolescents is not significant. It has a stronger impact on the self - assessed health of male residents than on female residents and is more effective in promoting the mental health of females than males. Moreover, it has a more substantial impact on the self - assessed health and mental health of rural residents than on urban residents. This discovery offers important insights for policymakers. By promoting energy technology innovation, governments can not only reduce environmental pollution but also create high - skilled employment opportunities, increase residents' economic income, and enhance their ability to invest in health. Specifically, the government should encourage enterprises to engage in green technology innovation through tax incentives, subsidies, and technological support, especially in high - polluting industries such as manufacturing and construction. This can promote clean - production technologies, reduce pollutant emissions, and improve the working environment.

Thirdly, this study conducted robustness tests based on the benchmark regression, using two methods: indicator deletion and the Oprobit model. The results showed that the positive effects of environmental regulation and energy technology innovation remained consistent across different methods, further enhancing the credibility of the research conclusions.

Finally, energy technology innovation negatively moderates the promotion effect of environmental regulation on residents' health, indicating the existence of a substitution effect between environmental regulation and energy technology innovation. By comparing the regression coefficients of the interaction terms, it can be seen that the interaction term of environmental regulation and energy technology innovation has a more significant weakening effect on residents' mental health.

Discussion

This study verifies the effects of environmental regulation and energy technology innovation on residents' self-assessed health and mental health through empirical tests, and the results show that environmental regulation and energy technology innovation can positively improve residents' self-assessed health and mental health. This section provides a point-by-point discussion.

Environmental regulation can promote residents' self-assessed health and mental health for the following possible reasons: First, environmental pollution consists of a variety of components, and with the government's introduction of various environmental control policies [23], increasing the greening rate of the city [24], applying various advanced technologies for the "harmless" treatment of pollutants [47], and increasing the proportion of investment in environmental management to GDP [25], the joint promotion of these methods has contributed to the improvement of environmental quality, avoiding acute and chronic diseases caused by environmental pollution, and improving the health of Chinese residents. This finding is consistent with the Porter Hypothesis, which suggests that strict environmental regulations can incentivize companies to engage in technological innovation, thereby improving production efficiency and environmental performance. In addition, the theory of innovation diffusion further explains how environmental regulations and technological innovation can promote the improvement of environmental quality and the enhancement of residents' health through policy synergy. Secondly, with the improvement of environmental quality, residents can appropriately reduce the defensive expenditures necessary because of environmental pollution [39], and the increase of disposable funds is conducive to the reduction of psychological pressure on the residents, thus promoting mental health. Meanwhile, for the residents themselves, atmospheric pollution reduces the frequency of outdoor activities of the population and not going out for a long period of time may increase the residents' psychological pressure [38]. The improvement of environmental quality not only increases the frequency

of residents' outing activities, but also helps to increase the frequency of residents' traveling, thus promoting the growth of tourism economy. Finally, soil pollution [27] and water pollution [28] in environmental pollution will lead to the accumulation of toxic substances in food crops and aquatic products. Improving the quality of the environment through environmental regulation avoids the negative impacts of the residents' consumption of food with excessive toxic substances, which indirectly improves the residents' physiological health and psychological health.

In the regression results of energy technology innovation on residents' health, it can be seen that energy technology can positively improve residents' self-rated health and mental health. Possible reasons are as follows: Firstly, energy technology innovation reduces the emissions of air and water pollutants and improves environmental quality [45] by promoting clean energy [43] and improving energy utilization efficiency [44], thereby reducing the incidence of respiratory and cardiovascular diseases and contributing to the improvement of residents' physical and mental health. Secondly, energy technology innovation has created high skilled employment opportunities [49], increased residents' economic income, and enhanced their ability to invest in health [68]. And the increase in income helps residents purchase better medical services, improve their quality of life, etc. Through these means, it also helps to improve residents' physical and mental health. Finally, energy technology innovation has technology spillover effects [69], which promote the improvement of environmental quality throughout society. The improvement of environmental quality helps to reduce the impact of environmental pollutants on residents' health. Through the above methods, the improvement of residents' health level has been directly or indirectly promoted.

Recommendations and limitations

Recommendations

Based on the empirical results of this study, environmental regulations and energy technology innovation have a significant promoting effect on residents' health, and this effect varies among different age, gender, and urban - rural groups. Therefore, the following policy recommendations are proposed to further enhance the positive impacts of environmental regulations and energy technology innovation on residents' health:

Firstly, strengthen environmental regulations and optimize policy implementation. The empirical results indicate that environmental regulations have the most significant impact on promoting the self - rated health of elderly residents. Thus, the government should prioritize strengthening environmental regulations in areas with a large elderly population. Specifically, efforts should be focused on reducing air pollution and noise pollution to lower the risk of chronic diseases among the elderly. Empirical research also shows that environmental regulations have a more pronounced effect on promoting the health of rural residents. As such, the government should increase investment in rural environmental governance, particularly in the treatment of water and soil pollution, to ensure that rural residents have access to clean drinking water and safe food. Additionally, the government can encourage rural areas to adopt clean energy technologies and reduce industrial pollution through financial subsidies and policy support.

Secondly, promote energy technology innovation and encourage green production. The heterogeneity test results suggest that energy technology innovation has a more significant effect on promoting the self - rated health of male residents, which may be related to their higher involvement in high - polluting industries. The government should encourage enterprises to engage in green technology innovation through tax incentives, subsidies, and technological support, especially in industries like manufacturing and construction. This can promote the adoption of clean - production technologies, reduce pollutant emissions, and improve the working environment. Moreover, considering that energy technology innovation has a more significant promoting effect on the health of rural residents, the government should promote inter - regional technological cooperation. In particular, it should encourage the promotion of clean energy technologies such as solar and wind energy in rural areas, reducing their reliance on traditional fossil fuels and improving the rural environmental quality.

Thirdly, enhance residents' participation and improve the effectiveness of environmental governance. Research has found that environmental regulations have a significant promoting effect on residents' mental health, especially among female residents. Therefore, local governments can encourage residents, especially those in urban areas, to participate in environmental supervision by establishing a resident - environmental - supervision mechanism. This can raise residents' awareness and participation in environmental issues. For example, residents can report environmental pollution problems in real - time through mobile applications or community platforms, enhancing the transparency and public participation in environmental governance.

Finally, this study has identified a substitution effect between environmental regulation and energy technology innovation, meaning that as energy technology innovation improves, the effectiveness of environmental regulation may weaken. To address this issue, the government should take the following measures in policy design: First, establish a policy - coordination mechanism to ensure that while promoting energy technology

innovation, the intensity of environmental regulation is maintained or even appropriately increased. This can prevent a reduction in environmental - governance investment due to technological innovation. Second, introduce a dynamic - adjustment mechanism to flexibly adjust the intensity of environmental regulations based on the progress of energy technology innovation and changes in environmental quality. This ensures the continuous improvement of environmental quality. Third, through fiscal incentives such as tax breaks and subsidies, encourage companies to simultaneously engage in environmental governance and technological innovation. This maximizes the synergistic effect of environmental regulation and energy technology innovation, promoting the comprehensive improvement of residents' health.

Limitations

This study provides a more comprehensive analytical perspective by integrating micro and macro data, revealing the positive impact of environmental regulations and energy technology innovation on residents' health. This finding not only supports the core viewpoint of the environmental - exposure - and - health theory but also offers a scientific basis for policymakers. It indicates that strengthening environmental regulations and promoting energy technology innovation can effectively improve residents' health, promote social equity, and foster inclusive development. Additionally, the heterogeneity analysis results of this study can serve as a reference for other countries in formulating more targeted environmental policies, especially in balancing economic growth and environmental protection. However, this study has certain limitations.

Firstly, in the empirical testing process, this study used the indicator of residents' self - rated health. However, residents' self - rated health may be highly subjective and may not fully reflect their actual health status. Therefore, in future research, it is desirable to obtain more objective indicators reflecting residents' health levels, although this may be constrained by funding. This will enable a more in - depth exploration of the impact of environmental regulations and energy technology innovation on residents' health.

Secondly, although this study empirically verified the positive impact of environmental regulations and energy technology innovation on residents' health, there are still some data limitations that may affect the research results. For example, CGSS data may not cover certain remote areas or specific populations, which limits the generalizability of the research findings. Moreover, the data in the China Statistical Yearbook and the China National Intellectual Property Administration may be subject to late reporting or omission, affecting the accuracy of environmental - regulation and energy - technology - innovation data. Future research can expand the sample coverage and adopt more up - to - date data sources to further validate the conclusions of this study.

Global significance of China's experience

The main reasons for choosing China as the research object in this study are as follows: Firstly, as the world's largest developing country, China has achieved rapid industrialization in a relatively short period. However, it also faces severe environmental pollution problems. Despite this, China has managed to strike a balance between economic development and environmental governance, achieving remarkable results in both aspects. For example, China's environmental policies have provided valuable practical experience for global environmental governance. Secondly, as the largest developing country, China's environmental governance and the application and promotion of renewable - energy technologies offer valuable technological paths for other countries to learn from. In contrast, developed countries such as the United States and EU countries have started earlier in environmental governance and energy technology innovation, but their policy effects and technological paths may not be fully applicable to developing countries. Therefore, studying China's experience not only helps to understand the potential of developing countries in environmental governance and health improvement but also provides new ideas for formulating global environmental policies.

Analyzing China's experience has important implications for global environmental governance and health policies. Firstly, China's experience demonstrates that strong environmental regulations and energy technology innovation can effectively improve residents' health, especially in reducing air and water pollution. This conclusion is of great reference significance for other developing countries facing similar environmental problems, such as India and Indonesia. Secondly, China's successful experience in energy technology innovation, such as the promotion and application of renewable - energy technologies, provides a feasible technological path for the global transition to green energy. Finally, the heterogeneity analysis of this study (such as age, gender, and urban - rural differences) can be used as a reference for other countries to develop more targeted environmental policies, especially in balancing economic growth and environmental protection.

Acknowledgements
The above statements are correct and in line with reality.

Author contributions
Yang Xifeng independently collected, summarized, and analyzed the data, and completed the paper.

Funding
This study did not receive any financial support.

Data availability
Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate
The CGSS data used in this study has been introduced in the questionnaire survey description, including the purpose, social value, scope of information collection, as well as the signatures and contact information of the researchers and research institutions.
①. Prior to conducting the study, a voluntary informed consent form has been obtained from the study participants. The research content and purpose are within the scope of standardized informed consent.
②. This study conducted research using anonymized information data.
③. This study does not cause harm to the human body and does not involve sensitive personal information or commercial interests.
Based on this, this study complies with the basic principles of the Helsinki Declaration and meets the ethical exemption requirements of the "Ethical Review Measures for Research Involving Human Life Sciences and Medical Sciences" issued by China, which can exempt ethical review.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 22 December 2024 / Accepted: 22 April 2025
Published online: 02 May 2025

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