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Environmental regulation, human capital, and pollutant emissions: The case of SO_2 emissions for China

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Abstract: To investigate whether the impact of environmental regulation on pollution emissions varies across China's regions under different human capital levels, this study empirically examines the environmental regulation-human capital-pollution nexus by using a provincial sample dataset from 2004 to 2017. We also explore whether environmental regulation will affect sulfur emissions through human capital. The empirical results conclude that: (1) increased environmental protection investment cannot effectively contribute to sulfur emission reduction for the full sample; (2) increased environmental regulation can aggravate pollution emissions when human capital is low, while in regions with a high-level of human capital, enhanced environmental regulation intensity is negatively associated with pollution emissions; and (3) environmental regulation can help strengthen sulfur reduction through human capital accumulation; however, the reduction of sulfur emissions by human capital cannot offset the direct positive effect of environmental regulation on sulfur emissions.

Keywords: Environmental Regulation; Human capital; Pollution emissions; Mediation effect; China

JEL Classification: C31; E24; Q56; R11

1. Introduction

China has experienced rapid economic development since the reform and opening-up policy in 1978 (Chen et al., 2021; Dong et al., 2018; Dong, Dong, and Ren, 2020; Duan et al., 2021; Ren et al., 2022; Zhao et al., 2021). However, along with the continuous advancement of urbanization and industrialization, the environmental pollution issue, an inevitable product of industrial progress, has attracted widespread attention (Cai, Sam, and Chang, 2018; Dou et al., 2021; Pan et al., 2017; Xie, Yuan, and Huang, 2017). Specifically, according to the statistics of former British Petroleum (BP, 2019), in 2017, the total energy consumption in China was 3.27 billion tons of oil equivalent, accounting for 23.6% of total global energy consumption. To solve pollution emissions effectively, the Chinese government has implemented numerous policies to strengthen environmental regulation (Li and Lin, 2016; Xie, Xu, and Liu, 2019; Zhao et al., 2020a). For instance, local governments have successively issued relevant policies to close high-polluting enterprises, levy pollution taxes, or increase environmental investment (Chen et al., 2020a). In particular, the input of environmental protection funds, as a typical environmental governance measure, has become an effective choice for local governments to deal with environmental degradation. As the China Statistical Yearbook (CSY, 2018) shows, the total amount invested to improve the living environment and prevent further environmental degradation in 2017 has reached 953.9 billion yuan, accounting for 1.2% of annual gross domestic product (GDP).

In addition, since Lucas (1988) highlighted the role of human capital accumulation in facilitating the rapid development of the economy, human capital has become increasingly prominent (Chi, 2008). Based on this, numerous scholars have gradually begun to pay attention to the potential role of human capital in environmental pollutant emissions. In this regard, some scholars reach a favorable conclusion: the gradual accumulation of human capital is a valid measure for reducing environmental pollution emissions (Azam, 2019; Lu, Yang, and Shao, 2014). Furthermore, Salim, Yao, and Chen (2017) and Yang, Wang, and Shi (2017) confirm the active role of human capital in inhibiting the continuous deterioration of the ecological environment in the long run. However, Lan, Kakinaka, and Huang's (2012) research triggers our thinking on the differentiated role of human capital across various areas. They underscore that the effect of foreign investment on pollution emissions is greatly influenced by the difference of regional human capital. Thus, we are interested in establishing whether there is any heterogeneity in the impact of environmental regulation on pollutant emissions when human capital is different. In addition, how environmental regulation affects pollution emissions, that is, the specific impact mechanism, is also an issue worthy of attention. At present, although a growing body of literature has checked the impact of environmental regulation or human capital on pollution emissions (see Sections 2.1 and 2.2), very few studies have checked the regional heterogeneity of environmental regulation on pollution emissions when a difference in human capital exists. Also, previous studies have consistently ignored the influencing mechanism between environmental regulation and pollution emissions by affecting human capital accumulation. Under these circumstances, by employing a balanced panel dataset comprising 30 Chinese provinces between 2004 and 2017, this study examines the impact of environmental regulation on pollution emissions in China's regions under different human capital levels. We also conduct an analysis of whether increased environmental regulation will have an impact on pollutant emissions through continuous human capital accumulation in China.

Notably, this study makes a contribution to the existing environmental regulation-human capital-pollution nexus from the following two aspects. First, this study theoretically and empirically investigates the impact of environmental regulation on pollutant emissions when a difference exists in human capital levels. This approach is particularly useful for formulating targeted environmental regulation policies in different regions. Second, we conduct the mediation effect of environmental regulation on pollution emissions through human capital accumulation, which not only helps provide a reference for setting reasonable environmental regulation policies, but is also of great value in drawing government attention to education and the introduction of talent.

The rest of this study is presented in the following framework. Relevant literature regarding environmental regulation, human capital, and pollutant emissions is reviewed in Section 2, followed by the theoretical framework analyzed in Section 3. In Section 4, we present the model and data, while in Section 5, the estimated steps and empirical results are provided. Section 6 further conducts a mediation analysis on the regulation-pollutant nexus. The last section summarizes the entire study.

2. Literature review

2.1. Studies on the environmental regulation-pollution nexus

As a typical form of environmental regulation, the pollution control effect of local governments' investment in environmental governance has not received much attention. Several scholars have investigated the effectiveness of environmental regulation policies in the emission reduction of different types of pollutants by using comprehensive indices or methods for classifying environmental regulation types. To date, the most striking contradictory views related to the regulation-pollution nexus include two main categories. Specifically, the green paradox effect proposed by Sinn (2008) stresses that gradually strengthening environmental governance can exacerbate environmental pollution emissions. For instance, Edenhofer and Kalkuhl (2011) propose that levying carbon taxes on enterprises is not conducive to alleviating increasing global warming. The reason may be that enterprises are worried about increased taxation in the future and choose to intensify resource extraction at the current stage, which will promote carbon dioxide (CO_2) emissions. Furthermore, Smulders, Tsur, and Zemel (2012) suggest that an early announcement of carbon tax would cause increased resource exploitation in the interim period (i.e., from announcement to actual implementation), thereby increasing CO_2 emissions. This green paradox effect is also supported by Ritter and Schopf (2014).

On the contrary, the reverse emission-reduction effect verifies the effectiveness of environmental regulation policies. To be specific, by applying data of 248 cities in China from 2003 to 2016, Wang, Peng, and Wu (2021) systematically analyze the regulation-pollution nexus, and conclude that both direct government regulation and market manipulation can accelerate the achievement of carbon neutrality goals at the municipal level. Also using city-level data, Song et al. (2020) empirically examine the underlying effect of environmental regulation on pollutant emissions based on the two-stage least squares (2SLS) method, verifying the significant effectiveness of regulation policies in solving pollutant emissions. Zhang et al. (2019) obtain the same conclusion by using haze pollution as their main research variable. The negative regulation-pollution nexus is also confirmed by Cairns (2014), Guo and Wang (2018), Hashmi and Alam (2019), Pei et al. (2019), Wang and Liu (2019), Zhang, Sun, and Wang (2020), and Zhao et al. (2020a).

Regarding nonlinear characteristics, using sample data of China's 277 cities between 2002 and 2010, Zhou et al. (2019) creatively employ spatial econometric models, and find an inverted U-shaped relationship between environmental regulation and haze pollution. This finding is also consistently supported by Wang, Hu, and Lin (2021), who consider the mediating effect of the skill premium. To sum up, given the differences in research subjects and sample periods, no consensus has been reached in the regulation-pollution nexus, and few scholars have assessed the potential pollutant emission-reduction effect of environmental regulation from the perspective of government investment; put differently, considering the validity of local government investment in environmental protection is imperative.

2.2. Studies on the human capital-pollution nexus

The second strand of this study attempts to summarize current relevant studies on the human capital-pollution emissions nexus. In recent years, many scholars have investigated whether human capital accumulation can help alleviate environmental degradation. To be more specific, Lan, Kakinaka, and Huang (2012) discuss the potential effect of accumulated human capital on pollutants from a provincial perspective. They find that the regional human capital level will significantly influence the pollutant emission-reduction effect of foreign direct investment (FDI); in other words, the FDI-pollutant nexus relies highly on human capital. Only in areas with lower human capital levels can foreign investment facilitate pollutant emissions. Sapkota and Bastola (2017) make the same conclusion. Furthermore, Lu et al. (2014) apply the quantile regression technique to check the human capital-pollutant nexus at the city level. They suggest that strengthening the cultivation and introduction of human capital is a powerful weapon to prevent environmental degradation, which is consistent with the viewpoints of Azam (2019), Bano et al. (2018), and Mahmood, Wang, and Hassan (2019). Additionally, by using a panel dataset for the period 1978-2015, Li and Ouyang (2019) conclude that both human capital and CO_2 emissions exhibit an inverted N-shaped relationship.

Some scholars also have investigated the role of air pollution on human capital accumulation. For instance, utilizing a sample dataset of 35 developed cities in China between 2006 and 2016, Liu et al. (2021) show that cities with severe air pollution can restrict the accumulation of human capital. Furthermore, under a unified framework of

China’s 31 provinces, Zhao et al. (2020b) suggest that severe environmental pollution emissions can cause a huge loss of human capital.

2.3. Studies on the other determinants of environmental pollution

To achieve the sustainable development of the economy, the environmental Kuznets curve (EKC) hypothesis developed by Grossman and Krueger (1991) emphasizes an inverted U-shaped linkage between economic growth and pollution; put differently, economic growth facilitates pollutant emissions in the initial stage, and then reduces environmental pollution after crossing the inflection point. For instance, by using data spanning 1971 to 2013, Sarkodie and Ozturk (2020) verify the inverted U-shaped curve between economic growth and pollution in Kenya. Churchill et al. (2018), Dogan and Inglesi-Lotz (2020), Sinha and Shahbaz (2018), and Suki et al. (2020) also reach the same conclusion on the EKC. Other scholars also emphasize that no evidence of the EKC hypothesis is found by using different data and econometric approaches (Aung, Saboori, and Rasoulinezhad, 2017; Du et al., 2018; Özokcu and Özdemir, 2017; Pal and Mitra, 2017). To sum up, the impact of economic growth on pollution cannot be ignored.

With the publicity and advocacy of the new economic normal, industrial transition and upgrading have been gradually launched, and many scholars have explored their effect on inhibiting pollutant emissions. For instance, Zhang, Sun, and Wang (2020) examine the role of industrial transition in haze control from two aspects — rationalization and optimization; they find that the role of industrial optimization in slowing down haze pollution has emerged, while the effect of industrial rationalization is insignificant. Tertiary industry will produce less pollutant emissions then secondary industry because the latter has more environmental pollution emissions (Li et al., 2018; Mi et al., 2015; Zhou, Zhang, and Li, 2013). Similarly, the gradual deepening of international or regional trade stimulates the production and business activities of most enterprises, and thus plays an increasingly prominent role in pollutant emissions, mainly including the pollution haven hypothesis (PHH) (Omri, Nguyen, and Rault, 2014; Pao and Tsai, 2011) and the pollution halo hypothesis (Hao and Liu, 2015; Zhang and Zhou, 2016).

2.4. Literature gaps

Although a large number of scholars engaged in environmental research have explored the effect of environmental regulation and accumulated human capital on pollutant emissions, respectively (see Section 2.1 and 2.2), few scholars have integrated environmental regulation, human capital, and pollutant emissions into a research framework for systematic analysis, or considered whether human capital will influence the effect of environmental regulation on pollutant reduction, an aspect that lacks systematic theoretical analysis. In addition, the specific impact channel between environmental regulation and pollution emissions from the perspective of human capital has not been explored.

3. Theoretical framework

To the best of our knowledge, the aim of local governments to strengthen environmental regulation is to prevent the continuous deterioration of the ecological environment. Since Lucas (1988) emphasized the role of human capital and Lan, Kakinaka, and Huang (2012) explored the potential moderating effect of human capital in affecting the foreign regulation-pollution nexus, it is necessary to test whether the effect of environmental regulation on pollutant emissions will be different due to regional differences in human capital. Accordingly, based on the analysis framework of Copeland and Taylor (2003), we construct a theoretical model to analyze the moderating role of human capital.

To simplify the theoretical model, we first propose some assumptions, as follows:

(1) In some Chinese provinces with relatively backward economic development, residents usually focus on commodity production and consumption and ignore problems related to the deterioration of the ecological environment.

(2) Two types of commodities, i.e., X and Y, exist in these backward provinces. They represent polluting and cleaning products, respectively; that is, producing X emits pollutants, while producing Y emits none. This is in line with reality.

(3) The production of these two commodities (i.e., X and Y) does not require the support of physical capital, but requires the input of simple labor[1] and human capital[2]. Notably, we assume that the human capital density of commodity Y is higher than that of commodity X.

Following these three assumptions, residents' utility function can be presented in

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[1] Simple labor refers to workers who do not have training qualifications; in other words, unskilled labor; the specific definition can refer to: https://encyclopedia2.thefreedictionary.com/Simple+Labor;

[2] Human capital indicates a labor force with work experience, skills, and economic value that has undergone education and skills training. The specific definition can refer to: https://www.investopedia.com/terms/h/humancapital.asp.

the following equation:

$$U = X^{\alpha} Y^{1-\alpha} \tag{1}$$

where U represents the utility value of residents. α is the share of utility generated by residents' use of polluting products in the total utility.

Furthermore, the production functions of commodities X and Y as well as the pollution emission function are illustrated as follows:

$$X = F(H, S) \tag{2}$$

$$Y = G(H, S) \tag{3}$$

$$Z = Z(X) \tag{4}$$

where H and S indicate human capital and simple labor, respectively. Z represents environmental pollution emissions, which show a positive correlation with the output of X. Notably, the production functions (i.e., Eqs. (2) and (3)) satisfy the property of first-order homogeneity.

The equilibrium condition of consumer utility maximization states that the ratio of marginal substitution rate of commodities X and Y is equal to the ratio of the prices of the two commodities, which can be presented in the following equation:

$$\frac{MU_X}{MU_Y} = \frac{\partial U / \partial X}{\partial U / \partial Y} = \frac{P_x}{P_Y} \tag{5}$$

where MU_X and MU_Y indicate the marginal utility of commodities X and Y, respectively. P_X and P_Y represent the prices of commodities X and Y, respectively.

Following Eq. (1) (i.e., utility function) and Eq. (5), we can obtain:

$$\frac{\alpha Y}{(1-\alpha) X} = \frac{P_X}{P_Y} \tag{6}$$

The transformation form of Eq. (6) can be obtained as follows:

$$\frac{X}{Y}=\frac{\alpha}{1-\alpha}\frac{P_Y}{P_X}=\frac{\alpha}{1-\alpha}\frac{1}{P} \tag{7}$$

where P represents the relative price of commodity X to commodity Y, i.e., $P = P_X / P_Y$. Moreover, the DD curve in Figure 1(a) represents the curve of relative demand.

Additionally, to clearly analyze the supply-demand relationship of commodities, this study also draws the curve of relative supply of X and Y, which is listed in Figure 1(a) (i.e., the SS curve). To the best of our knowledge, the relative supply of commodities X and Y is determined by relative prices and production functions:

$$\frac{X}{Y}=\frac{X(P,H,S)}{Y(P,H,S)}=\frac{x(P,H/S)}{y(P,H/S)} \tag{8}$$

where relative supply and relative price (i.e., P) are positively correlated.

Moreover, according to the theory of supply and demand, it is obvious that the relative prices of commodities X and Y are jointly determined by the curves of relative supply (i.e., the SS curve) and relative demand (i.e., the DD curve), which are represented by P^* in Figure 1. Correspondingly, the relative price (i.e., P^*) determines the output of commodities X and Y in the production possibility curve in Figure 1(b), denoted by X^* and Y^*. Furthermore, following Eq. (4), the amount of pollution emissions (i.e., Z^*) is determined by the output of commodity X.

Along with the gradual implementation of environmental regulation policies, the government has begun to focus on the improvement and accumulation of human capital (Mahmood, Wang, and Hassan, 2019; Zhao et al., 2020b). Specifically, if $\frac{H}{L}>\frac{H^*}{L^*}$, the regions will have a comparative advantage in commodity Y, the human capital density of which is higher than that of commodity X. Therefore, the relative supply can be determined by the relative supply curve (i.e., S_1S_1) at the bottom right, and the relative equilibrium price will be decreased to P_1. From the production possibility curve in Figure 1(b), the output of commodities Y and X increases to Y_1 and decreases to X_1, respectively; accordingly, pollution emissions can be reduced.

Similarly, if the human capital level of a certain region is lower than the national human capital level, then $\frac{H}{L} < \frac{H^*}{L^*}$. According to the above analysis, it is obvious the relative supply curve (i.e., S_2S_2) determines the amount of relative supply, and the relative equilibrium price will be increased to P_2. For the production possibility curve in Figure 1(b), the output of commodities Y and X decreases to Y_2 and increases to X_2, respectively; therefore, pollution emissions can be exacerbated. Based on this, our study proposes the following hypothesis:

Hypothesis 1: If a region has a high human capital level, the implementation of environmental regulation policies can reduce regional pollution emissions; however, when the human capital level in a region is low, environmental regulation cannot help facilitate pollutant emissions.

Insert Figure 1

4. Model and data

4.1. Model setting

On the premise of constructing the theoretical framework, we try to empirically discuss the pollutant-reduction effect of environmental regulation from the perspective of environmental investment in the following sections. To this end, building an accurate and reasonable regression model is the premise for evaluating the environmental regulation-pollution emissions nexus (Chen et al., 2020b). In this model, sulfur dioxide (SO_2), as a typical environmental pollutant, is used as the main dependent variable, and environmental regulation is the core independent variable. Following previous studies related to pollution emissions, we introduce human capital, economic growth, industrial structure upgrading, and trade structure as control variables. Regarding the dynamic effect of pollution emissions, we choose the dynamic panel model for estimation regression by introducing the lagged term of pollution emissions, which denotes the impact of the previous period's pollution emissions on the current period. Accordingly, the specific multivariate model is highlighted as follows:

$$SO_{2it} = f(SO_{2i,t-1}, EI_{it}, Huma_{it}, Pgdp_{it}, Ind_{it}, Tra_{it}) \tag{9}$$

where i represents 30 Chinese provinces within the sample data, and t denotes the period 2004-2017. SO_2 indicates SO_2 emissions across various provinces, EI represents environmental regulation, $Huma$ refers to human capital, Ind means industrial structure upgrading, $Pgdp$ denotes economic growth, and Tra refers to trade structure.

To eliminate the influence of variable dimension and the effect of data fluctuation in the estimated model as much as possible, all variables employed in Eq. (9) are treated with a natural logarithm, as follows:

$$\begin{aligned} lnSO_{2it} = {} & \alpha_0 + \alpha_1 lnSO_{2i,t-1} + \alpha_2 lnEI_{it} + \alpha_3 lnHuma_{it} + \alpha_4 lnPgdp_{it} \\ & + \alpha_5 lnInd_{it} + \alpha_6 lnTra_{it} + \varepsilon_{it} \end{aligned} \tag{10}$$

where α_0 refers to the constant term, and ε_{it} is the error term. $\alpha_i (1 \le i \le 6)$ are the coefficients of the variables that need to be evaluated. We expect the coefficients of the independent variables and control variables to be negative.

As mentioned in the theoretical analysis in Section 3, the level of national/regional human capital can significantly affect the regulation-SO_2 nexus. To address this issue, we introduce an interactive item of environmental regulation and human capital into the econometric model for empirical analysis. Therefore, Eq. (10) can be presented in the following equation:

$$lnSO_{2it} = \beta_0 + \beta_1 lnSO_{2i,t-1} + \beta_2 lnEI_{it} + \beta_3 lnHuma_{it} * lnEI_{it} + \sum_{k=4}^{6} \beta_k lnZ_{it} + \varepsilon_{it} \quad (11)$$

where β_0 is the constant term, and $\beta_1 - \beta_6$ are the parameters to be estimated. In Eq. (11), to avoid multicollinearity, we remove human capital while introducing the interaction term. *Z* concludes *lnPgdp*, *lnInd*, and *lnTra*.

4.2. Data

Since the National Bureau of Statistics of China only released relevant data on the environment before 2017, we therefore apply the sample data of China's 30 provinces from 2004 to 2017 to conduct an empirical analysis. Other autonomous regions and special administrative regions are excluded due to missing data.

Furthermore, the specific measures and data sources are presented in Table 1, and the descriptive statistics are listed in Table 2. The relevant data were collected mainly from CSY (2018), the China City Statistical Yearbook (CCSY, 2018), and the Chinese Environment Statistical Yearbook (CESY, 2018).

Insert Table 1

Insert Table 2

5. Estimation steps and estimated findings

The estimated steps are: (1) the multicollinearity and correlation between variables are checked (step 1; see Section 5.1); (2) the baseline regression on the environmental regulation-SO_2 emissions nexus is conducted (step 2; see Section 5.2); (3) two robust tests are applied to check the reliability of the baseline findings (step 3; see Section 5.3); and (4) we perform the regional heterogeneous analysis by dividing the full sample into two regions (step 4; see Section 5.4).

5.1. Multicollinearity and correlation tests

After selecting appropriate estimated variables, the next step aims to check the potential multicollinearity within the explanatory variables. Ignoring this may result in a false regression of the baseline estimate. In this regard, we check the multicollinearity by observing the values of variance inflation factor (VIF) in the test results (see the first column of Table 3). Obviously, both the VIF value of each explanatory variable and the average VIF value are less than 10, which greatly satisfies the multicollinearity test rule. This suggests that no multicollinearity exists between the explanatory variables used in the estimation model.

In addition, we conduct a preliminary examination of the correlation between these variables used in our study (i.e., $\ln SO_2$, $\ln EI$, $\ln Huma$, $\ln Pgdp$, $\ln Ind$, and $\ln Tra$), and present their scatter plots in Figure 2. Obviously, with the exception of environmental regulation, all other variables contribute to curbing SO_2 emissions. However, due to the low degree of fit of these preliminary estimates, selecting a more complex estimated model with more control variables and utilizing appropriate regression methods to test the environmental regulation-SO_2 emissions nexus are imperative.

Insert Table 3

Insert Figure 2

5.2. Baseline regression

As Table 4 shows, the corresponding empirical results of estimating Eqs. (10) and (11) are reported based on the differential generalized method of moments (Diff-GMM), and system GMM (Sys-GMM) techniques simultaneously. Notably, the results without the interaction term are listed in (1) and (2) of Table 4, while (2) and (4) in Table 4 present the estimated results with the interaction terms of environmental regulation and human capital. Which method to choose as the benchmark regression is the key to accurately estimating the moderating role of human capital in the relationship between environmental regulation and SO_2 emissions. The commonly used techniques for estimating the dynamic model are the Diff-GMM developed by Arellano and Bond (1991) and the Sys-GMM proposed by Arellano and Bover (1995) and Blundell and Bond (1998), which mainly use the lagged terms of the explained variable and explanatory variable as instrumental variables to solve potential endogeneity problems in the regression model (Dong and Hao, 2018). Since the Sys-GMM is more efficient in estimation than the Diff-GMM, and the unit of cross-section in the panel data is significantly larger than that of time (Dong and Hao, 2018; Huang, 2010; Zhao, Shahbaz, and Dong, 2022), we take the estimated findings of Sys-GMM as the baseline regression findings.

The test values of the Arellano-Bond (A-B) and Sargan tests emphasize the rationality and reliability of the GMM approach (Roodman, 2009; Zhao et al., 2020a). The (3) in Table 4 suggests that an increase of environmental regulation by 1% promotes sulfur pollution by 0.033%. This indicates the ineffectiveness of the pollutant emission-reduction effect of increased environmental investment. According to the statistics from CSY (2018), the amount of investment is increasing every year; however, there are still many problems in controlling environmental pollution in China, such as insufficient investment and unreasonable allocation of investment capital. The historical experience of pollution control in developed countries shows that only 1.5 percent of GDP can be spent on environmental protection to effectively control pollutant emissions. Thus, how to allocate existing environmental protection investment effectively and reasonably has become a key issue local governments need to consider urgently. The reason for the positive environmental regulation-SO_2 nexus may be that the reduction effect of environmental regulation on pollution cannot effectively offset the continuous increase of pollutant emissions caused by the large amount of energy consumption.

In addition, human capital and SO_2 emissions show a significant positive linkage, which implies that an improvement of human capital is not conducive to environmental pollution control. As Lan, Kakinaka, and Huang (2012) and Li and Ouyang (2019) noted, accumulated human capital provides technological support for reducing pollution emissions and low-sulfur production, which is conducive to optimizing the low-sulfur allocation structure of resources and accelerating the research and development (R&D) of sulfur emission-reduction technologies. This measure can help improve energy utilization efficiency and reduce SO_2 emissions. Also, highly educated human capital usually has strong environmental awareness, which can promote consensus for the formation of a green society. Accordingly, the positive effect of human capital on SO_2 emissions may be due to the time lag effect of human capital's R&D of low-sulfur technologies. The negative sulfur emission effect of human capital is significantly less than the positive effect of economic growth on SO_2 emissions. Thus, continuing to strengthen the accumulation of human capital is an important measure for promoting sulfur reduction.

Another major finding worth exploring is the sulfur emission-reduction effect of the interaction term between environmental regulation and human capital in the last column of Table 4. Specifically, environmental regulation is positively associated with SO_2 emissions, while the coefficient of the interaction term between environmental regulation and human capital is significantly negative. This suggests that when the human capital level is low, increased environmental regulation will promote SO_2 emissions, while in regions with high human capital environmental regulation can help reduce SO_2 emissions. Such a finding emphasizes the regional heterogeneity of environmental regulation on SO_2 emissions in various regions with different human capital levels. The reason may be that regions with high human capital generally possess a higher awareness of environmental protection; when environmental regulation policies are implemented, regions with high human capital can also creatively conduct innovation and the development of low-sulfur technology to accelerate the pace of sulfur reduction. In contrast, regions with low human capital are not sensitive enough to environmental protection policies, and have no ability and motivation to carry out progressive innovation.

Regarding the other variables, improved economic growth and industrial transition show a negative correlation with SO_2 emissions. Rapid economic development in China has gathered a huge economic aggregate, which has provided sufficient environmental protection funds for pollutant emission reduction (Dong, Ren, and Zhao, 2021; Sinha and Bhattacharya, 2017; Ren et al., 2021; Wang, Han, and Kubota, 2016). Furthermore, tertiary industries with high value-added and low pollution features usually have an advantage in sulfur emission reduction over secondary industries, which need to be driven by large amounts of energy consumption (Jiang et al., 2020). On the contrary, foreign investment level and SO_2 emissions show a significant positive relationship (He, 2006). This confirms the PHH: increased foreign investment can promote sulfur emission reduction.

Insert Table 4

5.3. Robustness tests

5.3.1 Alternative dependent variable

To empirically check the reliability of the baseline regression, we first re-estimate Eqs. (10) and (11) by applying per capita sulfur emissions (denoted as PSO_2) and carbon emissions (denoted as CO_2) to replace total amount of SO_2 emissions based on the Diff-GMM and Sys-GMM techniques; the estimated results are reported in Table 5. We can find that the growth of environmental regulation positively affects per capita SO_2 emissions and CO_2 emissions. Thus, the empirical findings of our study are reliable and robust.

Insert Table 5

5.3.2 Alterative estimated methods

In addition to applying the alternative dependent variable, this study also estimates the two equations by alternative estimated methods — pooled ordinary least squares (OLS), panel fixed effect (FE), and panel random effect (RE); the corresponding results are listed in Table 6. In this regard, Aisen and Veiga (2013) and Dong et al. (2021) have stressed the inaccuracy and ineffectiveness of using pooled OLS to estimate a dynamic econometric model. Furthermore, applying the FE and RE methods cannot solve the underlying endogeneity problems within the econometric model. Thus, the results in Table 6 highlight the robustness of the SYS-GMM method in checking the impact of environmental regulation and human capital on SO_2 emissions.

Insert Table 6

5.4. Regional heterogeneous analysis

To further verify the theoretical expectations in Section 3, this study divides the 30 provinces in China into two regions (i.e., high human capital region and low human capital region) to explore the heterogeneous environmental regulation-SO_2 emissions nexus in regions with different human capital levels. Notably, this study utilizes the average value of human capital in all provinces in 2017 (i.e., 20.12) as the boundary. Provinces with a human capital value higher than 20.12 are high-capital regions, while provinces with a human capital lower than this value are low human capital regions; the specific provinces of the two regions are illustrated in Table A1 in the Appendix.

Table 7 reports the estimated results of the high human capital region and the low human capital region based on the Diff-GMM and Sys-GMM techniques. Similarly, to avoid multicollinearity, human capital is not included in the regression of sub-regions. From this table, in regions with high human capital, the coefficient of environmental regulation is significantly negative, implying that increased environmental regulation in regions with high human capital can effectively reduce SO_2 emissions. In regions with low human capital levels, environmental regulation and SO_2 emissions present a positive relationship, which indicates that environmental regulation is not conducive to sulfur reduction. The findings of regional heterogeneity not only verify the robustness of the baseline regression, but also examine the theoretical model discussed in Section 3.

Insert Table 7

6. Further discussion on the mediating role of human capital

6.1. Model Setting

In the previous section, we empirically examined how accumulated human capital influences the dynamic effect of environmental regulation on SO_2 emissions. Based on this, we attempt to examine whether environmental regulation has an impact on SO_2 emissions by affecting human capital accumulation. In this respect, the mediation effect model is an effective choice to solve this problem, and the specific equations are constructed below:

$$lnSO_{2it} = \alpha_0 + \alpha_1 lnEI_{it} + \sum_{k=2}^{4} \alpha_k lnZ_{it} + \varepsilon_{it} \tag{12}$$

$$lnHuma_{it} = \varphi_0 + \varphi_1 lnEI_{it} + \sum_{k=2}^{4} \varphi_k lnZ_{it} + \varepsilon_{it} \tag{13}$$

$$lnSO_{2it} = \eta_0 + \eta_1 lnEI_{it} + \eta_2 lnHuma_{it} + \sum_{k=3}^{5} \eta_k lnZ_{it} + \varepsilon_{it} \tag{14}$$

where $\alpha_k(\mathrm{k} = 0,1,\ldots,4)$, $\varphi_k(\mathrm{k} = 0,1,\ldots,4)$, and $\eta_k(\mathrm{k} = 0,1,\ldots,4)$ represent the regression coefficients that need to be estimated. Other variables and symbols are consistent with the model building in Section 4.1. Notably, the coefficient of environmental regulation in Eq. (12) represents the total effect in the environmental regulation-SO_2 nexus, and η_1 refers to the direct effect. The product of φ_1 and η_2 is the indirect effect (i.e., mediation effect).

Currently, there are two methods to estimate the mediation effect model: (1) the causal stepwise regression technique proposed by Baron and Kenny (1986). In this method, stepwise regression is performed on the test equations to check the significance of the regression coefficients separately. Although this commonly used technique is simple and easy to understand, some scholars believe that the efficiency of testing this method is low; and (2) product coefficient technique. The principle of this method is to test the significance of the product of the coefficients φ_1 and η_2. It includes mainly the Sobel test with normal sampling distribution and a bootstrap sampling method with non-normal sampling distribution. In recent years, numerous scholars have come to favor this method. Accordingly, the Sobel test and bootstrap sampling are used to investigate the mediating role of human capital in affecting the relationship between environmental regulation and SO_2 emissions.

6.2. Results and discussion

Table 8 clearly shows the estimated results of the Sobel test and bootstrap sampling. As this table shows, the value of the Sobel test is -0.041, which is significant as the 1% level. This emphasizes that the mediating role of human capital between environmental regulation and SO_2 emissions is established. More importantly, the total effect, direct effect, and indirect effect are 0.157, 0.199, and -0.041, respectively. Furthermore, the proportion of total effect that is mediated is 26.37%, i.e., $(\varphi_1 * \eta_2)/\alpha_1 = 26.37\%$, which suggests that the contribution of human capital accumulation in influencing the environmental regulation-SO_2 emissions nexus is 26.37%. In addition, in the bootstrap test, *_bs_1* and *_bs_2* represent the indirect and direct effects, respectively, and the confidence intervals of the two effect tests do not contain 0. This finding further confirms the robustness of the mediating effect of human capital on the impact of environmental regulation on SO_2 emissions.

Specifically, Models (1)-(3) in this stable report the regression results of estimating Eqs. (12)-(14), respectively. In Model (1), the coefficient of environmental regulation is 0.157, which is the total effect. The coefficient of environmental regulation in Model

(3) is 0.199, which is the direct effect; this implies that gradually increasing investment in environmental governance by local governments is not conducive to accelerating sulfur reduction. In addition, the coefficients of environmental regulation in Model (2) and human capital in Model (3) are 0.068 and -0.608, respectively, which underscores that increased environmental investment can help mitigate SO_2 emissions by facilitating the accumulation of human capital. Continued growth of green investment can provide an economic foundation for enterprises to strengthen innovation activities, stimulate clean technology research and development, and accelerate human capital recruitment. As Sun, Li, and Ghosal (2020) stress, human capital is the guarantee of technological innovation.

In summary, we can conclude that an increase in environmental regulation can directly facilitate SO_2 emissions, and reduce SO_2 emissions by strengthening the accumulation of human capital. Notably, the promotion effect of environmental regulation on sulfur emission reduction through human capital cannot effectively offset the direct positive effect of environmental regulation on SO_2 emissions. Accordingly, to achieve the win-win situation of rapid economic growth and improved environmental quality, it is necessary to strengthen environmental protection investment, reasonably allocate environmental governance funds, and increase the proportion of environmental investment in pollution reduction technologies, thus promoting the significant reduction of SO_2 emissions. To clearly identify the influence mechanism between environmental regulation and SO_2 emissions, we also draw the chart in the investment-SO_2 nexus (see Figure 3).

Insert Table 8

Insert Figure 3

7. Conclusions and policy implications

To explore whether environmental regulation affects pollution emissions under different levels of human capital, we investigate the environmental regulation-human capital-pollution nexus by applying the Sys-GMM technique based on balanced panel data for 30 provinces in China from 2004 to 2017. Moreover, we analyze the mediation effect of human capital on the environmental regulation-SO_2 emissions nexus. The main findings of this study are as follows:

(1) The primary finding of the benchmark regression emphasizes that increased environmental regulation is positively associated with SO_2 emissions in China; in other words, the strengthening of environmental regulation cannot effectively contribute to the reduction of sulfur emissions.

(2) The coefficient of the interaction term between environmental regulation and human capital is significantly negative, suggesting that when a region has low human capital, improved environmental regulation will increase SO_2 emissions; conversely, in regions with high human capital levels, environmental regulation can promote sulfur emission reduction. This is supported by the results of regional heterogeneous analysis.

(3) The empirical results of the mediation effect insist that environmental regulation can help facilitate sulfur reduction by strengthening human capital accumulation; however, the sulfur emission-reduction effect of environmental

regulation by affecting human capital cannot effectively offset the direct effect of environmental regulation on SO_2 emissions.

Following the above conclusions, we propose several policy implications in the following three aspects. First, the main conclusion of the benchmark regression of our study emphasizes the ineffectiveness of environmental regulation in controlling SO_2 emissions. In addition, the specific impact mechanism also highlights the unreasonable allocation of environmental investment. Thus, effective means to promote sulfur emission reduction are to continuously strengthen investment in environmental control and reasonably allocate existing environmental protection funds while increasing the R&D capital of low-polluting technologies. In addition, improving the regulations and audit systems of enterprises, particularly high-polluting industrial enterprises, is very important for the effective use of environmental protection funds.

Second, the impact of increased environmental regulation on SO_2 emissions in China depends on the levels of human capital. In particular, when a region has low human capital, an increase in environmental regulation can increase SO_2 emissions, while in regions with high human capital levels environmental regulation can improve environmental quality. Therefore, the government should comprehensively consider the importance of human capital when formulating environmental regulation policies. Specifically, in regions with high human capital, loose regulation policies should be implemented, focusing on the conscious awareness of high human capital and the R&D of pollution-control technologies. On the contrary, regions with low human capital should implement strict environmental regulation strategies, and investment in environmental governance should be increased gradually.

Third, the interaction term of environmental regulation and human capital in SO_2 emissions is significantly negative, indicating the promotion impact of the coordination effect of increased environmental regulation and human capital accumulation on sulfur emission reduction. Therefore, to achieve a win-win situation for sustainable economic growth and environmental protection, the government should strive to increase environmental investment and accumulate human capital by increasing investment in education, particularly in regions with low human capital, which will help avoid the further deterioration of the environment in regions with low human capital.

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No potential conflict of interest was reported by the author(s).

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Appendix A

Table A1. The specific provinces of the two sub-regions.

Classification	**Province**
High human capital region	Beijing, Tianjin, Shanxi, Inner Mongolia, Liaoning, Shanghai, Jiangsu, Zhejiang, Shaanxi, Ningxia, Xinjiang
Low human capital region	Hebei, Jilin, Heilongjiang, Anhui, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangxi, Hainan, Sichuan, Guizhou, Yunnan, Gansu, Qinghai, Fujian, Guangdong, Chongqing

Table A2. Abbreviation list.

Abbreviations			
A-B	Arellano-Bond	GDP	Gross domestic product
BP	formal British Petroleum	OLS	Ordinary least square
CCSY	China City Statistical Yearbook	PHH	Pollution haven hypothesis
CESY	China Environment Statistical Yearbook	R&D	Research and development
CO_2	Carbon dioxide	RE	Random effect
CSY	China Statistical Yearbook	SO_2	Sulfur dioxide
Diff-GMM	Differential generalized method of moments	Sys-GMM	System generalized method of moments
EKC	Environment Kuznets curve	2SLS	Two-stage least square
FDI	Foreign direct investment	VIF	Variance inflation factor
FE	Fixed effect		

References

Aisen, A., and Veiga, F. J. 2013. “How does political instability affect economic growth?.” *European Journal of Political Economy* 29: 151-167. doi: 10.1016/j.ejpoleco.2012.11.001.

Arellano, M., and Bond, S. 1991. “Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations.” *The Review of Economic Studies* 58(2): 277-297. doi: 10.2307/2297968.

Arellano, M., and Bover, O. 1995. “Another look at the instrumental variable estimation of error-components models.” *Journal of Econometrics* 68(1): 29-51. doi: 10.1016/0304-4076(94)01642-D.

Aung, T. S., Saboori, B., and Rasoulinezhad, E. 2017. “Economic growth and environmental pollution in Myanmar: an analysis of environmental Kuznets curve.” *Environmental Science and Pollution Research* 24(25): 20487-20501. doi: 10.1007/s11356-017-9567-3.

Azam, M. 2019. “Relationship between energy, investment, human capital, environment, and economic growth in four BRICS countries.” *Environmental Science and Pollution Research* 26(33): 34388-34400. doi: 10.1007/s11356-019-06533-9.

Bano, S., Zhao, Y., Ahmad, A., Wang, S., and Liu, Y. 2018. “Identifying the impacts of human capital on carbon emissions in Pakistan.” *Journal of Cleaner Production* 183: 1082-1092. doi: 10.1016/j.jclepro.2018.02.008.

Baron, R. M., and Kenny, D. A. 1986. “The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations.” *Journal of Personality and Social Psychology* 51(6): 1173. doi: 10.1037/0022-3514.51.6.1173.

Blundell, R., and Bond, S. 1998. “Initial conditions and moment restrictions in dynamic panel data models.” *Journal of Econometrics* 87(1): 115-143. doi: 10.1016/S0304-4076(98)00009-8.

BP, 2019. BP Statistical Review of World Energy 2019. http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html.

Cai, Y., Sam, C. Y., and Chang, T. 2018. “Nexus between clean energy consumption, economic growth and CO_2 emissions.” *Journal of Cleaner Production* 182: 1001-1011. doi: 10.1016/j.jclepro.2018.02.035.

Cairns, R. D. 2014. “The green paradox of the economics of exhaustible resources.” *Energy Policy*, 65, 78-85. doi: 10.1016/j.enpol.2013.10.047.

CCSY, 2018. National Bureau of Statistics, China City Statistical Yearbook. http://www.tjcn.org/.

CESY, 2018. National Bureau of Statistics, China Environment Statistical Yearbook. http://www.tjcn.org/tjnj/HHH/36980.html.

Chen, J., Gao, M., Huang, S., and Hou, W. 2021. “Application of remote sensing satellite data for carbon emissions reduction.” *Journal of Chinese Economic and*

Business Studies 19(2): 109-117. doi: 10.1080/14765284.2021.1920329.

Chen, J., Gao, M., Li, D., and Song, M. 2020a. “Analysis of the rebound effects of fossil and nonfossil energy in China based on sustainable development.” *Sustainable Development* 28(1): 235-246. doi: 10.1002/sd.1991.

Chen, J., Gao, M., Mangla, S. K., Song, M., and Wen, J. 2020b. “Effects of technological changes on China’s carbon emissions.” *Technological Forecasting and Social Change* 153: 119938. doi: 10.1016/j.techfore.2020.119938.

Chi, W. 2008. “The role of human capital in China’s economic development: Review and new evidence.” *China Economic Review* 19(3): 421-436. doi: 10.1016/j.chieco.2007.12.001.

Churchill, S. A., Inekwe, J., Ivanovski, K., and Smyth, R. 2018. “The environmental Kuznets curve in the OECD: 1870–2014.” *Energy Economics* 75: 389-399. doi: 10.1016/j.eneco.2018.09.004.

Copeland, B., and Taylor, S. 2003. “Trade and the environment: Theory and evidence.” *Princeton University Press*.

CSY, 2018. National Bureau of Statistics, China Statistical Yearbook. http://www.stats.gov.cn/tjsj/ndsj/.

Dogan, E., and Inglesi-Lotz, R. 2020. “The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis: evidence from European countries.” *Environmental Science and Pollution Research* 27(11): 12717-12724. doi: 10.1007/s11356-020-07878-2.

Dong, C., Dong, X., Jiang, Q., Dong, K., and Liu, G. 2018. "What is the probability of achieving the carbon dioxide emission targets of the Paris Agreement? Evidence from the top ten emitters." *Science of the Total Environment* 622: 1294-1303. doi: 10.1016/j.scitotenv.2017.12.093.

Dong, K., Dong, X., and Ren, X. 2020. "Can expanding natural gas infrastructure mitigate CO_2 emissions? Analysis of heterogeneous and mediation effects for China." *Energy Economics* 90: 104830. doi: 10.1016/j.eneco.2020.104830.

Dong, K., Jiang, Q., Shahbaz, M., and Zhao, J. 2021. "Does low-carbon energy transition mitigate energy poverty? The case of natural gas for China." *Energy Economics* 99: 105324. doi: 10.1016/j.eneco.2021.105324.

Dong, K., Ren, X., and Zhao, J. 2021. "How does low-carbon energy transition alleviate energy poverty in China? A nonparametric panel causality analysis." *Energy Economics* 103: 105620. doi: 10.1016/j.eneco.2021.105620.

Dong, X. Y., and Hao, Y. 2018. "Would income inequality affect electricity consumption? Evidence from China." *Energy* 142 215-227. doi: /10.1016/j.energy.2017.10.027.

Dou, Y., Zhao, J., Dong, X., and Dong, K. 2021. "Quantifying the impacts of energy inequality on carbon emissions in China: A household-level analysis." Energy Economics 102: 105502. doi: 10.1016/j.eneco.2021.105502.

Du, G., Liu, S., Lei, N., and Huang, Y. 2018. "A test of environmental Kuznets curve for haze pollution in China: Evidence from the penal data of 27 capital cities."

Journal of Cleaner Production 205: 821-827. doi: 10.1016/j.jclepro.2018.08.330.

Duan, K., Ren, X., Shi, Y., Mishra, T., and Yan, C. 2021. “The marginal impacts of energy prices on carbon price variations: evidence from a quantile-on-quantile approach.” *Energy Economics* 95: 105131. doi: 10.1016/j.eneco.2021.105131.

Edenhofer, O., and Kalkuhl, M. 2011. “When do increasing carbon taxes accelerate global warming? A note on the green paradox.” *Energy Policy* 39(4): 2208-2212. doi: 10.1016/j.enpol.2011.01.020.

Grossman, G. M., Krueger, A. B. 1991. “Environmental impacts of a North American free trade agreement.” *National Bureau of Economic Research*. Paper No. w3914. doi: 10.3386/w3914.

Guo, L., and Wang, Y. 2018. “How does government environmental regulation “unlock” carbon emission effect?—evidence from China.” *Chinese Journal of Population Resources and Environment* 16(3): 232-241. doi: 10.1080/10042857.2018.1496703.

Hao, Y., and Liu, Y. M. 2015. “Has the development of FDI and foreign trade contributed to China’s CO_2 emissions? An empirical study with provincial panel data.” *Natural Hazards* 76(2): 1079-1091. doi: 10.1007/s11069-014-1534-4.

Hashmi, R., and Alam, K. 2019. “Dynamic relationship among environmental regulation, innovation, CO_2 emissions, population, and economic growth in OECD countries: A panel investigation.” *Journal of Cleaner Production* 231, 1100-1109. doi: 10.1016/j.jclepro.2019.05.325.

He, J. 2006. "Pollution haven hypothesis and environmental impacts of foreign direct investment: The case of industrial emission of sulfur dioxide (SO_2) in Chinese provinces." *Ecological Economics* 60(1): 228-245. doi: 10.1016/j.ecolecon.2005.12.008.

Huang, Y. 2010. "Political institutions and financial development: an empirical study." *World Development* 38(12): 1667-1677. doi: 10.1016/j.worlddev.2010.04.001.

Jiang, L., He, S., Cui, Y., Zhou, H., and Kong, H. 2020. "Effects of the socio-economic influencing factors on SO_2 pollution in Chinese cities: A spatial econometric analysis based on satellite observed data." *Journal of Environmental Management* 268: 110667. doi: 10.1016/j.jenvman.2020.110667.

Lan, J., Kakinaka, M., and Huang, X. 2012. "Foreign direct investment, human capital and environmental pollution in China." *Environmental and Resource Economics* 51(2): 255-275. doi: 10.1007/s10640-011-9498-2.

Li, K., and Lin, B. 2016. "Impact of energy conservation policies on the green productivity in China's manufacturing sector: Evidence from a three-stage DEA model." *Applied Energy* 168: 351-363. doi: 10.1016/j.apenergy.2016.01.104.

Li, L., Lei, Y., Wu, S., He, C., Chen, J., and Yan, D. 2018. "Impacts of city size change and industrial structure change on CO_2 emissions in Chinese cities." *Journal of Cleaner Production* 195: 831-838. doi: 10.1016/j.jclepro.2018.05.208.

Li, P., and Ouyang, Y. 2019. "The dynamic impacts of financial development and human capital on CO_2 emission intensity in China: an ARDL approach." *Journal* *of Business Economics and Management* 20(5): 939-957. doi: 10.3846/jbem.2019.10509.

Liu, X., Dong, X., Li, S., Ding, Y., and Zhang, M. 2021. "Air pollution and high human capital population migration: An empirical study based on 35 major cities in China." *Sustainable Production and Consumption* 27: 643-652. doi: 10.1016/j.spc.2021.01.032.

Lu, J. Y., Yang, J., and Shao, H. Y. 2014. "FDI, human capital and environmental pollution in china: a quantile regression analysis based on panel data of 249 cities." *Journal of International Trade* 4: 118-125. doi: 10.13510/j.cnki.jit.2014.04.012.

Lucas Jr, R. E. 1988. "On the mechanics of economic development." *Journal of Monetary Economics* 22(1): 3-42. doi: 10.1016/0304-3932(88)90168-7.

Mahmood, N., Wang, Z., and Hassan, S. T. 2019. "Renewable energy, economic growth, human capital, and CO_2 emission: an empirical analysis." *Environmental Science and Pollution Research* 26(20): 20619-20630. doi: 10.1007/s11356-019-05387-5.

Mi, Z. F., Pan, S. Y., Yu, H., and Wei, Y. M. 2015. "Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing." *Journal of Cleaner Production* 103: 455-462. doi: 10.1016/j.jclepro.2014.06.011.

Omri, A., Nguyen, D. K., Rault, C. 2014. "Causal interactions between CO_2 emissions, FDI, and economic growth: Evidence from dynamic simultaneous-equation models." *Economic Modelling* 42: 382-389. doi: 10.1016/j.econmod.2014.07.026.

Özokcu, S., and Özdemir, Ö. 2017. "Economic growth, energy, and environmental

Kuznets curve." *Renewable and Sustainable Energy Reviews* 72: 639-647. doi: 10.1016/j.rser.2017.01.059.

Pal, D., and Mitra, S. K. 2017. "The environmental Kuznets curve for carbon dioxide in India and China: Growth and pollution at crossroad." *Journal of Policy Modeling* 39(2): 371-385. doi: 10.1016/j.jpolmod.2017.03.005.

Pan, X., Ai, B., Li, C., Pan, X., and Yan, Y. 2019. "Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in China." *Technological Forecasting and Social Change* 144: 428-435. doi: 10.1016/j.techfore.2017.12.012.

Pao, H. T., and Tsai, C. M. 2011. "Multivariate Granger causality between CO_2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries." *Energy* 36(1): 685-693. doi: 10.1016/j.energy.2010.09.041.

Pei, Y., Zhu, Y., Liu, S., Wang, X., and Cao, J. 2019. "Environmental regulation and carbon emission: The mediation effect of technical efficiency." *Journal of Cleaner Production* 236: 117599. doi: 10.1016/j.jclepro.2019.07.074.

Ren, X., Cheng, C., Wang, Z., and Yan, C. 2021. "Spillover and dynamic effects of energy transition and economic growth on carbon dioxide emissions for the European Union: A dynamic spatial panel model." *Sustainable Development* 29(1): 228-242. doi: 10.1002/sd.2144.

Ren, X., Li, Y., Shahbaz, M., Dong, K., and Lu, Z. 2022. “Climate Risk and Corporate Environmental Performance: Empirical Evidence from China.” *Sustainable Production and Consumption* 30: 467-477.

Ritter, H., and Schopf, M. 2014. “Unilateral climate policy: harmful or even disastrous?.” *Environmental and Resource Economics* 58(1): 155-178. doi: 10.1007/s10640-013-9697-0.

Roodman, D. 2009. “How to do xtabond2: An introduction to difference and system GMM in Stata.” *The Stata Journal* 9(1): 86-136. doi: 10.1177/1536867x0900900106.

Salim, R., Yao, Y., and Chen, G. S. 2017. “Does human capital matter for energy consumption in China?.” *Energy Economics* 67: 49-59. doi: 10.1016/j.eneco.2017.05.016.

Sapkota, P., and Bastola, U. 2017. “Foreign direct investment, income, and environmental pollution in developing countries: Panel data analysis of Latin America.” *Energy Economics* 64: 206-212. doi: 10.1016/j.eneco.2017.04.001.

Sarkodie, S. A., and Ozturk, I. 2020. “Investigating the environmental Kuznets curve hypothesis in Kenya: a multivariate analysis.” *Renewable and Sustainable Energy Reviews* 117: 109481. doi: 10.1016/j.rser.2019.109481.

Sinha, A., and Bhattacharya, J. 2017. “Estimation of environmental Kuznets curve for SO_2 emission: A case of Indian cities.” *Ecological Indicators* 72: 881-894. doi: 10.1016/j.ecolind.2016.09.018.

Sinha, A., and Shahbaz, M. 2018. "Estimation of environmental Kuznets curve for CO_2 emission: role of renewable energy generation in India." *Renewable Energy* 119: 703-711. doi: 10.1016/j.renene.2017.12.058.

Sinn, H. W. 2008. "Public policies against global warming: a supply side approach." *International Tax and Public Finance* 15(4): 360-394. doi: 10.1007/s10797-008-9082-z.

Smulders, S., Tsur, Y., and Zemel, A. 2012. "Announcing climate policy: can a green paradox arise without scarcity?." *Journal of Environmental Economics and Management* 64(3): 364-376. doi: 10.1016/j.jeem.2012.02.007.

Song, Y., Yang, T., Li, Z., Zhang, X., and Zhang, M. 2020. "Research on the direct and indirect effects of environmental regulation on environmental pollution: Empirical evidence from 253 prefecture-level cities in China." *Journal of Cleaner Production* 269: 122425. doi: 10.1016/j.jclepro.2020.122425.

Suki, N. M., Sharif, A., Afshan, S., and Suki, N. M. 2020. "Revisiting the Environmental Kuznets Curve in Malaysia: The role of globalization in sustainable environment." *Journal of Cleaner Production* 264: 121669. doi: 10.1016/j.jclepro.2020.121669.

Sun, X., Li, H., and Ghosal, V. 2020. "Firm-level human capital and innovation: Evidence from China." *China Economic Review* 59: 101388. doi: 10.1016/j.chieco.2019.101388.

Wang, A., Hu, S., and Lin, B. 2021. "Can environmental regulation solve pollution problems? Theoretical model and empirical research based on the skill premium." *Energy Economics* 94: 105068. doi: 10.1016/j.eneco.2020.105068.

Wang, H., and Liu, H. 2019. "Foreign direct investment, environmental regulation, and environmental pollution: an empirical study based on threshold effects for different Chinese regions." *Environmental Science and Pollution Research* 26(6): 5394-5409. doi: 10.1007/s11356-018-3969-8.

Wang, T., Peng, J., and Wu, L. 2021. "Heterogeneous effects of environmental regulation on air pollution: evidence from China's prefecture-level cities." *Environmental Science and Pollution Research* 28(20): 25782-25797. doi: 10.1007/s11356-021-12434-7.

Wang, Y., Han, R., and Kubota, J. 2016. "Is there an environmental Kuznets curve for SO_2 emissions? A semi-parametric panel data analysis for China." *Renewable and Sustainable Energy Reviews* 54: 1182-1188. doi: 10.1016/j.rser.2015.10.143.

Xie, Q., Xu, X., and Liu, X. 2019. "Is there an EKC between economic growth and smog pollution in China? New evidence from semiparametric spatial autoregressive models." *Journal of Cleaner Production* 220: 873-883. doi: 10.1016/j.jclepro.2019.02.166.

Xie, R. H., Yuan, Y. J., and Huang, J. J. 2017. "Different types of environmental regulations and heterogeneous influence on "green" productivity: evidence from China." *Ecological Economics* 132: 104-112. doi: 10.1016/j.ecolecon.2016.10.019.

Yang, L., Wang, J., and Shi, J. 2017. “Can China meet its 2020 economic growth and carbon emissions reduction targets?.” *Journal of Cleaner Production* 142: 993-1001. doi: 10.1016/j.jclepro.2016.08.018.

Zhang, C., and Zhou, X. 2016. “Does foreign direct investment lead to lower CO_2 emissions? Evidence from a regional analysis in China.” *Renewable and Sustainable Energy Reviews* 58: 943-951. doi: 10.1016/j.rser.2015.12.226.

Zhang, M., Liu, X., Ding, Y., and Wang, W. 2019. “How does environmental regulation affect haze pollution governance?—An empirical test based on Chinese provincial panel data.” *Science of the Total Environment* 695: 133905. doi: 10.1016/j.scitotenv.2019.133905.

Zhang, M., Sun, X., and Wang, W. 2020. “Study on the effect of environmental regulations and industrial structure on haze pollution in China from the dual perspective of independence and linkage.” *Journal of Cleaner Production* 256: 120748. doi: 10.1016/j.jclepro.2020.120748.

Zhao, J., Jiang, Q., Dong, X., and Dong, K. 2020a. “Would environmental regulation improve the greenhouse gas benefits of natural gas use? A Chinese case study.” *Energy Economics* 87: 104712. doi: 10.1016/j.eneco.2020.104712.

Zhao, J., Jiang, Q., Dong, X., and Dong, K. 2021. “Assessing energy poverty and its effect on CO_2 emissions: The case of China.” *Energy Economics* 97: 105191. doi: 10.1016/j.eneco.2021.105191.

Zhao, J., Shahbaz, M., and Dong, K. 2022. “How does energy poverty eradication promote green growth in China? The role of technological innovation." *Technological Forecasting and Social Change* 175: 121384.

Zhao, X., Huang, S., Wang, J., Kaiser, S., and Han, X. 2020b. "The impacts of air pollution on human and natural capital in China: a look from a provincial perspective." *Ecological Indicators* 118: 106759. doi: 10.1016/j.ecolind.2020.106759.

Zhou, Q., Zhang, X., Shao, Q., and Wang, X. 2019. "The non-linear effect of environmental regulation on haze pollution: Empirical evidence for 277 Chinese cities during 2002–2010." *Journal of Environmental Management* 248: 109274. doi: 10.1016/j.jenvman.2019.109274.

Zhou, X., Zhang, J., and Li, J. 2013. "Industrial structural transformation and carbon dioxide emissions in China." *Energy Policy* 57: 43-51. doi: 10.1016/j.enpol.2012.07.017.

Tables

Table 1. Description of the variables.

Variable	Definition	Specific measures	Data sources
SO_2	Sulfur dioxide (SO_2) emissions	Industrial SO_2 emissions	CESY (2018)
EI	Environmental regulation	The proportion of industrial pollution control investment to regional GDP	CESY (2018); CSY (2018)
Huma	Human capital	The proportion of employees with a college degree or above to the total employment	CCSY (2018)
Pgdp	Economic growth	Per capita GDP	CSY (2018)
Ind	Industrial structure upgrading	The ratio of the added value of the tertiary industry to the secondary industry	CSY (2018)
Tra	Trade structure	The proportion of total import and export trade to GDP	CSY (2018)

Table 2. Descriptive statistics of the variables.

Variable	**Mean**	**Std. Dev.**	**Minimum**	**Maximum**
National sample				
SO_2	684926.7	439532.6	14271.49	2002000
EI	0.0016344	0.0013893	0.000674	0.0099185
Huma	13.40417	9.160513	3	55.9
Pgdp	36974.72	24196.75	4317	128994
Ind	0.9992974	0.5352551	0.4970531	4.236677
Tra	5.703602	7.060924	0.6554735	75.0313
High human capital region				
SO_2	680643.6	435889.7	18502.23	1557000
EI	0.002068	0.0018568	0.0000674	0.0099185
Huma	19.53071	11.68763	5.81	55.9
Pgdp	50580.91	29184.69	8587	128994
Ind	1.14069	0.7632416	0.5969427	4.236677
Tra	7.784789	6.327498	0.6554735	26.32095
Low human capital region				
SO_2	687406.3	442427.7	14271.49	20020000
EI	0.0013834	0.0009427	0.0002094	0.0059924
Huma	9.857218	4.4014	3	19.5
Pgdp	29097.45	16250.94	4317	82677
Ind	0.9174384	0.3135506	0.4970531	2.512521
Tra	4.498704	7.193036	0.8978392	75.0313

Notes: Std. Dev. represents standard deviation.

Table 3. Results of multicollinearity and correlation tests.

Variable	VIF	$lnSO_2$	*lnEI*	*lnHuma*	*lnPgdp*	*lnInd*	*lnTra*
$lnSO_2$		1.0000					
lnEI	1.33	0.3611*	1.0000				
		(0.0000)					
lnHuma	4.92	-0.4248*	-0.3131*	1.0000			
		(0.0000)	(0.0000)				
lnPgdp	4.62	-0.2677*	-0.3921*	0.8484*	1.0000		
		(0.0000)	(0.0000)	(0.0000)			
lnInd	1.78	-0.6284*	-0.3536*	0.5206*	0.3338*	1.0000	
		(0.0000)	(0.0000)	(0.0000)	(0.0000)		
Lntra	1.39	-0.4182*	-0.3324*	0.3459*	0.4176*	0.3912*	1.0000
		(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
Mean VIF	2.81						

Notes: * indicates statistical significance at 1% level.

Table 4. Estimated results of baseline regression.

Dependent variable: ***$lnSO_2$***

Variable	**Diff-GMM estimation**		**Sys-GMM estimation**	
	(1)	**(2)**	**(3)**	**(4)**
$lnSO_{2i,t-1}$	0.803^{***}	0.805^{***}	0.933^{***}	0.914^{***}
	(39.58)	(42.67)	(62.84)	(54.71)
lnEI	0.029^{***}	0.109^{***}	0.033^{***}	0.110^{***}
	(4.32)	(10.53)	(4.79)	(18.96)
lnHuma	0.236^{***}		0.156^{***}	
	(15.90)		(12.01)	
*lnEI*lnHuma*		-0.032^{***}		-0.026^{***}
		(-11.90)		(-17.13)
lnPgdp	-0.306^{***}	-0.282^{***}	-0.175^{***}	-0.175^{***}
	(-25.03)	(-20.63)	(-16.19)	(-16.93)
lnInd	-0.745^{***}	-0.750^{***}	-0.720^{***}	-0.788^{***}
	(-16.79)	(-18.42)	(-15.92)	(-14.26)
lnTra	-0.102^{***}	-0.101^{***}	0.057^{***}	0.080^{***}
	(-6.68)	(-6.55)	(2.83)	(3.41)
_Cons	5.391^{***}	5.695^{***}	2.326^{***}	3.021^{***}
	(15.65)	(16.83)	(9.60)	(13.54)
AR(1)	0.0001	0.0001	0.0001	0.0001
AR(2)	0.2080	0.3006	0.4599	0.5068
Sargan test	0.1233	0.1227	0.9998	0.6689

Notes: *** indicates statistical significance at the 1% level; the values in parentheses indicate z-statistics.

Table 5. Robust results of the alternative dependent variable.

Variable	**Per capita SO_2 emissions**		**CO_2 emissions**	
	(1)	**(2)**	**(3)**	**(4)**
$lnPSO_{2i,t-1}$	0.869^{***}	0.867^{***}		
	(37.05)	(39.35)		
$lnCO_{2i,t-1}$			0.711^{***}	0.713^{***}
			(57.49)	(60.97)
lnEI	0.050^{***}	0.128^{***}	0.021^{***}	0.026^{***}
	(7.16)	(15.86)	(3.73)	(3.40)
lnHuma	0.219^{***}		0.029^{**}	
	(23.74)		(2.49)	
*lnEI*lnHuma*		-0.032^{***}		-0.003^{*}
		(-14.37)		(-1.81)
lnPgdp	-0.228^{***}	-0.220^{***}	0.111^{***}	0.120^{***}
	(-17.74)	(-19.76)	(6.69)	(6.94)
lnInd	-0.811^{***}	-0.823^{***}	-0.302^{***}	-0.318^{***}
	(-11.88)	(-12.42)	(-15.10)	(-13.33)
lnTra	0.087^{***}	0.082^{***}	-0.044^{***}	-0.026^{*}
	(2.68)	(2.65)	(-3.13)	(-1.79)
_Cons	2.561^{***}	3.020^{***}	0.561^{***}	0.488^{***}
	(9.94)	(13.43)	(5.72)	(4.53)
AR(1)	0.0001	0.0001	0.0211	0.0212
AR(2)	0.3504	0.4825	0.7327	0.7532
Sargan test	0.9587	0.9566	0.9999	0.9999

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate z-statistics.

Table 6. Robust results of the alternative estimated methods.

Dependent variable: $lnSO_2$						
Variable	**Pooled OLS**		**Panel FE**		**Panel RE**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
$lnSO_{2i,t-1}$	0.779^{***}	0.738^{***}	0.981^{***}	0.984^{***}	0.984^{***}	0.983^{***}
	(3.99)	(3.70)	(27.98)	(28.03)	(73.90)	(75.47)
lnEI	0.188^{***}	-0.054	-0.016	0.015	-0.002	0.041^{**}
	(3.72)	(-0.82)	(-1.25)	(0.70)	(-0.16)	(2.45)
lnHuma	-0.829^{***}		0.070^{*}		0.110^{***}	
	(-6.11)		(1.66)		(3.00)	
*lnEI*lnHuma*		0.091^{***}		-0.012^{*}		-0.017^{***}
		(4.56)		(-1.89)		(-3.31)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
_Cons	8.409^{***}	8.169^{***}	-1.280	-1.223	2.015^{***}	2.328^{***}
	(8.36)	(6.52)	(-1.61)	(-1.53)	(7.56)	(7.37)
R-squared	0.5008	0.4804	0.9589	0.9549	0.9664	0.9666

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate t-statistics.

Table 7. Estimated results of the regional heterogeneous analysis.

Dependent variable: *lnSO₂*				
Variable	**High human capital region**		**Low human capital region**	
	Diff-GMM	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**
$lnSO_{2i,t-1}$	0.976^{***} (12.34)	1.100^{***} (13.48)	0.694^{***} (18.77)	0.841^{***} (25.81)
lnEI	-0.047^{***} (-3.21)	-0.091^{***} (-2.75)	0.037^{***} (3.71)	0.061^{***} (5.78)
lnPgdp	-0.134^{***} (-3.10)	-0.046 (-0.82)	-0.163^{***} (-8.71)	-0.100^{***} (-5.79)
lnInd	-0.552^{***} (-3.97)	-0.664^{***} (-3.15)	-0.550^{***} (-10.00)	-0.537^{***} (-8.32)
lnTra	-0.168^{***} (-2.60)	0.128 (1.19)	-0.165^{***} (-5.06)	-0.119^{***} (-2.75)
_Cons	1.653 (1.22)	-1.707 (-1.30)	5.998^{***} (10.86)	3.532^{***} (7.55)
AR(1)	0.0046	0.0050	0.0010	0.0009
AR(2)	0.7823	0.8115	0.1507	0.1216
Sargan test	0.9999	0.9999	0.9792	0.9887

Notes: *** indicates statistical significance at the 1% level; the values in parentheses indicate z-statistics.

Table 8. Results of the mediation effect.

Variable	**Model (1)**	**Model (2)**	**Model (3)**
lnEI	0.157^{***}	0.068^{***}	0.199^{***}
	(3.08)	(3.51)	(3.94)
lnHuma			-0.608^{***}
			(-4.84)
lnPgdp	0.048	0.713^{***}	0.481^{***}
	(0.81)	(31.66)	(4.52)
lnInd	-1.345^{***}	0.511^{***}	-1.035^{***}
	(-12.54)	(12.51)	(-8.44)
lnTra	-0.206^{***}	-0.061^{***}	-0.243^{***}
	(-4.36)	(-3.42)	(-5.22)
_Cons	13.857^{***}	-4.351^{***}	11.212^{***}
	(23.04)	(-19.00)	(14.00)
Adj_R^2	0.4373	0.7949	0.4662
Sobel test	-0.041^{***} (-2.84)		
	Total effect		0.157^{***} (3.08)
	Direct effect		0.199^{***} (3.94)
	Indirect effect		-0.041^{***} (-2.84)
	Proportion of total effect that is mediated		26.37%
Bootstrap test			
	_bs_1	-0.041	[-0.070 -0.015]
	_bs_2	0.199	[0.091 0.310]

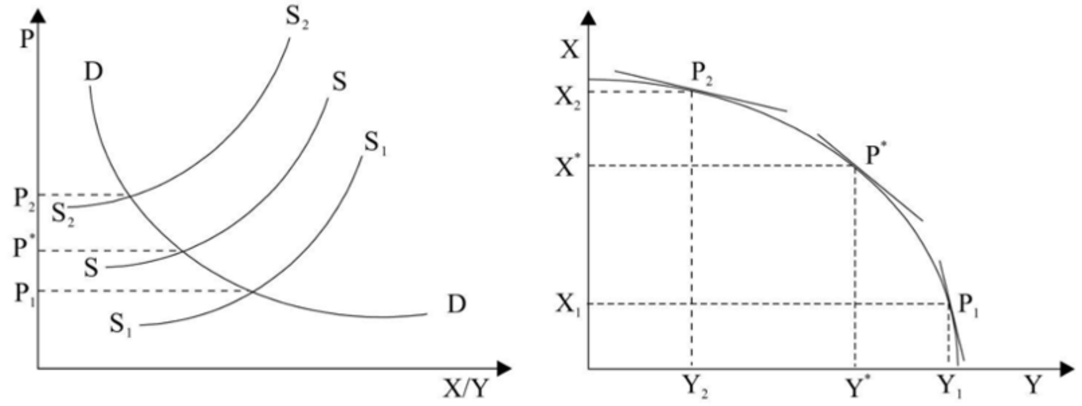
Notes: *** indicates statistical significance at the 1% level; the values in parentheses indicate z-statistics.

Figures

Figure 1. The curves of relative demand and supply (a) and production possibility curve (b).

Figure 2. Correlation chart between environmental regulation, human capital, and SO_2 emissions.

Figure 3. The mediation effect diagram of environmental regulation on SO_2 emissions.



(a) (b)

Figure 1. The curves of relative demand and supply (a) and production possibility curve (b).

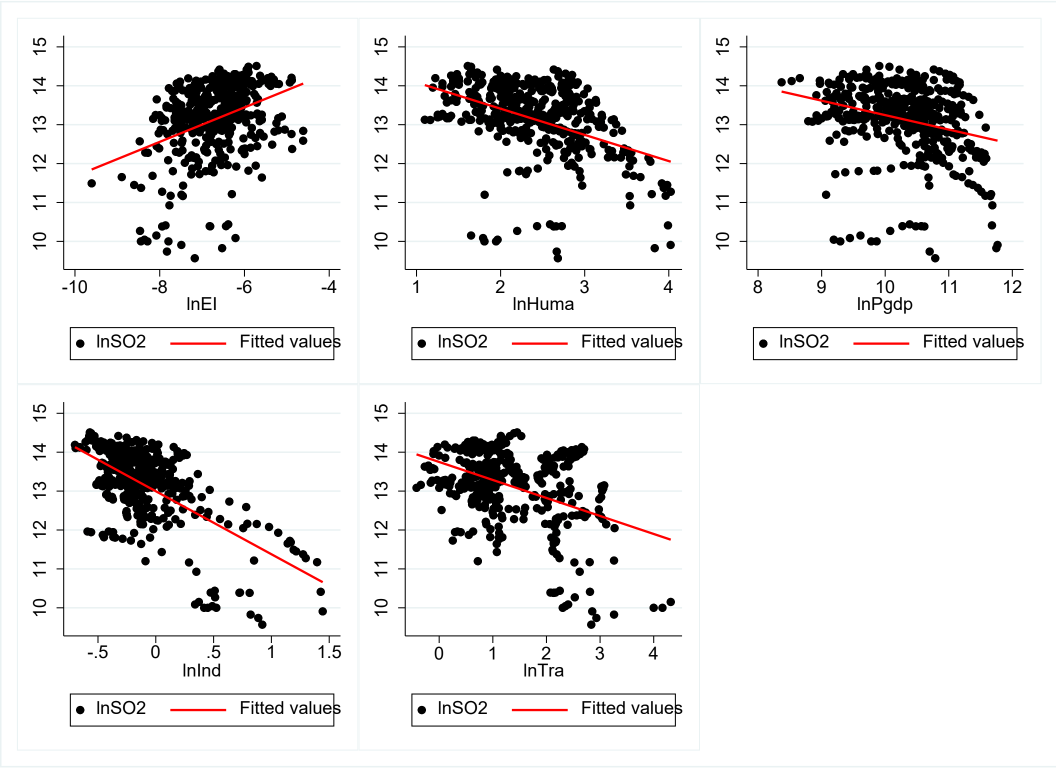
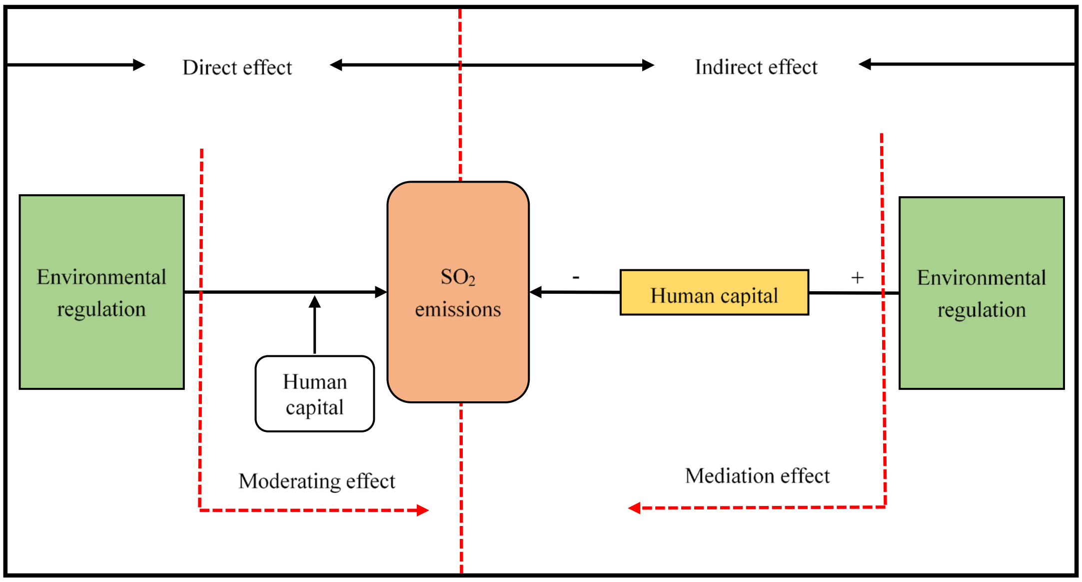


Figure 2. Correlation chart between environmental regulation, human capital, and SO_2 emissions.



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