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Environmental pollution, trade openness and the health of middle-aged and elderly people: an analysis of threshold effect based on data from 111 prefecture-level cities in China

Jin-Dan Zhang[1†], Xiao-Fen Cheng[1], Yan-Ting He[1], Lu-Shi Kong[1], Duo Chen[1], Yi-Li Zhang[1*] and Bei Li[1*]

Abstract

Background Environmental pollution seriously endangers people's physical and mental health, especially the health of middle-aged and elderly people. Environmental pollution, trade openness, and population health are interconnected. Environmental pollution may have a nonlinear impact on health, and the impact of trade openness on the health effects of environmental pollution may not be a simple strengthening or weakening effect. However, few studies have used threshold effects model to explore the nonlinear mechanisms of environmental pollution's impact on health in China. As a result, this study incorporates trade openness into the research framework on the health effects of environmental pollution, aiming to study the mechanism of environmental pollution on health.

Methods Using the China Health and Retirement Longitudinal Study (CHARLS) data from 2013 to 2020 and the data of 111 prefecture-level cities in China, we combine two-way fixed-effects models and threshold models to explore the effects of environmental pollution on the health of middle-aged and elderly people and the role of trade openness in the path of environmental pollution affecting health.

Results Environmental pollution impairs the health of middle-aged and elderly people, and there is a single threshold effect and regional heterogeneity in this negative impact. Trade openness has the effect of first weakening and then strengthening in the inhibitory effect of environmental pollution on health.

Conclusion The negative impact of environmental pollution on health has regional heterogeneity, and there is a nonlinear relationship between environmental pollution and the health of middle-aged and elderly people. The health effect of environmental pollution is mainly long-term effect, and trade openness has a threshold effect on the

†Jin-Dan Zhang is the first author.

*Correspondence:
Yi-Li Zhang
zhangyi1223882953@163.com
Bei Li
45510307@qq.com

Full list of author information is available at the end of the article

impact of environmental pollution on health. Therefore, instead of adopting a one-size-fits-all policy, environmental and economic policies should be customized according to the degree of environmental pollution, trade openness, and regional variations, so as to safeguard the health of middle-aged and elderly individuals through effective environmental governance.

Keywords Environmental pollution, Health of middle-aged and elderly people, Trade openness, Threshold model

Text box 1. Contributions to the literature

- This study is the first attempt to use threshold effect model to investigate the nonlinear relationship between environmental pollution and the health of middle-aged and elderly people, and the mechanism of trade openness in the pathway of environmental pollution's impact on health.
- The negative health effects of environmental pollution are cumulative and regionally heterogeneous, which suggests that we should take timely and targeted environmental governance policies for different regions.
- Attention should be paid to the threshold effect of trade openness in environmental pollution affecting health in order to balance the relationship between economic development and ecological environment.

Background

Environmental pollution is considered to affect climate change, causing a sharp decline in biodiversity and destroying the overall ecological balance. Not only does it threaten the well-being of the planet, but it also poses a crisis to the survival and development of human beings. A research report from the Lancet pointed out that about 9 million people worldwide suffer from diseases and premature deaths annually due to environmental problems such as air, water, and soil pollution [1]. There are significant differences in the impact of environmental pollution on the health of people of different ages [2]. Middle-aged and elderly people are in the stage of physiological function and immune function decline. Compared with young people, they are more vulnerable to ecological environment sensitivity [3]. At present, the degree of global population aging is deepening, and China is also facing the socio-economic problems brought about by the acceleration of the aging process. Healthy aging may be an effective measure to actively respond to the aging of the population. Hence, paying attention to the role of environmental pollution on the health of middle-aged and elderly people and controlling environmental pollution has become an important task for maintaining social stability and sustainable development. Industrial pollutant emissions have been recognized by scholars as one of the major sources of environmental pollution [4]. For example, industrial nitrogen oxides and industrial smoke and dust emissions contribute to air pollution [5, 6], while industrial wastewater discharge is an important cause of water pollution [7], and industrial solid waste emission leads to soil pollution [8]. Many examples of environmental pollution endangering public health have shown that environmental pollution caused by industry is closely related to human health, as demonstrated by historical incidents like Minamata disease in Japan, the photochemical smog incident in Los Angele, the United States, and the smog incident in London, the United Kingdom. Therefore, environmental governance actions should be carried out with a focus on industrial pollution emissions.

The mainstream research on the health effects of environmental pollution is theoretically based on the health production function initiated by Crossman in 1972 [9]. Subsequently, in 1986, Gerking and Stanley incorporated environmental factors into the health production function and constructed an analytical framework for environmental factors affecting health depreciation rates [10]. According to the theory of the health production function, we know that the natural environment has an impact on human health, the economy is also one of the social determinants of health, as evidenced by previous studies. For example, the development of digital finance contributes to the improvement of the overall and mental health of residents at low socioeconomic levels [11]. Trade openness has built a bridge for the circulation of knowledge, information, and technology in various industries around the world, such as healthcare, education, and culture, promoted transnational cooperation and trade globalization, and has a profound impact on residents' health. Since the reform and opening up, China's trade openness has gradually increased [12], which has contributed to the rapid growth of China's economy and improved the level of health care and education, but also brought about environmental pollution problems [13]. As an important part of national economies, trade openness is closely linked to technological innovation in industrial production and industrial structure. Promoting green innovation and environmental governance therefore also requires attention to trade openness.

A review of past studies reveals that many scholars have discussed the health effects of environmental pollution and the relationship between trade openness and environmental pollution.

Firstly, the linear relationship between environmental pollution and health. Previous studies have confirmed the close relationship between environmental pollution and health. Based on longitudinal data from two waves of the Chinese Family Panel Study (CFPS), Liao L et al. used the recentered influence function regressions method to find that environmental pollution magnified people's income-related health inequality [14]. In the existing literature, environmental pollution is considered to threaten people's health mainly from the following two aspects. On the one hand, environmental pollution damages physical health. For example, drinking contaminated water may cause parasitic diseases [15], acute gastrointestinal diseases such as diarrhea [16], and even life-threatening [17]. Bishop KC et al. found that long-term exposure to fine particulate matter air pollution was associated with Alzheimer's disease in the elderly [18]. Studies have also shown that air pollution may lead to reduced sleep time and physical exercise time [19], reduces life expectancy and increases the risk of cardiovascular and respiratory diseases [20–22]. Zhang HW et al. used Monte Carlo simulation to evaluate the health risks of heavy metals in the Zhundong mining area in Xinjiang and found that the soil polluted by heavy metals is harmful to people's health [23]. On the other hand, environmental pollution may have a negative impact on mental health. Yao HH et al. used a propensity score matching method to study the relationship between dusty weather exposure and the degree of cognitive impairment in the elderly. They found that the elderly living in dusty weather areas for a long time had higher cognitive impairment than those living in other areas [24]. Air pollution may cause negative emotions by reducing personal outdoor work and social activity time. Many studies have confirmed that exposure to pollutants such as PM2.5, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) increases the number of outpatient or inpatient visits for depression and anxiety disorders or hospitalizations [25, 26], and increases the risk of suicide [27]. Thus, we propose Hypothesis 1 (H1): Environmental pollution is negatively correlated with the health of middle-aged and elderly people.

Secondly, the regional heterogeneity in the health impacts of environmental pollution. The impact of environmental pollution on health may be heterogeneous due to the regional differences in the degree of environmental pollution, ecological purification capacity, population density, and economic and social policies. Butt EW, et al. found that there were regional differences in the health burden attributable to ambient PM2.5 [28]. China has a vast territory, and there are huge differences in ecological conditions and cultural conditions between its eastern and western regions. In addition, China has adopted an economic policy of prioritizing the development of the eastern coastal regions [29], which has aggravated the imbalance of social and economic development in eastern and western China. These may be the reasons for the differences in the regional environmental pollution degree. Therefore, there may also be regional variability in the health effects of environmental pollution in China. Based on the above analyses, we propose Hypothesis 2 (H2): There is regional heterogeneity in the effects of environmental pollution on the health of middle-aged and elderly people.

Thirdly, the non-linear effects of environmental pollution on health. Yan ML et al. used generalized linear models (GLM) and segmented linear regression models to analyze the concentration-response relationship between PM2.5 and mortality in Beijing, China. The results showed that there was a nonlinear relationship between PM2.5 and mortality [30]. Chen Q et al. found that cumulative exposure to air pollutants for nearly one month would increase the mortality of ischemic heart disease through the Poisson generalized additive model (GAM). They validated the cumulative effect of the health risks of air pollution [31]. It has also been found in the literature that the health effects of environmental pollution are related to the concentration of pollutants [32]. It can be seen that the impact of environmental pollution on health may be stage-specific, that is, the effects of different degrees of environmental pollution on the health of middle-aged and elderly people may be different. When the negative health effects of environmental pollution have not yet appeared or are small, people tend to ignore its hazards, thus delaying environmental governance and leading to more serious environmental pollution. However, most of the current studies on the health impact of environmental pollution have used ordinary least squares (OLS), GLM, and GAM to explore the correlation. Nevertheless, there is a lack of literature on the use of threshold models to study the nonlinear effects of environmental pollution on health in China. Consequently, we propose Hypothesis 3 (H3): There is a threshold effect of environmental pollution on the health of middle-aged and elderly people.

Fourth, the mechanism of trade openness on the health effects of environmental pollution. The impact of trade openness on the environment has attracted much attention, but there has been a debate in the academic community about the positive and negative effects of this impact. There are two main points of view in previous studies: one is that trade openness exacerbates environmental pollution. With the deepening of trade openness, the 'pollution haven effect' emerges. Enterprises in some countries with strict environmental regulations would transfer production or industries with high pollution emissions and low product-added value to developing countries with relatively loose environmental regulations, and at the same time transfer environmental costs. Peng X and Pu Y found that trade openness increased emissions of pollutants such as SO_2 and industrial smog [33]. A study with a sample of China, Japan, and Korea, found that trade openness is directly linked to carbon emissions and is indirectly related through three main effects:

scale effect, technology effect, and structural effect [34]. Another view is that trade openness is conducive to alleviating environmental pollution. Scholars holding this view believe that economic development is the driving force of green innovation and the environmental performance of enterprises [35]. Trade openness can promote the survival of the fittest in the market, push local enterprises to increase the input of green production factors [36], promote the upgrading of the industrial structure, and reduce carbon emissions [37]. Our review of the existing literature finds that trade openness has also been proven to be an important factor affecting population health. For example, a study found that competition from trade openness increased injury rates among United States manufacturing workers [38]. Some studies have found that trade openness is associated with " desperate deaths " such as drug overdoses, suicides, and liver disease [39]. The research on the relationship between trade openness and health is mostly discussed from the perspective of social economy, and few studies are conducted from the perspective of the impact of environmental pollution on health. Residents' health is affected by both environmental pollution and trade openness. Environmental pollution, trade openness, and health are interconnected and the mechanism is complex. To promote the health of middle-aged and elderly people, it is necessary to examine whether the impact of environmental pollution on their health is affected by trade openness. As a result, we propose Hypothesis 4 (H4): There is a threshold effect of trade openness in the inhibitory effect of environmental pollution on health.

In view of the analysis above, based on the data from 111 prefecture-level cities in China from 2013 to 2020, we put environmental pollution, trade openness, and health of middle-aged and elderly people into a research framework, and examine the direct and nonlinear effects of environmental pollution on the health by constructing two-way fixed effects regressions and threshold regressions model. The regional heterogeneity of the health effects of environmental pollution is discussed and the threshold effect of trade openness in the impact of environmental pollution on health is explored in order to provide help for China's environmental pollution management and improve the health of middle-aged and elderly people.

Materials and methods

Data description

The health data for this study are derived from the China Health and Retirement Longitudinal Study (CHARLS), a survey organized by the National Development Research Institute of Peking University (NDRI). CHARLS focuses on the middle-aged and elderly population aged 45 years and above in China, which uses a four-stage random sampling method at the county-village-household-individual level to obtain samples. The survey covers a large sample size of more than 17,000 people in 150 county-level units and 450 village-level units in 28 provinces in China. This data contains multi-dimensional information such as personal health status, family situation, income and expenditure, and work or retirement of the research object, which is an important source of data for scientific research on aging. Informed consent was obtained from all respondents. Each round of CHARLS was approved by the Biomedical Ethics Review Board of Peking University (No. IRB00001052-11015). Considering the principles of data availability, consistency, and completeness, this study uses four periods of follow-up data from 2013, 2015, 2018, and 2020, and deleted samples under the age of 45 and those with missing values in key variables. The data at the prefecture-level city level are derived from the China Statistical Yearbook, China City Statistical Yearbook, National Economic and Social Development Statistical Bulletin, China Environmental Statistical Yearbook, China Health Statistical Yearbook, and local government work reports. A few missing values in the key variables are complemented by linear interpolation or mean value method. After matching the micro data with the city-level data, we obtain balanced panel data containing 111 prefecture-level cities and 22,736 valid observations.

The Hu Huanyong line (Hu line), also known as the "Aihui-Tengchong" line (Aihui is now renamed Heihe), is the boundary of China's population distribution proposed by Chinese geographer Hu Huanyong in the 1930s [40]. The areas on both sides of the Hu line show great differences in ecological carrying capacity, natural environment, economic development, and humanity. Therefore, in this paper, the Hu line is used as the dividing line between the eastern and western regions of China, and a dummy variable is constructed with this line as the boundary. The area east of the Hu line is assigned a value of 1, and the area west of the Hu line is assigned a value of 0 to study the regional heterogeneity of the health effects of environmental pollution.

Variable selection

Dependent variable: health (Health)

The existing literature mainly uses self-rated health, mental health, disease incidence, mortality, and other indicators to characterize the health status. Considering the availability and consistency of data, we refer to the existing literature [41, 42] and measure the health status of middle-aged and elderly people through the Activity of Daily Living Scale (ADL). The ADL score is obtained by adding up the scores of six basic activities: bathing, dressing, eating, toileting, getting in and out of bed, and controlling urination and defecation, with responses of "no difficulty", "difficulty but still able to do it", "difficulty and need help", "unable to do it" being assigned a score of 3−0, respectively. ADL scores range from 0 to 18, with higher scores representing higher levels of health.

Independent variable: environmental pollution (POL)

Concerning the degree of environmental pollution, some studies have comprehensively measured it from multiple dimensions such as air, solid waste, and water [43], while others have used a single pollution indicator as a proxy variable for environmental pollution [44]. In China, industrial waste emissions such as industrial waste gas and waste water are the main sources of environmental pollution [4]. In order to evaluate the degree of environmental pollution more comprehensively and avoid the deviation caused by human factors, based on the data of industrial sulfur dioxide emission, industrial smoke and dust emission, and industrial wastewater emission from the China City Statistical Yearbook, we use the entropy weight method to assign certain weights to each of the three indicators, and then calculate the environmental pollution index to characterize the level of environmental pollution in cities. The weight calculation steps of the three indicators are as follows:

Firstly, after determining that the three environmental pollution indicators are all negative indicators, we use the following formula to standardize them:

$$y_{ij} = \frac{maxx_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}} + 0.0001,\ 1 \leqslant i \leqslant m,\ 1 \leqslant j \leqslant n$$

y_{ij} represents the standardized value of the index j in city i and x_{ij} is its original value.

Secondly, after calculating the proportion of index j in city i, we calculate the entropy of index j, e_j.

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}},\ 0 \leqslant p_{ij} \leqslant 1$$

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} p_{ij} lnp_{ij},\ 0 \leqslant e_{ij} \leqslant 1$$

Thirdly, we need to calculate the information entropy redundancy g_j.

$$g_j = 1 - e_{ij}$$

Fourthly, we finally determine the weights of the indicators w_j.

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j}$$

Threshold variable: trade openness (OPEN)

Previous studies have used the ratio of total imports and exports to GDP, that is, foreign trade dependence [45], and foreign direct investment (FDI) [46] as proxy variables for trade openness. Since FDI only reflects the inflow of foreign capital, we use a more comprehensive index of foreign trade dependence to measure the degree of trade openness. The larger the value, the greater the degree of trade openness.

Control variables

Medical level (lnMED): The city medical level affects the accessibility of medical resources to the residents and is closely related to their health [47]. Accordingly, we use the number of medical and health institutions to indicate the level of the city, which is logarithmized to reduce the effects of heteroscedasticity and non-stationarity.

Environmental regulation (ER): The frequency of environment-related words mentioned in the government work reports can reflect the importance that the local government attaches to environmental issues and the intensity of environmental regulation. Scholars generally believe that the intensity of environmental governance will directly affect the degree of environmental pollution [48]. Therefore, this study refers to Chen Z et al. [49], and retrieves the frequency of environmental-related words such as "environmental protection", "pollution", "energy consumption", "emissions reduction", "low carbon", "ecology", "green" and "PM2.5" in the government work reports of various cities in 2013, 2015, 2018 and 2020, and calculates the proportion of word frequency in the total number of words to characterize environmental regulation.

Industrial structure (IND): Industrial structure is a typical indicator of environmental conditions and is related to environmental quality [50]. Additionally, industrial structure may also be contributing to the development of healthcare, thereby promoting public health. So we use the ratio of tertiary industry output to secondary industry output as a proxy variable for industrial structure.

Human capital (HC): Some researchers have verified the correlation between pollution and productivity from the perspective of human capital [51], and health human capital also affects public health. So it is reasonable to use human capital as a control variable, and we select the ratio of the number of people with a general college degree or higher to the total population to measure the level of regional human capital.

Descriptive statistics for the variables are shown in Table 1.

Table 1 Descriptive statistics of variables ($N=22736$)

Variable	Mean	SD	Min	Max
ADL	17.0046	2.1858	0.0000	18.0000
IADL	16.0743	3.6421	0.0000	20.0000
Total	33.0789	5.3107	0.0000	38.0000
POL	16.9854	1.0828	13.5534	20.1824
pol	16.4207	1.0821	12.9897	19.6165
OPEN	0.1410	0.1814	0.0006	2.1850
lnMED	8.0698	0.7914	4.4308	9.9486
ER	0.0034	0.0014	0.0004	0.0124
IND	1.0766	0.4568	0.3125	5.2982
HC	0.0191	0.0266	0.0000	0.1330

Models and methods

Two-way fixed effects regression model

The health production function theory proposed by Crossman regards health as both a consumer and an investment good, integrating the effects of various factors on health, including economy, healthcare, health human capital, and education [9, 43]. In order to explore the impact of environmental pollution on the health of middle-aged and elderly people, based on the theoretical framework of the health production function, we select environmental pollution as an input factor of health production and construct a baseline regression model. Since the data used in this study are balanced panel data, we use the Hansman test to select the appropriate panel data regression model among the random effects model (RE) and fixed effects model (FE). According to the Hansman test results, the fixed effect model is more effective in this study. Therefore, we construct a two-way fixed effects regression model to eliminate the influence of uncontrollable factors at the city level and time level. Previous studies exploring the health effect of a certain factor have also used the fixed effects regression models [52, 53]. The model is as follows:

$$Health_{ijt} = \alpha_0 + \alpha_1 POL_{jt} + \alpha_2 C_{it} + \mu_j + \nu_t + \varepsilon_{ijt} \tag{1}$$

In Eq. (1), $Health_{ijt}$ is the dependent variable of this paper, which represents the health status of individual i in city j in year t. POL_{jt} is the independent variable in this article, indicating the degree of environmental pollution in the city j in year t. C_{jt} is a series of control variables, including medical level (lnMED), environmental regulation (ER), industrial structure (IND), and human capital (HC). μ_j is the city fixed effect, v_t denotes the year fixed effect. ϵ_{ijt} represents the random disturbance term.

Threshold effect model

The threshold effect model is a standard method to describe the characteristics of skip or structural break and to test whether there is a threshold effect between variables [54]. Threshold effect refers to the phenomenon of a change in the direction or amount of an independent variable when the threshold variable reaches a certain inflection point value [54]. The threshold variable can be the independent variable itself [55] or another new variable [56]. This method was proposed by Hansen in 1999 [57]. When there is a nonlinear relationship between variables, the threshold regression model can divide the interval endogenously according to the characteristics of the data [56], avoiding the deviation caused by artificial division of the interval. Threshold regression has been widely used in the study of the nonlinear relationship between economic development and environmental pollution [55, 56, 58].

Previous studies have shown that the impact of environmental pollution on the health of middle-aged and elderly people varies at different stages [30, 32]. In order to further investigate the nonlinear relationship between environmental pollution and health, we refer to Hansen's panel threshold regression model and construct a threshold regression model with environmental pollution itself as the threshold variable:

$$\begin{aligned} Health_{ijt} = \beta_0 + \beta_1 POL_{jt} I\left(POL_{jt} \leqslant \mathrm{Th1}\right) \\ +\beta_2 POL_{jt} I\left(POL_{jt} > \mathrm{Th1}\right) \\ +\beta_3 C_{it} + \mu_i + \nu_t + \varepsilon_{ijt} \end{aligned} \tag{2}$$

In addition, previous studies have confirmed that trade openness is associated with environmental pollution [33–35], and trade openness is also an influencing factor on health [38, 39]. However, research on the relationship between trade openness and health lacks a discussion from the perspective of the impact of environmental pollution on health. In order to further explore the mechanism of environmental pollution on the health of middle-aged and elderly people, based on Crossman's theory of health production function, we introduce trade openness as a threshold variable into the health production function model with environmental pollution as the key input factor. And then we conduct regression analysis on how environmental pollution affects the health of middle-aged and elderly people with the change of trade openness. The model is as follow:

$$\begin{aligned} Health_{ijt} = \gamma_0 + \gamma_1 POL_{jt} I\left(OPEN_{jt} \leqslant \mathrm{Th1}\right) \\ +\gamma_2 POL_{jt} I\left(OPEN_{jt} > \mathrm{Th1}\right) \\ +\theta C_{it} + \mu_i + \nu_t + \varepsilon_{ijt} \end{aligned} \tag{3}$$

Before estimating the model, it is necessary to estimate the threshold number and threshold value of the threshold model. Based on the research idea of panel threshold model, we refer to the existing studies [54, 55] and use Bootstrap sampling method Bootstrap [59] to conduct the existence test of the panel threshold model with environmental pollution and trade openness as the threshold variables. That is, the following three sets of hypotheses are tested with two threshold variables respectively:

(i) HI 0: there is no threshold, HI 1: there is one threshold;
(ii) HII 0: there is only one threshold; HII 1: two thresholds exist;
(iii) HIII 0: there is only two threshold; HIII 1: three thresholds exist.

Equations (2) and (3) show the case when there is a single threshold effect. If the existence test of double threshold effect is passed, Eqs. (2) and (3) will be further extended to Eqs. (4) and (5), respectively. The models are as follow:

$$\begin{aligned} Health_{ijt} = \beta_0 + \beta_1 POL_{jt} I\left(POL_{jt} \leqslant Th1\right) \\ +\beta_2 POL_{jt} I\left(Th1 < POL_{jt} \leqslant Th2\right) \\ +\beta_3 POL_{jt} I\left(POL_{jt} > Th2\right) \\ +\theta\, C_{it} + \mu_i + \nu_t + \varepsilon_{ijt} \end{aligned} \tag{4}$$

$$\begin{aligned} Health_{ijt} = \gamma_0 + \gamma_1 POL_{jt} I\left(OPEN_{jt} \leqslant Th1\right) \\ +\gamma_2 POL_{jt} I\left(Th1 < OPEN_{jt} \leqslant Th2\right) \\ +\gamma_3 POL_{jt} I\left(OPEN_{jt} > Th2\right) \\ +\theta\, C_{it} + \mu_i + \nu_t + \varepsilon_{ijt} \end{aligned} \tag{5}$$

In Eqs. (2)-(5), *I(.)* are the indicator functions, POL_{jt} and $OPEN_{jt}$ are the threshold variables, $Th1$ and $Th2$ denote the threshold values to be estimated.

Results

Two-way fixed effects regression results

Before regression, we use the Hansman test to select the appropriate panel regression model in the random effect model (RE) and the fixed effects model (FE). The result of the Hansman test showed that the p-value was 0.0166, which passed the significance test at the 5% level. Therefore, we use the fixed effects model (FE) for regression in this study.

In this paper, based on four periods of balanced panel data in 2013, 2015, 2018, and 2020, we use the two-way fixed effects regressions model to demonstrate the impact of environmental pollution on the health of middle-aged and elderly people. The results are shown in column (1) of Table 2. The regression coefficient of the dependent variable, environmental pollution, is -0.0582 and passes the test of significance at the 5% level, which indicates that environmental pollution significantly reduces the daily living ability of middle-aged and elderly people, that is to say, environmental pollution has a significant inhibitory effect on the health of middle-aged and elderly people. It can be seen that the hypothesis H1 proposed in this study is verified. In terms of control variables, the regression coefficient of the medical level is significantly positive, indicating that a high level of medical care can promote the health of middle-aged and elderly people.

Table 2 Two-way fixed effects regression results

	(1)	(2)	(3)
	Health	**Health**	**Health**
POL	-0.0582**	-0.0615**	0.4439
	(0.0284)	(0.0289)	(0.3067)
lnMED	0.0635*	0.0617	1.1411
	(0.0375)	(0.0379)	(1.2983)
ER	-4.7010	-2.2236	-1.4436
	(11.4206)	(11.8789)	(79.0225)
IND	-0.0480	-0.0022	0.1997
	(0.0630)	(0.0679)	(0.4058)
HC	-3.2778	-4.4323*	43.1638
	(2.5450)	(2.5899)	(28.7488)
_cons	17.9489***	18.0003***	0.0813
	(0.5451)	(0.5488)	(11.7844)
City fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	22,736	21,788	948
R^2	0.031	0.030	0.068

Standard errors in parentheses

***, **, and *, respectively, indicates significance at the 1%, 5%, and 10% level

Regional heterogeneity

To demonstrate the degree of environmental pollution in different regions more intuitively, we take 2020 as an example, calculate the environmental pollution index based on the environmental pollution data of Chinese cities using the entropy weight method, and use ArcGIS10.8 software for visual mapping, as shown in Fig. 1. We divide the degree of environmental pollution according to the value of the environmental pollution index as follows: low (≤14.88435), slightly low (14.884351–16.02036), medium (16.020361–17.07446), slightly high (17.074461–17.98784) and high (17.987841–20.18237). It can be found that the majority of the high level of environmental pollution is concentrated in the southeastern coastal area of China.

Table 2, columns (2) to (3) examine the effect of environmental pollution on the health of middle-aged and elderly people in the area east of the Hu line and west of the Hu line, respectively. The coefficient of environmental pollution in the area east of the Hu line is significantly negative at the 5% level, while the impact of environmental pollution on health in the area west of the Hu line is not significant, which verifies the hypothesis H2 in this

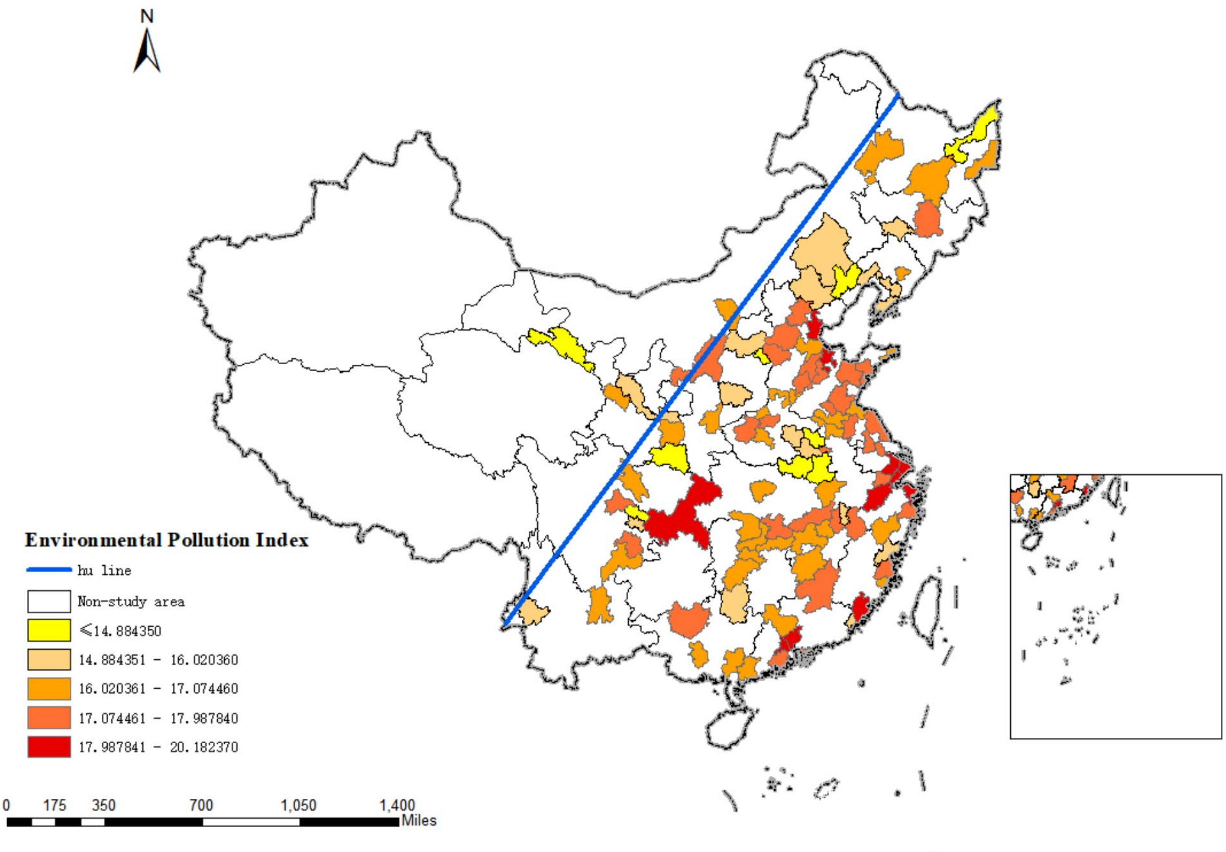

Fig. 1 Map of the environmental pollution index of 111 prefecture-level cities in China in 2020

Table 3 Robustness test results

	(1)	(2)	(3)
	Health	**Total**	**Health**
POL		-0.1264**	-0.0706**
		(0.0644)	(0.0293)
pol	-0.0582**		
	(0.0284)		
lnMED	0.0635*	0.1656*	0.0756**
	(0.0375)	(0.0849)	(0.0384)
ER	-4.7024	-15.9264	2.3408
	(11.4206)	(25.8850)	(11.9929)
IND	-0.0479	0.0657	-0.0364
	(0.0630)	(0.1429)	(0.0678)
HC	-3.2782	-2.0385	-1.7814
	(2.5450)	(5.7683)	(5.3240)
_cons	17.9159***	34.7760***	17.9854***
	(0.5322)	(1.2354)	(0.5532)
City fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	22,736	22,736	19,744
R^2	0.031	0.034	0.031

Standard errors in parentheses

***, **, and *, respectively, indicates significance at the 1%, 5%, and 10% level

study. Combined with Fig. 1, we speculate that the reason for this difference may be that the level of industrial development in the west of Hu line is lower than that in the east of Hu line. The emissions of industrial sulfur dioxide, industrial smoke and dust, and industrial wastewater are relatively low in the western region.

Robustness test

For verifying the robustness of the two-way fixed effects regression, this study conducts robustness tests in three ways. The first way is to replace the method of the independent variable calculation. Referring to the existing article [45], we take the logarithm after averaging the three industrial pollutant emission indicators to represent environmental pollution (pol). The results are shown in column (1) of Table 3, where the coefficient of environmental pollution is significantly negative at the 5% level. The second method is to replace the dependent variable. We use the sum of activities of daily living (ADL) and instrumental activities of daily living (IADL) scores to measure the health of middle-aged and elderly people. The results of column (2) in Table 3 show that the

Table 4 The results of the existence test of threshold effects

Threshold variable	Threshold test	F-value	*P*-value	Crit10	Crit5	Crit1	bootstrap
POL	Single	20.02	0.0200	13.8101	16.0294	21.1721	300
	Double	22.11	0.0367	13.9202	20.3128	41.1435	300
	Triple	12.70	0.2267	16.4595	19.8527	26.7923	300
OPEN	Single	19.63	0.0233	16.2743	17.9100	20.8535	300
	Double	16.12	0.0400	13.5345	15.4818	23.9521	300
	Triple	18.71	0.3033	28.5090	32.1717	40.3153	300

coefficient on environmental pollution is -0.1264, which is significantly negative at the 5% level.

The disparity between city levels may bring errors to the analysis results, so we use the third method to exclude the four major municipalities and provincial capitals in China before conducting the regression. The results of Column (3) in Table 3 show that environmental pollution still has a negative impact on the health of middle-aged and elderly people. The results of all three tests above prove the robustness of the regression results.

Threshold effect analysis

Threshold effect test

Before estimating the model, it is necessary to estimate the threshold number and threshold value of the model. Based on the idea of the panel threshold model, we use the Bootstrap sampling method to test the panel threshold model with environmental pollution and trade openness as threshold variables.

Firstly, this study sets environmental pollution as the threshold variable to test the existence of the threshold effect, and the results are shown in Table 4. The *P*-value of the single threshold model F-statistics is 0.02, and the double threshold model is 0.0367, both of which are significant at the level of 5%. The *P* value of the triple threshold model is 0.2267, which does not pass the significance level test.

It is worth noting that if the original hypothesis of the first group and second groups are rejected and the original hypothesis of the third group is accepted, that is, when the model has a double threshold effect, the coefficients of the core independent variables in all intervals of the first threshold and the second threshold are not significant, indicating that if the effect of environmental pollution on health is divided into three intervals, the health effect of environmental pollution is weak. In fact, there is a significant single threshold effect in the impact of environmental pollution on health. Hence, we believe that when environmental pollution is a threshold variable, there is only a single threshold effect.

In addition, we take trade openness as a threshold variable to verify the threshold number of threshold effects. Table 4 shows that both the single threshold effect and the double threshold effect pass the 5% significance level test. Therefore, we reject the null hypothesis of the first and second groups and accept the null hypothesis of the third group, which means that the model has a double threshold effect.

Table 5 Threshold estimation results

Threshold variable	Threshold test	Threshold estimation	95% confidence interval
POL	Single	19.0203	[18.9086, 19.0951]
OPEN	Single	0.0276	[0.0272, 0.0277]
	Double	0.2881	[0.2622, 0.2891]

Table 6 Threshold regression results

	(1)	(2)	(3)
	Health	Health	Health
POL(POL ≤ 19.0203)	-0.0433		
	(0.0286)		
POL(POL > 19.0203)	-0.0669**		
	(0.0285)		
POL(OPEN ≤ 0.0276)		-0.0611**	-0.0656**
		(0.0284)	(0.0284)
POL(0.0276 < OPEN ≤ 0.2881)		-0.0787***	-0.0523*
		(0.0289)	(0.0285)
POL(OPEN > 0.2881)			-0.0699**
			(0.0290)
_cons	17.6353***	18.0354***	18.0092***
	(0.5508)	(0.5453)	(0.5452)
Controls	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	22,736	22,736	22,736
R^2	0.032	0.032	0.033

Standard errors in parentheses

***, **, and *, respectively, indicates significance at the 1, 5, and 10% level

It can be concluded that the relationship between environmental pollution and the health of middle-aged and elderly people is not a simple linear form. Specifically, the impact of environmental pollution on health has a double threshold effect with trade openness as the threshold variable and a single threshold effect with environmental pollution index as the threshold variable.

Table 5 reports the estimation results and confidence intervals of the threshold values, and Table 6 is the result of the panel threshold regression. The results indicate that the coefficient of environmental pollution is -0.0611 when OPEN ≤ 0.0276, -0.052 when 0.0276 < OPEN ≤ 0.2881, and

−0.0699 when OPEN > 0.2881. All three coefficients of the intervals pass the significance test. It suggests that the impact of trade openness on the health suppression effect of environmental pollution presents a double threshold effect that first weakens and then strengthens.

When POL ≤ 19.0203, the coefficient of environmental pollution is -0.0433; when POL > 19.0203, the coefficient is -0.0669. The environmental pollution in the first threshold interval is at a low level, and the coefficient of the independent variable does not pass the significance test, suggesting that the health suppression effect of environmental pollution at this level is not obvious. However, when the threshold estimate is crossed, the coefficient of environmental pollution is significantly negative at the 5% level and the absolute value of the coefficient increases significantly. As a result, we believe that the health risk of middle-aged and elderly people gradually increases as the level of environmental pollution increases.

We next verify the validity of the estimation results of the single threshold estimation of environmental pollution and the double threshold estimation of trade openness by constructing likelihood ratio function graphs, as shown in Figs. 2 and 3, respectively. The single threshold estimate in Fig. 2 and the two threshold estimates in Fig. 3 are the values when the likelihood ratio statistic LR values are close to 0, they are the lowest point on their respective LR graphs. In the graph, the area below the red dotted line is an interval of candidate thresholds at a 5% significance level, and the lowest points do not exceed the critical value, indicating that the test is passed. All three threshold estimates can be considered to be valid.

Discussion

Environmental pollution is a risk factor for health, which has been confirmed by many studies [14, 60]. When the emission of pollution is unavoidable, the amount and temporal conditions under which this harm occurs become the focus of attention. In addition, the impact of trade openness on the environment and health may be positive or negative. In order to balance the relationship between economic development and the ecological environment, it is necessary to pay attention to whether there is a threshold effect with trade openness as the threshold variable in the impact of environmental pollution

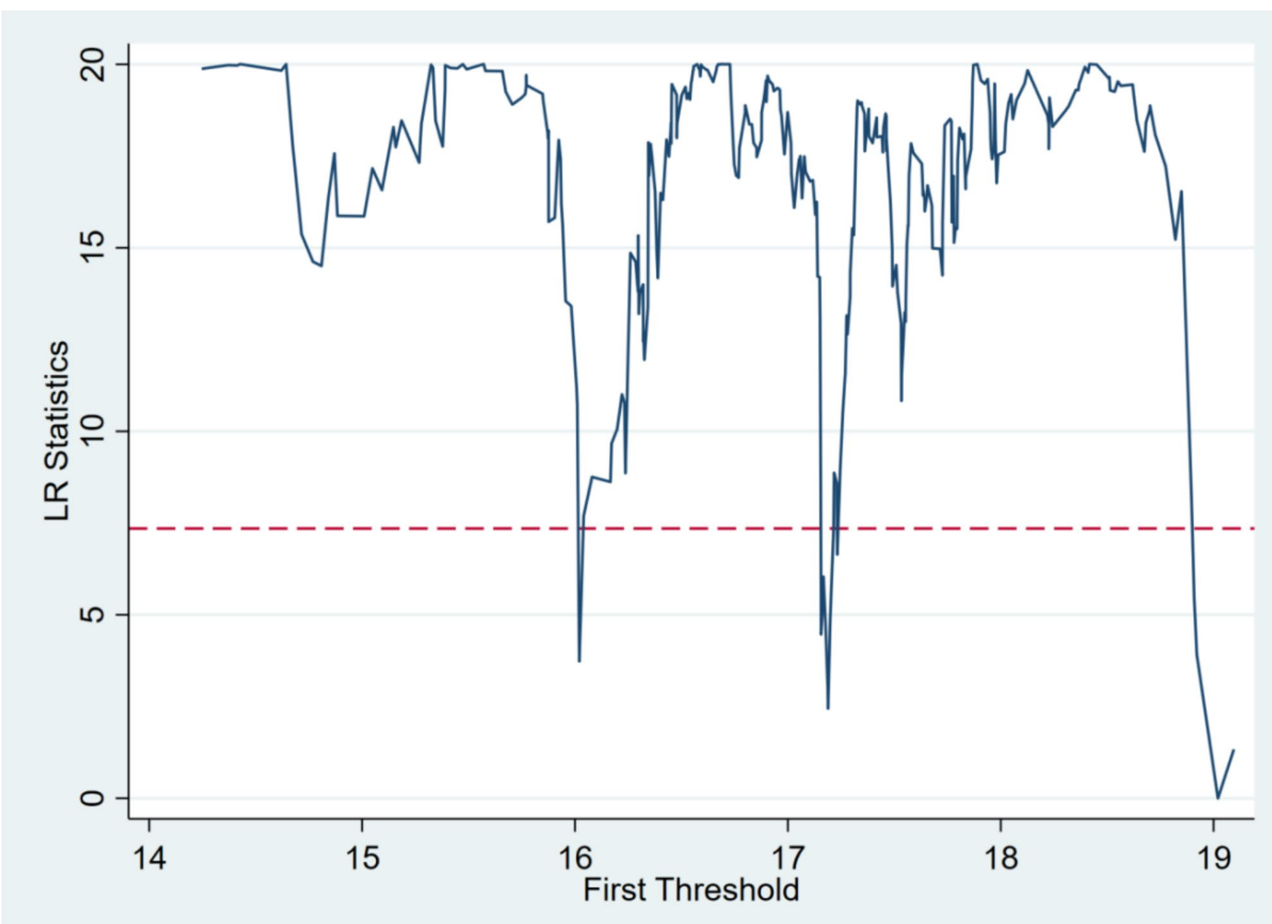

Fig. 2 LR chart of single threshold effect with environmental pollution as threshold variable

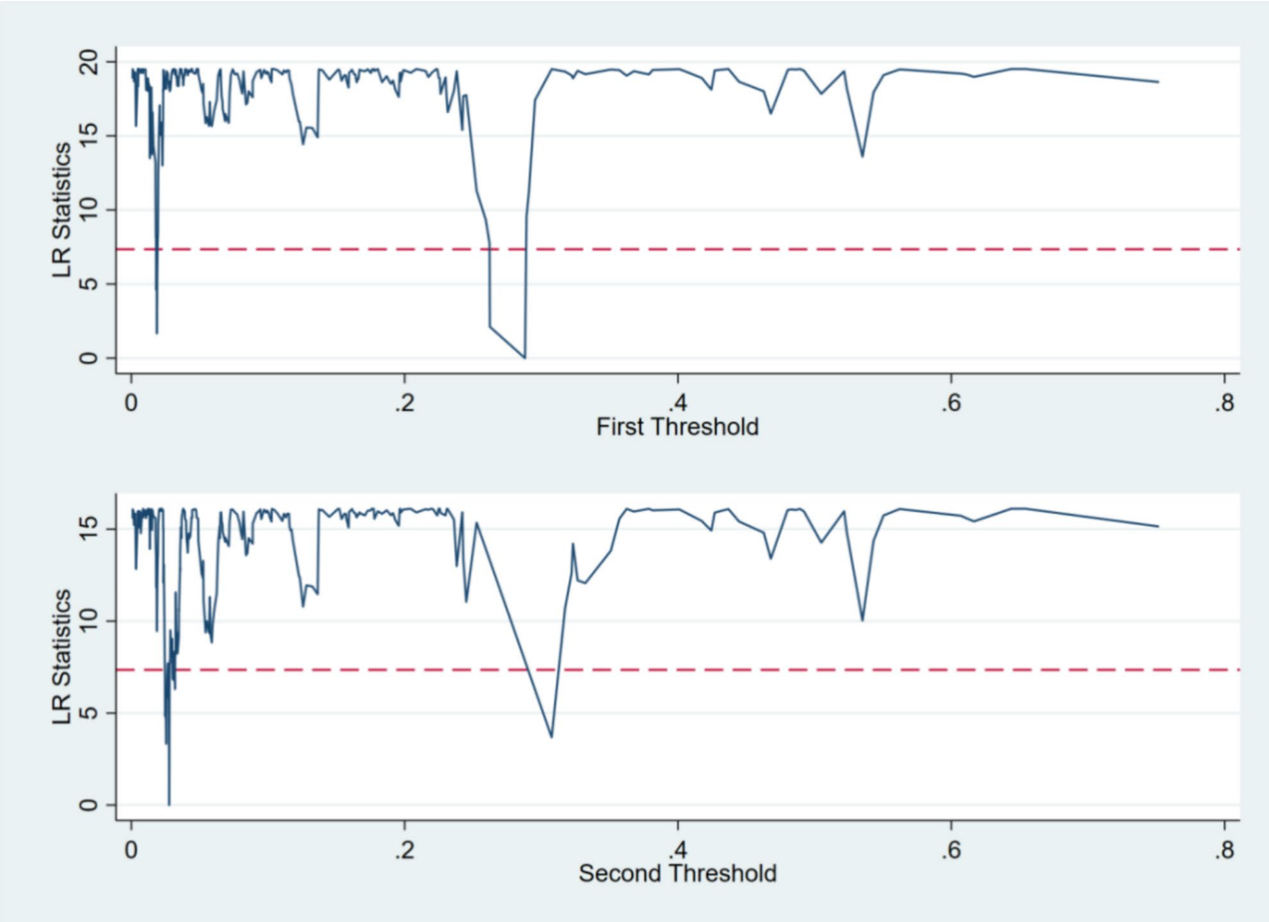

Fig. 3 LR chart of double threshold effect with trade openness as threshold variable

on health. Nevertheless, there is little literature on the nonlinear relationship between environmental pollution, trade openness, and health. Therefore, this paper uses the CHARLS health data from 2013 to 2020 and the corresponding data on environmental pollution and trade openness in 111 prefecture-level cities in China. On the basis of verifying the effect of environmental pollution on the health of middle-aged and elderly people and exploring the regional heterogeneity of this effect, we further study the nonlinear role of environmental pollution in the health effect of environmental pollution and explore whether trade openness has a threshold effect in the health effect of environmental pollution. The results of our study are as follows:

Firstly, from the regression results of two-way fixed effects, it is clear that environmental pollution impairs the health of people and many studies have confirmed this view [61, 62]. For example, a study in the United States discovered that older adults living in areas with high PM2.5 concentrations had worse cognitive functioning than those in areas with low concentrations [3]. Halder JN et al. concluded that pollution of the Turag River in Bangladesh was associated with health problems such as skin, dysentery, and respiratory diseases among residents in the region [63]. Liu H's research showed that the disability reduction effect achieved by the laborious reduction of serious diseases can be achieved through minimal efforts to improve air quality [64]. The results of all these studies showed that environmental pollution would be extremely harmful to human health, and it is highly beneficial to promote health by improving environmental quality. With the increase in the number of vulnerable populations, such as the elderly, the global health burden caused by environmental pollution will become higher and higher [65]. Therefore, on the one hand, we should strengthen pollution prevention and reduce the emission of environmental pollutants, on the other hand, we should ensure the health of middle-aged and elderly people by promoting the development of medical technology and improving the level of medical service provision. It is worth mentioning that the threshold regression results with environmental pollution as the threshold variable show that there is a single threshold effect on the impact of environmental pollution on health. When environmental pollution crosses the threshold value, the health suppression effect becomes significant. It means that the health effects of environmental pollution are mainly long-term effects, which have been confirmed by previous studies [66]. Moreover, a cohort study of elderly Medicare participants in the United States found that long-term air pollution exposure increased the risk of depression in later life, which also reflected the lag of the health damage of environmental pollution [67]. The cumulative impact of environmental pollution on health reminds us that environmental governance should not only reduce the generation of pollution from the source, but also manage the existing environmental pollution in time to avoid falling into the predicament of "first development and then governance". It will, to a large extent, reduce the harm to health caused by environmental pollution.

Secondly, the negative impact of environmental pollution on health has regional heterogeneity. The inhibitory effect of environmental pollution on health is significant in the area east of the Hu line, while it is not significant in the area west of the Hu line. The phenomenon of significant differences in the characteristics of the natural environment and economic development of the areas on both sides of the Hu line has been proved by many scholars. Current studies have found that the extent of environmental pollution in China is differentiated by the Hu line. For example, Wu YF et al. found that the air pollution levels on both sides of the Hu line showed a significant difference in China [68].

The health suppression effect of environmental pollution in the west of the Hu line is not obvious. We speculate that one of the reasons may be that the industrial development time in the western region of China is short [69], and the stock of environmental pollution is not enough to exert its negative effect on health. The low population density in the region and the insufficient impact of environmental pollution on health may be another reason. However, in recent years, the distribution of pollution in China has begun to migrate with the transfer of heavily polluting industries from east to west [70]. The central and western regions of China have become a potential health risk area for environmental pollution. Thus, the area east of the Hu line should avoid the "pollution haven" effect and rely on green technology innovation, industrial structure upgrading, and environmental regulation to reduce pollution [71, 72]. The western region should reasonably and orderly undertake polluting enterprises based on considering the carrying capacity of the ecological environment. The government should pay close attention to the adverse impact of industries inflow on the environment, provide more policy support, and apply pollution reduction technologies to production as soon as possible [73], so as to minimize the impact of environmental pollution on the health of residents in the western region. Thirdly, there is a double threshold effect with trade openness as the threshold variable in the path of environmental pollution affecting health. In general, this effect is first weakened and then enhanced. Specifically, when trade openness reaches the first threshold, trade openness can mitigate the negative effects of environmental pollution on health. This may be due to the fact that trade openness can improve the health of the population by promoting the economic development of the region and facilitating the development of the medical and education sectors. The health-promoting effects of trade openness have also been verified in some literature. For example, Feng J et al. found that trade liberalization improves the health status of China's labor force by increasing income and reducing malnutrition [74]. Elnaiem A et al. believed that international trade and financial development affect health outcomes [75]. On the other hand, trade openness can also have a positive impact on the environment by promoting the use of clean energy and technology, thereby improving health. However, as the level of trade openness further increases to cross the second threshold, trade openness exacerbates the health inhibition of environmental pollution. Whether local enterprises undertake high-input, high-consumption, and high-pollution production projects in response to the rapid growth of export orders to foreign trade, or foreign investors locate high-emission factories in developing countries to avoid domestic environmental regulations, there is a risk of aggravating regional environmental pollution. Le TH et al. used PM10 emissions as a measure of environmental quality and found that trade openness was beneficial to the environment of high-income countries, while the impact on the environment in low-income and middle-income countries is the opposite [76]. If we cannot deal with the imbalance of industrial structure caused by trade openness and grasp the dependence of foreign trade, it may lead to serious environmental pollution problems, thus aggravating the damage of environmental pollution to health. Therefore, it is necessary for local governments to formulate strict standards for the export and import of foreign trade, curb the pollution emissions from foreign trade-related enterprises, and promote pollution reduction and emission reduction by influencing the scale effect, technical effect, and structural effect.

There are several limitations in this study. First, for the sake of data consistency and integrity, this study does not include cities and regions with many missing data on core variables such as Tibet, Qinghai, Xinjiang, Hong Kong, Macao, and Taiwan in China. Consequently, there is a problem that the data sample covers the cities incompletely, which may lead to the analysis of heterogeneity in the eastern and western regions is not very good. Second, limited by data availability, the environmental pollution index value used in this paper is calculated by combining three industrial waste emission indicators of industrial smoke and dust, industrial wastewater, and industrial sulfur dioxide emissions, excluding other aspects of environmental pollution such as agriculture and domestic life. This may underestimate the actual degree of environmental pollution in China. In addition, the data of this study are obtained by matching the health of middle-aged and elderly people at the individual level with the environmental pollution and trade openness data at the city level, which may lead to the risk of error in the estimation results. Therefore, in future studies, consideration should be given to using the same level and more comprehensive data to examine the relationship between environmental pollution, trade openness and the health of middle-aged and elderly people.

Conclusions and policy implications

Firstly, although previous studies have identified that environmental pollution impair physical and mental health, which is related to the concentration of pollutants [30, 32]. However, few studies have used threshold effect model to explore the nonlinear effects of environmental pollution on health, especially in middle-aged and elderly people. When environmental pollution is unavoidable, it is necessary to study whether there are different effects of environmental pollution on health at different stages. Secondly, due to the significant differences in the characteristics of natural environment and economic development between the regions on both sides of the Hu line, it is essential for policy makers to understand the regional heterogeneity of environmental pollution's effects on the health of middle-aged and elderly people. Thirdly, previous studies have confirmed that trade openness is an important factor affecting the environment and population health [33, 34, 38, 39]. However, scholars mainly discuss the impact of trade openness on health from the perspective of social economy, and lack of research from the perspective of the health effects of environmental pollution.

This study tests the linear and nonlinear relationship between environmental pollution and the health of middle-aged and elderly people by constructing fixed effects regression models and threshold effect models. The role of trade openness in the pathway of environmental pollution effects on health is also explored. In addition, we also concern with the regional heterogeneity of the health effects of environmental pollution. This study makes up for the lack of nonlinear relationship and potential mechanism analysis in current researches of the environmental pollution's health effects.

This paper matches the CHARLS health data of four periods with the data of 111 prefecture-level cities in China and verifies the negative effects and regional heterogeneity of environmental pollution on the health of middle-aged and elderly people. We integrated trade openness into the research framework of the health effects of environmental pollution and constructed a threshold effect model with environmental pollution and trade openness as the threshold variables. We find that the health effects of environmental pollution are significantly inconsistent before and after the single threshold estimation. It is also found that trade openness has an impact in the path of environmental pollution inhibition on health, showing a double threshold effect of "first weakening and then strengthening".

We find that environmental pollution harms health, and this effect is regionally heterogeneous, which suggests that we cannot adopt a one-size-fits-all economic and environmental policy. Furthermore, we also conclude that the significant inconsistency of the health effects of environmental pollution before and after the single threshold estimation may be due to the cumulative negative effects on the health of environmental pollution. It is worth noting that there is a double threshold effect with trade openness as the threshold variable in the impact of environmental pollution on health, showing a trend of' first weakening and then strengthening ', which suggests that trade openness is not simply exacerbating or weakening the impact of environmental pollution on health effects. Overall, we clarify the nonlinear relationship between environmental pollution, trade openness, and the health of middle-aged and elderly people. The findings of this paper is helpful for local governments to formulate environmental policies according to local conditions, balance the relationship between economic development and ecological environment, and protect the health of middle-aged and elderly people through environmental governance.

Based on the findings above, we draw several policy implications. First, environmental pollution has a negative impact on the health of middle-aged and older adults, and this impact may be cumulative. Environmental governance should both reduce the generation of environmental pollution and manage existing environmental pollution in a timely manner. Second, the health inhibitory effects of environmental pollution on both sides of the Hu line are heterogeneous, so one-size-fits-all economic and environmental policies should be adopted. The eastern region of the line should pay attention to the upgrading of industrial structure and environmental regulation, while the western region should apply pollution reduction technology to production as soon as possible. Third, the influence of trade openness on the health effects of environmental pollution is not simply intensified or weakened. Government staff should grasp the degree of trade openness and control the pollution emissions from foreign trade enterprises. In summary, the findings of this paper are helpful in clarifying the nonlinear relationship between environmental pollution, trade openness and the health of the middle-aged and the elderly. It is helpful for local governments to adjust regional industrial structure more prospectively, formulate environmental policies according to local conditions, and balance the relationship between economic development and ecological environment.

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Author contributions
JDZ did the statistical analysis and drafted the manuscript. BL and JDZ conceptualized the paper. XFC and YTH conducted the research and data collection. LSK and DC did data management and provided advice. JDZ, BL and YLZ reviewed and co-revised the manuscript from the English language perspective. All authors made significant intellectual contributions to multiple revisions of the draft. All authors have read and agreed to the published version of the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The ethical approval is not warranted for our work as the data used in this article are publicly available. A link to the raw data can be found in the data description section. All methods in this study were carried out in accordance with relevant guidelines and regulations.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]School of Health Management, Southern Medical University, Guangzhou 510515, China

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