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Original Paper

Exploring the impact of economic growth and energy consumption on SO_2 emissions in China based on the Environmental Kuznets Curve hypothesis

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ABSTRACT

This study aims to analysis the influence of economic growth (EG) and energy consumption (EC) on sulfur dioxide emissions (SE) in China. Accordingly, this study explores the link between EG, EC, and SE for 30 provinces in China over the span of 2000–2019. This study also analyzes cross-sectional dependence tests, panel unit root tests, Westerlund panel cointegration tests, Dumitrescu-Hurlin (D-H) causality tests. According to the test results, there is an inverted U-shaped association between EG and SE, and the assumption of the Environmental Kuznets Curve (EKC) is verified. The signs of EG and EC in the fixed effect (FE) and random effect (RE) methods are in line with those in the dynamic ordinary least squares (DOLS), fully modified ordinary least squares (FMOLS) and autoregressive distributed lag (ARDL) estimators. Moreover, the results verified that EC can obviously positive impact the SE. To reduce SE in China, government and policymakers can improve air quality by developing cleaner energy sources and improving energy efficiency. This requires the comprehensive use of policies, regulations, economic incentives, and public participation to promote sustainable development.

1. Introduction

The global climate issue has garnered extensive attention to reduce EC and emission, especially in China (Fang et al., 2018). Since the initiation of economic reform policy in China, economic and social development has received global acclaim for its advances. Meanwhile, the proportion of China's major economic and social indicators in the world has continued to increase (Cui and Cao, 2023). GDP has increased more than eightfold in China, from 10,162.36 billion CNY in 2000 to 85,470.56 billion CNY in 2019. Along with the rapid advancement of urbanization, economic development has increased energy utilization and resulting in serious environmental issues (Yao et al., 2018). The process of industrialization has become a dilemma between ecology and EG (Wu et al., 2023). This problem has been caused mainly by industrial structure, which is dominated by heavy industry (Jahanger et al., 2023). At the same time, the foundation of agricultural development is weak, the development of tertiary industry lags behind that of other industries, and the demand for energy is large. China's economic and industrial development has been driven by heavy pollution and high EC for a long time (Li and Lin, 2015). The country's rapid development has driven the growth of fossil fuel consumption, which has generated large amounts of SE (Huang, 2018). Therefore, EG, industrial structure, and EC patterns are clearly affecting air quality in China (Yang et al., 2021). Sulfur dioxide (SO_2) is the main pollutants in the atmosphere and an important indicator of whether the atmosphere is contaminated (Wang et al., 2007). In 2005, the World Health Organization published recommended levels of exposure to SO_2, and set a range of medium-term targets to encourage gradual improvements in air quality. Specifically, the value of 500 $\mu g/m^3$ for SO_2 should not be exceeded within an average time of 10 min. In addition, SE are associated with many hazards that affect human health, agriculture, and metals. Acid rain caused by SE is also harmful, mainly for its effects on water quality, soil pollution, and the corrosion of buildings (Ghose, 2015). It also causes soil acidification and the

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destruction of vegetation, which can significantly cut down food production (Kavian et al., 2019). Specific health problems caused by SE include cardiovascular abnormalities, lung diseases, and immune system deficiencies. Such emissions can even lead to increased mortality (Qin et al., 2015; Lee et al., 2017).

Based on the abovementioned significant impacts of SE on social and economic development and the urgent need to control SE in China, this study attempts to explore various factors that impact the generation of SE. Some scholars have discussed the relation between EG and SE and verified the assumptions of EKC (He and Lin, 2019). The EKC basically suggests that environmental pollution is low during the initial stages of EG. Later, resource consumption increases substantially and environmental pollution begins to increase until pollution peaks with the development of industrial technology. Finally, environmental pollution begins to decrease, presenting an inverted U-shaped curve as EG and technological progress are achieved (Grossman and Krueger, 1996). Grossman and Krueger (1991) conducted a statistical regression analysis to reveal the association between the concentration of urban air pollution and GDP. Their results show that there exists such relation between pollutants and GDP. This hypothesis has received validation from many studies, such as those by Tsurumi and Managi (2010), Benavides et al. (2017) and Sarkodie and Strezov (2018).

The subsequent sections of this study are organized as follows. Part 2 provides the literature review. In part 3, the model, methods, and data are examined. Part 4 presents the empirical results and discussions. Part 5 gives relevant conclusions and recommendations.

2. Literature review

2.1. SO_2 emissions and economic growth

SE are not only a problem of air pollution, but also an issue for the environment, economy, and society. More importantly, the economy, as the core factor affecting SE, deserves special attention. In the initial phases of EG, there is a tendency for environmental pollution to worsen alongside EG until a critical turning point is reached. Following this turning point, environmental pollution starts to decrease, leading to an enhancement in environmental quality. This suggests the presence of an inverse U-shaped correlation between environmental pollution and EG (Hou et al., 2023). Hao et al. (2015) employed panel data spanning from 2002 to 2012 to check the convergence of per capita SE in China. The findings revealed a positive correlation between GDP and secondary industry ratio in GDP with SE. Lyu et al. (2016) conducted an investigation into the impacts of key factors on atmospheric pollution during the period of 1997–2012 by LMDI method in China. The findings indicated that EG had effects on PM2.5, SE, and nitrogen oxide emissions. In addition, some studies substantiated the credibility of the EKC hypothesis concerning the correlation in SE and EG (De Groot et al., 2004; Poon et al., 2006; Maddison, 2006; Stern, 2006). For example, El Hédi Arouri et al. (2011) examined the association between SE and GDP for 12 African countries throughout the years 1981–2005 by bootstrap panel unit root tests. The results indicated the presence of an EKC in the cases of Egypt and Tunisia. Selden and Song (1994) used a cross-national panel of data to evaluate the inverted U-shaped association between EG and SE. Roca et al. (2001) confirmed the EKC hypothesis regarding the association in SE and income. Elfaki and Heriqbaldi (2023) evaluated the association in CO_2 emissions, EC, industrialization, and EG, and the results proved the validity of that hypothesis. In addition, many studies validated the EKC (Adebayo, 2021; Jahanger et al., 2022; Pata et al., 2023).

2.2. SO_2 emissions and energy consumption

The association between SE and EC is a hot topic in the category of energy and environmental economics (Hu and Xu, 2022; Liu and Jiang, 2022). For example, Sinha (2016) used panel data of 139 Indian cities from 2001 to 2013 to explore the impact of energy intensity and EG on pollution emissions. The results suggest a feedback assumption between EG, SO_2 and NO_2 emissions. Han and Tian (2022) indicated that most SE are caused by coal combustion which commonly employs coal-fired boilers. They found that polluting enterprises reduced the number of coal-fired boilers to lessen SE. Zhao et al. (2018) concluded that higher consumption of fossil energy contributed significantly to SE, and that optimizing the energy structure is an important tool for reducing SO_2 intensity. Liu et al. (2019) analyzed multiple time points from 2004 to 2016 to capture changes in SE. They found that urbanization, industrial structure, and energy affect SE with different trends. Bakhsh et al. (2022) employed the 3SLS technique to examine the association between EG, EC, SE, and foreign direct investment (FDI) in Pakistan. The findings indicate a significant correlation between EC and SE (Liu et al., 2022). Other factors that drive SE include technical progress, research and development, urbanization, population density, green innovation and industrial agglomeration (Zhou et al., 2017; Tang et al., 2023; Fuladlu and Altan, 2022; Luo et al., 2023; Ye et al., 2022).

2.3. Literature gaps

Based on the above background, to underscore the gravity of environment pollution in China and address the research gaps, the present study employs panel data from 30 provinces in China spanning the period from 2000 to 2019. It aims to examine the interrelationships between EG, EC, and SE. Additionally, we investigates the EKC hypothesis validity and analyzes the reasons for the production of SE and countermeasures to reduce these emissions. The findings generated three main contributions: (1) This study uses SE as the dependent variable and adds SE into the econometric model to fill the research gap. (2) This study demonstrates the existence of an inverse U-shaped correlation between EG and SE, providing new insights into the potential mechanism by which EG affects SE. (3) Due to the lack of robustness of previous studies, combined regression models including FE and RE model are utilized to comprehensively evaluate the results, and the results are consistent.

3. Methodology

3.1. The model

Controlling SE is a key step in addressing major environmental problems in China. The objective of this study is to analyze the relationship among EG, EC, and SE over the period 2000–2019 in China. Specifically, the study uses SE as the dependent variable and employs EG and EC as the independent variables. Accordingly, to fill the research gap, this study adds SE per capita into the econometric model. All of variables were converted to per capita values, including EGP, ECP and SEP. The SEP model under that hypothesis can be specified in Eq. (1) as follows:

$$\mathrm{SEP}_{it} = f\left(\mathrm{EGP}_{it}, \mathrm{EGP}_{it}^2, \mathrm{ECP}_{it}\right) \tag{1}$$

where SEP indicates SO_2 emissions per capita; EGP (EGP^2) represents gross domestic product (squared) per capita; energy consumption per capita is represented as ECP; i denotes 30 provinces;

and t represents time period. To overcome the heteroscedasticity of these variables, all variables undergo a natural logarithm transformation, and Eq. (2) can be interpreted as follows:

$$\ln \mathrm{SEP}_{it} = \alpha + \beta_1 \ln \mathrm{EGP}_{it} + \beta_2 (\ln \mathrm{EGP}_{it})^2 + \beta_3 \ln \mathrm{ECP}_{it} + \varepsilon_{it} \quad (2)$$

where lnSEP_{it} is the dependent variable; β_1, β_2, and β_3 refer to the coefficients of the independent variables including lnEGP_{it}, $(\mathrm{lnEGP}_{it})^2$, and lnECP_{it}, respectively; α and ε_{it} denotes the intercept and error term, respectively. This study predicts that inverted U-shaped curve exists in EGP and SEP, that is, the coefficients of β_1 and β_2 are predicted to be positive and negative. ECP may positively impact the SEP, that is, the sign of β_3 is predicted to be positive.

3.2. Econometric approaches

First, to check the association among EGP, ECP, and SEP in the panel data, this study uses the Breusch-Pagan LM, Pesaran CD tests posed by Pesaran (2004) to investigate cross-sectional independence in collected data. Second, the parameters in the panel data, cross-sectional Im, Pesaran, and Shin (CIPS) unit root tests proposed by Pesaran (2007) are required to check these variables and avoid spurious regression. In addition, the variance ratio panel cointegration test proposed by Westerlund (2005) is non-parametric. It does not require a clear assumption of the data-generation process, and all the relevant redundant parameter estimates take a certain form. To obtain more reliable results, this study uses the Westerlund cointegration test to check if a panel cointegration association exists between these variables, including EGP, ECP and SEP. Third, we estimate the long-term parameters after verifying that a cointegration relationship exists. This study uses the DOLS method proposed by Stock and Watson (1993) and the FMOLS developed by Pedroni (2001), and the ARDL put forward by Pesaran and Shin (1995; Pesaran et al., 2001) to appraise the long-term parameters. The advantage of ARDL is that it is relatively more effective in the case of small and limited sample data and can obtain unbiased estimates of long-term models (Harris and Sollis, 2003). Finally, if a cointegration relationship exists between the variables, they have at least one direction of causality. This study uses the D-H panel data causality test proposed by Dumitrescu and Hurlin (2012) to explore the causal association among EGP, ECP and SEP. The D-H causality test applies to a stable time series, and is highly efficient for the analysis of heterogeneous panel data.

3.3. Data

Considering the availability of data, the sample selection for this study covered the period 2000–2019 in China. Thirty provinces (four regions including Tibet, Hong Kong, Macao, and Taiwan are excluded for data unavailability) were selected as the research object when constructing the balanced panel data. The data on SE, as one of the main pollutants in waste gas, come from the China Energy Statistical Yearbook. The data on GDP was obtained from the National Bureau of Statistics of China. The data on EC come from the China Energy Statistical Yearbook, the Provincial and the Municipal Bureau of Statistics. Moreover, the data on permanent residents representing the population are from the National Bureau of Statistics of China. All of variables were converted to per capita values, including EGP, ECP and SEP. Table 1 illustrates a statistical analysis of the data and shows the mean, standard deviation (SD), minimum, maximum, kurtosis of the natural logarithm of EGP, ECP and SEP. As depicted in Table 1, this study uses Jarque-Bera test to check whether the skewness of the data corresponding to the normal distribution. The absolute magnitude of skewness represents the skewness level of the distribution. The value of the skewness of each variable is relatively small and close to zero, indicating that the skewness can be regarded as symmetric. The absolute magnitude of kurtosis indicates the steepness of the distribution and the degree of difference between the normal distribution. The value of the kurtosis of each variable is very small, indicating that each variable is similar to the standard normal distribution. Moreover, due to the slow convergence speed of the Jarque-Bera test, the requirement for the sample size is relatively high. To further verify the normal distribution of the data, this study draws histograms to show the distribution of these variables conforms to the normal distribution. As depicted in Fig. 1, it shows a shape of high in the middle and low at both ends, indicating that all the variables are basically conform with the normal distribution.

Table 1
Descriptive statistics of the variables (after logarithm).

Variables	Mean	Std. Dev.	Min	Max	Obs.	Skewness	Kurtosis
lnSEP	4.794	0.832	1.939	6.451	630	0.000	0.043
lnEGP	5.581	0.824	3.478	7.408	630	0.000	0.000
$(\mathrm{lnEGP})^2$	31.820	8.974	12.100	54.880	630	0.356	0.000
lnECP	10.160	0.545	8.624	11.610	630	0.015	0.423

Note: Std. Dev., Max., Min., and Obs. denote standard deviation, maximum, minimum, and observations, respectively.

Based on these statistics, this study presents Fig. 2 to help understand the trend of SE, GDP, and EC in China. This study also displays Figs. 3–5 to observe the geographical distribution of SE in China. The results clearly indicate that SE increased between 2000 and 2006 from 19,306.39 thousand tons to 24,886.66 thousand tons. For the period 2006–2019, SE decreased from 24,886.66 thousand tons to 4,666.94 thousand tons. Between 2000 and 2019, GDP increased from 10,162.36 billion CNY to 85,470.56 billion CNY. Over the same period, EC increased from 1,545.295 million tons of Standard Coal Equivalent (SCE) to 4,670.96 million tons of SCE in China.

Fig. 3 presents the spatial characteristics of SE in 2000 and shows that SE were higher in Hebei, Shandong, Sichuan, and Guizhou. Figs. 4 and 5 presents the spatial characteristics of SE in 2010 and 2019, and indicate that northern China exhibited higher levels of SE compared to southern China. Specifically, provinces with particularly high SO_2 emissions include Inner Mongolia, Hebei, Shandong, Shanxi, and Henan in 2010.

4. Empirical results and discussions

4.1. Results of the cross-sectional dependence tests

The statistics for the Breusch-Pagan LM, Pesaran CD tests are presented in Table 2. Because these three statistics are significant, cross-sectional dependence exists between these variables in the 30 provinces of China. Hence, the next step of CIPS panel unit root tests are applied to inspect stationarity.

4.2. Results of the panel unit root, Johansen and Westerlund panel cointegration tests

The results of the CIPS panel unit root test are illustrated in Table 3. As shown, for EGP, ECP, and SEP, the CIPS test cannot reject the null hypothesis at level. But for the first difference of EGP, ECP, and SEP, the null assumptions was rejected. Hence, these variables can be considered stationary in the first-order single-step process. To obtain a more reliable conclusion, this study further performs

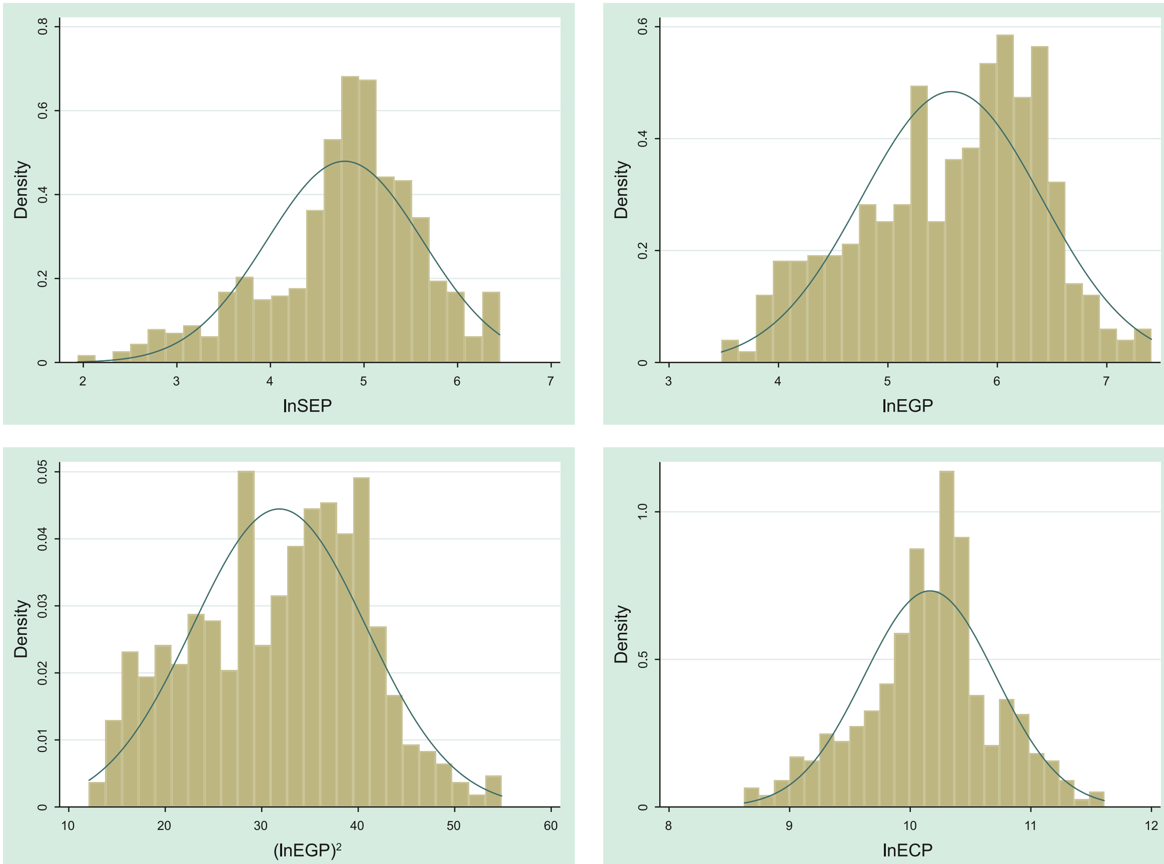

Fig. 1. Normal distribution of lnSEP, lnEGP, $(\text{lnEGP})^2$, and lnECP.

panel cointegration tests. Table 4 presents the Johansen and Westerlund panel tests result. Because the p-values of the panel v-statistic, panel ADF-statistic, variance ratio statistic with intercept and trend are 0.000, 0.049 and 0.007, respectively, the null hypothesis is strongly rejected. Therefore, a cointegration relationship exists among EGP, ECP, and SEP.

4.3. Results of panel long-term parameter estimates

The findings obtained from the DOLS, FMOLS, and ARDL estimators are shown in Table 5. All the methods indicate that the EKC assumption exists between EGP and SEP. These results are consistent with Pata (2018) and Dong et al. (2017), who verified the EKC assumption in Turkey and China. Suppose that EGP increases by 1% and SEP enhance by 6.598% in the DOLS estimator, 2.163% in the FMOLS estimator and 1.367% in the ARDL estimator, respectively. The coefficient of EGP in the DOLS estimator and FMOLS estimator is higher than that in the ARDL estimator. Provided the square of EGP enhances by 1%, SEP decrease by 0.753% in the DOLS estimator, 0.343% in the FMOLS estimator, and 0.195% in the ARDL estimator, respectively. Once ECP increases by 1%, SEP increase by 1.621% in the DOLS estimator, 2.017% in the FMOLS estimator, and 0.201% in the ARDL estimator, respectively. According to these results, it can be inferred that the results are basically consistent and relatively robust. However, it is possible that the parameters of the DOLS, FMOLS and ARDL estimators are overestimated or underestimated. Therefore, this study further conducted robustness testing to ensure the reliability of the results.

The FE and RE methods are used to verify the robustness test. As depicted in Table 6, the signs of EGP, and ECP in the two methods are in line with those in the DOLS, FMOLS and ARDL estimators. Precisely, a 1% enhancee in EGP caused a 2.413% and 2.124% increase in SEP for the FE, RE methods, respectively. The square of EGP has obvious negative influence on SEP. These results also verifiy the EKC hypothesis. Furthermore, ECP can effectively aggravate SEP in the 30 provinces of China. Consequently, the results of the robustness test are validated. To sum up, the results are supported by the DOLS, FMOLS, ARDL, FE, and RE methods.

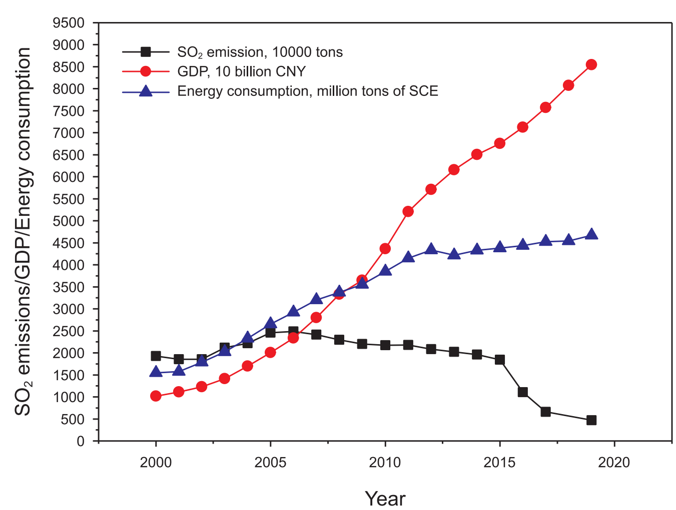

Fig. 2. Line chart of SO_2 emissions (SE), GDP, and energy consumption (EC) from 2000 to 2019 in China.

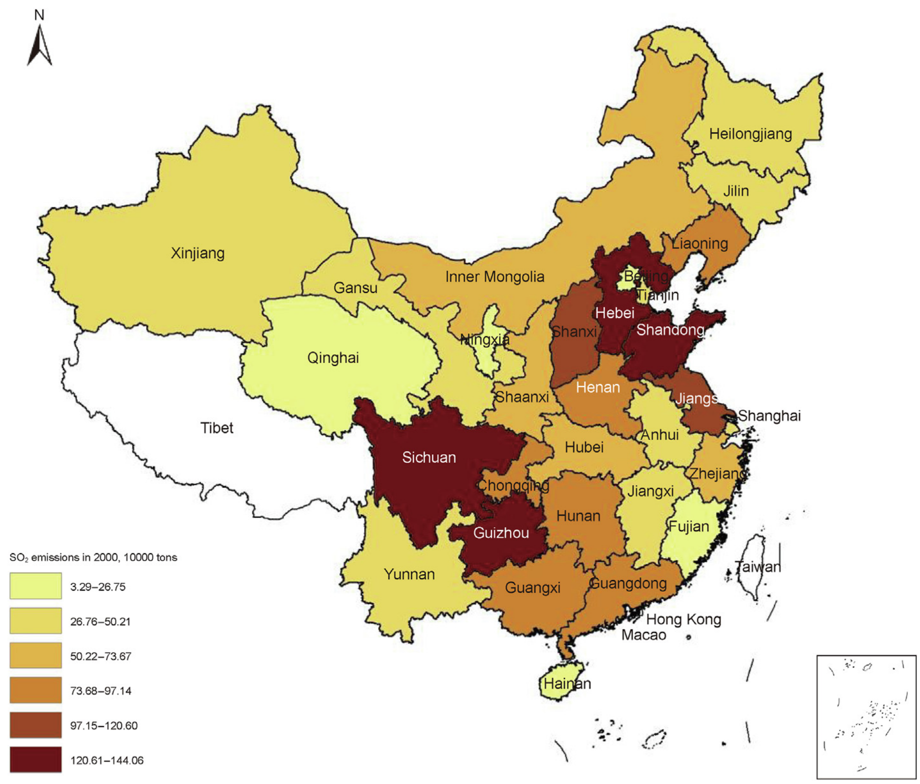

Fig. 3. Spatial characteristics of SO_2 emissions (SE) in 2000.

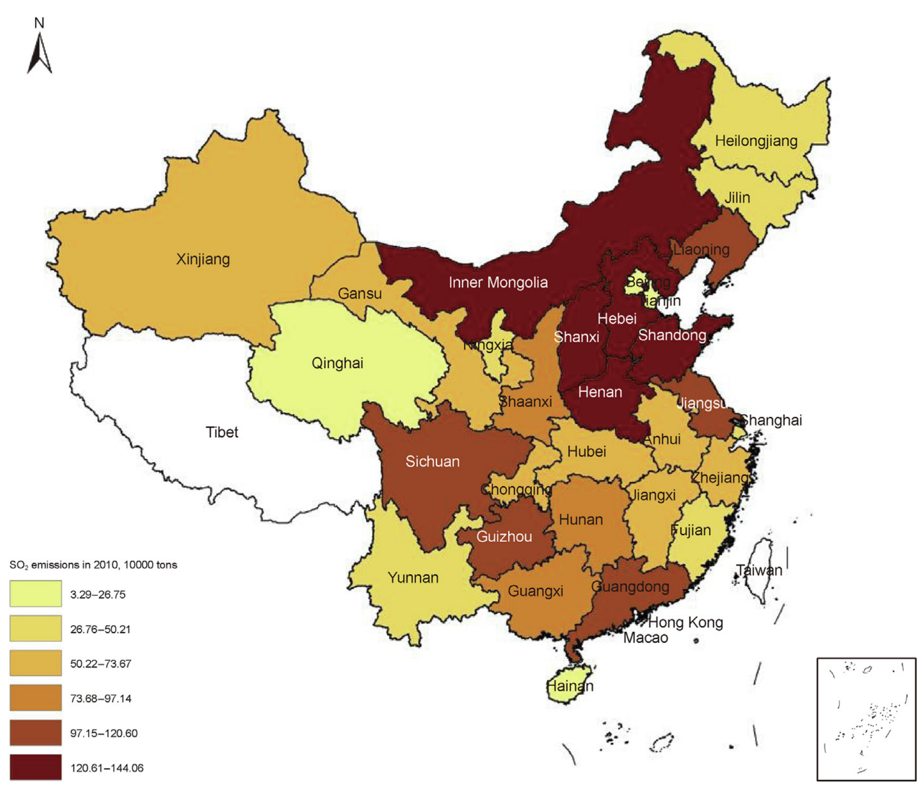

Fig. 4. Spatial characteristics of SO_2 emissions (SE) in 2010.

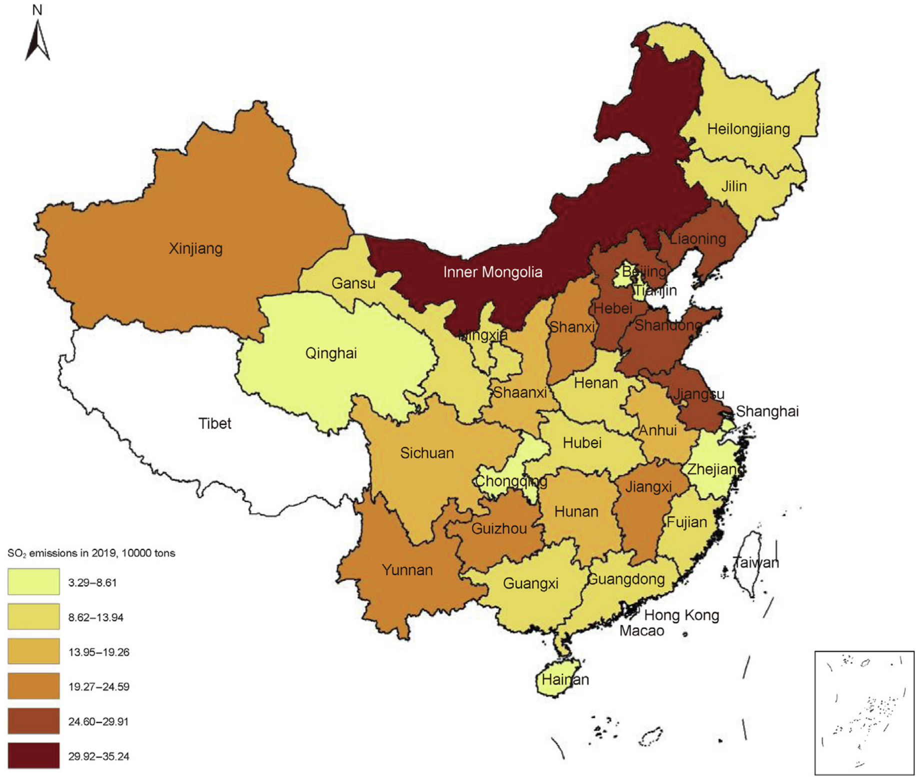

Fig. 5. Spatial characteristics of SO_2 emissions (SE) in 2019.

Table 2
Results of cross-sectional dependence test.

Test	Statistic	P-value
Breusch-Pagan LM	3922.376***	0.000
Pesaran scaled LM	118.233***	0.000
Pesaran CD	57.236***	0.000

Note: *** represents significance at 1%.

Table 3
Results of the Pesaran unit root test with cross-sectional dependence.

Variable	CIPS statistics	
	Level	1st difference
lnSEP	−2.339	−3.605***
lnEGP	−1.830	−2.928***
$(\ln EGP)^2$	−1.666	−2.870***
lnECP	−2.455	−4.300***

Notes: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Table 4
Results of the Johansen and Westerlund panel cointegration tests.

Test	Intercept		Intercept & trend	
	Statistic	p-value	Statistic	p-value
Panel v-statistic	2.591*	0.058	7.369***	0.000
Panel ADF- statistic	1.071	0.858	−1.816**	0.049
Variance ratio	−2.213**	0.013	−2.412***	0.007

Notes: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

4.4. Results of the D-H causality test

Table 7 exhibited the results of D-H causality tests. It can be inferred that a two-way causal relationship between EGP and SEP, EGP and ECP, respectively. A one-way causal association between ECP and SEP. SEP do not homogeneously cause ECP, but ECP does homogeneously cause EGP.

4.5. Discussion

To test the heterogeneity among provinces, a pooled regression model including FE and RE model are used to comprehensively prove the results, which are basically consistent. The results of the FE and RE model are in line with the model including the DOLS, FMOLS, ARDL methods. The Hausman test of FE and RE models was typically presented in the form of "Prob>chi2". This value represents the probability of observing the differences or more extreme differences under the assumption in the case of the null hypothesis being valid. Under condition of the Prob>chi2 value is relatively large (usually>0.05), the null hypothesis is valid, indicating that the difference of two estimators can be attributed to random error. In other words, there is no significant difference between the two estimates. On the other hand, if the Prob>chi2 value is relatively small (usually<0.05), the null hypothesis is not accepted. The results show that the Prob>chi2 value is 0.032, suggesting that the FE model is superior. Finally, according to Hausman test result, the null hypothesis is not valid at the 5% significance level. Therefore, the FE model can better explain the relationship between these selected variables. These findings suggest that the estimated results are consistent and stable.

5. Conclusions and policy implications

EC in China has witnessed a substantial and persistent growth from 2000 to 2019, making it a matter of utmost importance. By using cross-sectional dependence, panel unit root tests, Westerlund panel cointegration, D-H causality tests, this study is the first to

Table 5
Results of panel DOLS, FMOLS, and ARDL estimators.

Dependent variable: lnSEP			
Variables	DOLS estimator	FMOLS estimator	ARDL estimator
lnEGP	6.598*** (0.000)	2.163*** (0.000)	1.367***(0.000)
$(\ln EGP)^2$	−0.753*** (0.000)	−0.343*** (0.000)	−0.195***(0.000)
lnECP	1.621*** (0.005)	2.017** (0.000)	0.201***(0.000)

Notes: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively. The values in brackets represent the p-value.

Table 6
Results of fixed effect (FE) and random effect (RE) method estimation.

Dependent variable: ln SEP		
Variables	FE	RE
lnEGP	2.413*** (0.000)	2.124*** (0.000)
$(\ln EGP)^2$	−0.307*** (0.000)	−0.285*** (0.000)
lnECP	0.976*** (0.000)	1.078*** (0.000)
Hausman test	0.032	

Notes: ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively. The values in brackets represent the p-value.

Table 7
Results of the D-H causality test.

H_0	Z-bar	p-value
EGP does not homogeneously cause SEP	13.216***	0.000
SEP does not homogeneously cause EGP	16.991***	0.000
ECP does not homogeneously cause SEP	14.685***	0.000
SEP does not homogeneously cause ECP	1.058	0.289
EGP does not homogeneously cause ECP	49.067***	0.000
ECP does not homogeneously cause EGP	4.637***	0.000

examine the relationship nexus among EGP, ECP, and SEP from 30 provinces in China over the span of 2000–2019. The test results reflected that the EKC exists in the association between EGP and SEP, and ECP has a positive effect on SEP. Furthermore, unlike former studies, this study analyzes SE instead of CO_2 emissions and SE are one of the main sources of pollution in developing countries. Based on heterogeneity, this study can propose more targeted policy implications for environmental pollution and EC. More than 90% of SE come from coal in China, mainly in coal-fired power plants and energy industry. The Chinese government focused on taking control measures to significantly reduce SE from coal-fired power plants, causing total SE to peak in 2006. SE then steadily declined, pushing the EKC curve to reach an inflection point around 2005. This fully demonstrates the necessity for China to continue to formulate and implement air pollution prevention and control policies.

In summary, this study puts forward the following policy recommendations. First, economic development can positively influence the SE. With the continuous development of the economy, SE present a trend of first increasing and then decreasing. This is a common phenomenon in developing countries. Second, because EC has a significantly positive influence on SE, the government should improve the energy structure and provide impetus to use cleaner energy represented by natural gas rather than fossil fuels. The clean energy is becoming increasingly important for reducing SE, promoting the sustainable development of clean industry and achieving the government's goal of reducing harmful emissions. China has a large production capacity of clean energy, and expanding the scope of clean energy use is essential for solving the problem of environmental pollution. Given the importance of natural gas for energy structure adjustment and clean industrial development, comprehensive policy measures should be implemented to replace fossil fuels with natural gas. For example, the government can increase the cost of using fossil fuels through taxation and sewage charges, and can use tax revenues to subsidize enterprises and residents who use more natural gas.

Finally, the limitations of this study present some ideas for future investigation. Future research can add more factors to explore the causes of SE. Moreover, this study analyzes the 30 provinces in China at the overall level, but does not conduct a classified analysis by industry or region. Future research can analyze the influencing factors of SE from sub-industry or subregion, and provide more targeted SE reduction policies.

Data availability

The datasets used in this study are available on request.

CRediT authorship contribution statement

Bing-Jie Xu: Writing – original draft, Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yi-Fei Shen:** Writing – original draft, Investigation, Data curation. **Hui Qiao:** Methodology, Data curation, Conceptualization. **Zhi Gao:** Validation, Resources, Investigation.

Declaration of competing interest

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

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