Heterogeneous environmental regulations and green economic efficiency in China: the mediating role of industrial structure

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Abstract
Industrial upgrading is the key to promoting green economic efficiency. Coordination between environmental regulations and industrial structure can lead to sustainable economic growth. However, insufficient attention has been paid to the mechanism by which environmental regulation (ER) promote green economic efficiency (GEE) under the mediating role of industrial structure optimization. Using robust and comprehensive measures of green economic efficiency, we assess how various environmental regulations affect green economic efficiency as well as the intermediate effect of industrial structure of a certain province with provincial panel data during the period 2003–2017. The results of dynamic panel two-step system generalized method of moments (GMM) confirm the heterogeneous effects of the three types of ER, namely control-and-command regulation, market-based regulation, and voluntary regulation on GEE in China. The spatial analysis demonstrates that control-and-command and voluntary regulations significantly accelerate GEE in inland provinces, while they have insignificant effect in coastal provinces. Based on the mediating analysis, we find that market-based regulation is conducive to GEE through both advanced and rationalized industrial structure, whereas control-and-command regulation improves GEE through advanced industrial structure only. The voluntary-based regulation on one hand stimulates GEE through advanced industrial structure, but on other hand impedes it through rationalized industrial structure. The results could provide critical insights and a theoretical basis for policy makers in reasonable optimization of industrial structure and guaranteeing green economic efficiency.

Keywords Environmental regulation · Industrial structure · Green economic efficiency · Two-step system GMM · Mediating model · China

Nomenclature

| Symbol | Description |
|--------|-------------|
| SBM-DDF | Slacks-based direction distance function |
| GMM | Generalized method of moments |
| IS | Advanced industrial structure |
| IR | Industrial structure rationalization |
| GEE | Green economic efficiency |
| ER | Environmental regulation |
| CER | Control-and-command environmental regulation |
| MER | Market-based environmental regulation |
| VER | Voluntary environmental regulation |
| Z | Control indicators |
| \( \varepsilon_{it} \) | Random error term |
| \( P(x) \) | Production possibilities set |
| \( Z_t^i \) | Weight of period \( t \) |
| \( g \) | Directional vector |

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Introduction

In recent years, China’s economy has transformed from the rapid growth stage to the high-quality development stage and is in the critical period of changing the growth pattern, optimizing the industrial structure, and improving green economic efficiency. However, the massive consumption of fossil fuel resources and serious environmental pollution has become increasingly prominent in China (Wu et al. 2020), due to the extensive coal consumption, which accounted for 51.7% of the world’s overall coal consumption in 2019 (BP 2020). Moreover, the total amount of SO₂ emission and wastewater discharge was recorded 875.40 million and 69.97 billion tons, respectively, in 2017. Therefore, as the world’s largest polluter, there has been increasing pressure on China on both domestic and international fronts. To address the ecological challenges, China needs to improve its resource consumption efficiency and reduce the emission level. The concept of green economy aims at achieving the sustainable development without environmental degradation (UNEP 2011). To measure the level of green economy, scholars have extensively adopted green economic efficiency as an important determinant due to its close correlation with the sustainable development.

Green economic efficiency (GEE) is a significant determinant of evaluating the level of green economy (Zhao et al. 2020a). For economics perspective, economic efficiency generally implies that how to produce maximum output of economic products by the minimum consumption of input of productive factors. Green economic efficiency takes into account the means of social development and economic growth that targets economic efficiency, sustainable social development, and coordination between the economic growth and environment, and it has the implications for resource conservation and ecological protection (Luo et al. 2021). In green economic growth, the emphasis is placed on both the quantity and quality of economic development. The quality of economic growth depends on a detailed assessment of the economic expansion of an economy, while avoiding the quantity. Based on the conditions of environmental carrying capacity and resources shortage, achieving the efficiency of input is an important mechanism of economic growth than pursuing only the economic expansion. Over the course of economic development, China places primary importance on the quality and efficiency, such as total factor productivity, resource allocation efficiency, and urban ecological efficiency, which all partially indicate the concept of green economic efficiency. Under the sustainable development strategy, China has introduced five concepts including green, coordination, innovation, openness, and sharing. Green is the important condition for sustainable development and is the basis for accelerating green economic efficiency (Deng et al. 2019).

Environmental regulations, aim at resource conservation and environmental protection, indicate the direct and indirect intervention and control of the government in resource consumption by industries. Moreover, environmental regulation is an important tool to reduce energy intensity and alleviate the externalities of pollution (Bi et al. 2014). In recent years, the Chinese government took several initiatives in a bid to reform the current environmental monitoring system, safeguard public health, promote green economic efficiency, and enforce local governments to fulfill ecological responsibilities. To streamline the environmental monitoring system, China’s funding to environmental governance has increased from 175 billion RMB in 2003 to 954 billion RMB in 2017. In empirical research, many scholars have analyzed the roles of environmental regulations in the fields of environment and energy, such as energy efficiency (Liu et al. 2018a, b), SO₂ emission abatement (Pang et al. 2019), haze pollution reduction (Zhang et al. 2020b), CO₂ emission reduction (Wang and Wei 2020), and green economic efficiency promotion (Su and Zhang 2020), and found that environmental regulations play a vibrant role in improving energy efficiency and reducing environmental pollution. On contrary, some scholars argue that environmental regulation will increase the production cost as well the cost of pollution control and prevention, and will impede the competitiveness and cleaner production capacity of the firms (Li et al. 2019).

Coordination between environmental regulations and the optimization of industrial structure can stimulate energy efficiency and reduce pollution, improve resource consumption efficiency, optimize the allocation of resources, and accelerate green economic efficiency (Gollop and Roberts 1983). Through the execution of stringent environmental regulations, firms will be required to include the external costs caused by pollution in the production process, thus forcing pollution-driven companies to minimize production. However, if no external environmental policy is implanted, enterprises would not adopt green production practices and would not expedite green economic efficiency (Greenstone and Hanna 2014), and frequently ignore the environmental costs. Hence, the difference between the total costs of society and firms’ private costs will result in overproduction in the emission-driven industries.

Furthermore, the literature has claimed that there is heterogeneity in the promotion effects of environmental regulations on green economic efficiency and industrial structure transformation among regions due to different economic growth levels. Specifically, developed regions have extensive talents and funds to promote R&D activities and achieve green economic productivity. On the other hand, underdeveloped regions lack resources, which are not

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1 https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
enough to stimulate green innovation. Thus, regions with low economic development levels face more challenges in the development and diffusion of green technology innovation and achieving green economic efficiency. Also, environmental regulation will influence the production capacity of firms. For instance, industrial competitiveness is relatively low in underdeveloped regions. As a result, environmental regulations probably pull out production operations in these regions. In underdeveloped regions, secondary industry is the main driver of economic development, which consumes extensive energy and impedes green economic efficiency. Considering that the heterogeneous environmental regulations (i.e., command-and-control, market-based and voluntary regulations), industrial pattern, and remarkable differences in the levels of economic development across different regions, the levels of green economic efficacy may differ significantly among these regions. Therefore, it is of great practical importance to incorporate green economic efficiency, environmental regulations, and industrial structure into a unified research framework.

Driven by the above discussion, the motivation of this study is to develop a comprehensive understanding on how various environmental regulations affect green economic efficiency and whether industrial structure plays a mediating role or not in China. Therefore, this study proposes the following important research questions. (1) What is the recent trend in green economic efficiency of China, and does it show region-based heterogeneity? (2) What are the effects of different types of environmental regulations on green economic efficiency? Are there regional variations in their effects? (3) Do the effects of advanced and rationalized industrial structures on green economic efficiency have mediating characteristics? If yes, which industrial structure plays a beneficial mediating role?

To answer the above questions, this study makes the following three essential novelties: (1) This study employs the slacks-based direction distance function (SBM-DDF) method to assess the green economic efficiency across 30 provinces in China over the period from 2003 to 2017. Moreover, this study conducts both spatial and regional heterogeneity analysis to identify the spatial and regional differences in green economic efficiency. (2) This study disaggregates the environmental regulations into three types, such as control-and-command regulation, market-based regulation, and voluntary regulation, and comprehensively examines their effects on green economic efficiency. (3) We classify the industrial structure into advanced and rationalized industries and explore the mediating characteristics of both industrial structures in environmental regulations affecting green economic efficiency by using the two-step system generalized method of moments (GMM) method. Compared with previous studies, this study provides more robust empirical results and precisely identifies the effects of environmental regulations on green economic efficiency and industrial structure change.

The subsequent contents of this work are organized as follows: Literature review is elaborated in the “Literature review” section. In the “Theoretical basis and mechanism” section, the theoretical basis and mechanism of the study is debated. Analytical framework and variable selection are presented in the “Methodology” section. The “Results” section provides the findings of this study. Conclusions and policy implications are discussed in the “Conclusions and policy recommendations” section.

**Literature review**

**Measurement of green economic efficiency**

In the literature, scholars have used two main approaches namely the stochastic frontier analysis (SFA) and the data envelopment analysis (DEA) to calculate green economic efficiency. The SFA is a parametric approach, which requires setting the probability distribution from a random error term (Aigner et al. 1977). Another prerequisite of this method is to develop a priori production function form and distribution hypothesis, which might influence the precision and reliability of the green economic efficiency estimation results. Furthermore, this method simply considers a production process with one output and fails to efficiently tackle the case of several outputs, since green economic efficiency estimation requires both desirable and undesirable outputs simultaneously, which to some degree affect its application (Chen and Golley 2014). On the contrary, data envelopment analysis (DEA) method, which is a nonparametric approach, does not consider the assumption of the production function forms in advance, and effectively avoids the subjective factors, which simplifies the measurement by eliminating errors. Moreover, this method divides output into technological progress and efficiency change. Finally, this approach effectively analyzes the green economic efficiency with several outputs. Therefore, DEA method is relatively more popular and extensively used approach to measure green economic efficiency (Gao et al. 2021a, 2021b; Salman et al. 2022a).

**Environmental regulation and green economic efficiency**

In literature, the effects of environmental regulation on green economic efficiency have been extensively examined and did not reach to a unanimous conclusion. Jin et al. (2019) found that environmental regulation was not conducive to the green TFP of industrial water sources in China. Danish and Uluçak (2020) found that environmental-related technologies contribute positively to the green growth in BRICS countries.
Other group of scholars has considered the nexus between environmental regulations and green economic efficacy from nonlinear perspective. According to Li and Wu (2016), local environmental regulation positively affects green TFP of higher political attribute cities, while negatively affects in lower political attribute cities. Similarly, Wang et al. (2019) validated an inverted U-shaped relationship between environmental policy and green productivity across industrial sectors of OECD countries. The third stream of studies examined the role environmental regulation on green economic efficiency from heterogeneous standpoint. Zhao et al. (2015) argued that both market-based regulations and government subsidies significantly improved the production efficiency, while command and control regulations yield insignificant impact. Ren et al. (2018) found that voluntary environmental regulation and market-based have favorable effects on eco-efficiency in the eastern and central regions, whereas command-and-control regulation improves green growth in the central and western regions in China. Wang et al. (2021b) found that environmental regulations in 9% of cities promote green productivity in China. Based on the above literature, this study proposes hypothesis 1 as:

H1: The three types of environmental regulations have heterogeneous effects on China’s green economic efficiency.

Environmental regulation and industrial structure

Previous many scholars have analyzed the effect of environmental regulation on the transformation and modernization of industries. For example, Zhang et al. (2019) constructed quantitative indices of policy measures and objectives to explore the effects of environmental regulations on industrial structure and found that environmental regulation is conducive to industrial pattern transformation in the long run. From the perspective of industry chain, Zhu et al. (2019a, b) claimed that the implementation of strict environmental regulations will improve the productivity of steel industry. Ju et al. (2020) explored the effects of three different types of environmental regulations (voluntary compliance, mandatory control, and market incentive) on the green economic efficiency of different industries (low-polluting, middle-polluting, and high-polluting). They argued that various types of environmental regulations have differential effects on the same industry, and the energy efficiency and emission reduction capacity of middle-polluting industry is relatively higher. According to Zhai and An (2020), environmental regulations stimulate green economic efficiency of manufacturing industry through governmental behavior and financing capacity. Ouyang et al. (2020) found that environmental regulations significantly reduce carbon emissions of energy-intensive industries.

Other group of scholars empirically analyzed whether environmental regulation can cause industrial reallocation, in other words, whether the “pollution heaven effect” exists or not. Mulatu et al. (2010) estimated the effect of environmental regulation on the redistribution of 16 manufacturing industries across 13 European economies and validated the existence of pollution heaven effect. Bagayev and Lochard (2017) found that EU countries with strict environmental regulations are more intended to import pollution-intensive goods from emerging economies than to manufacture by themselves. Wu et al. (2019) investigated the role of environmental regulation in the restructuring of dirty industries. They verified the presence of both the Porter hypothesis and the pollution heaven hypothesis in China. Zhao et al. (2020c) argued that well-crafted environmental regulation will not only influence CO2 emissions in a direct way but also indirectly affect investment in emission-intensive industries, resulting in the redistribution of pollution-intensive industries within the region. Yu and Wang (2021) argued that environmental regulation has positive and significant effect on the upgrading of industrial structure, but there are apparent regional disparities in the effectiveness of environmental regulations. Thus, this study develops the hypothesis 2 as follows:

H2: Environmental regulations are conducive to the optimization of industrial structure in China. However, there are significant differences in the advantageous effects of heterogeneous environmental regulations.

Industrial structure and green economic efficiency

The mechanism underlying the influence of industrial structure on green economic efficiency can be explained in two ways. First, industrial structure is conducive to improving ecological efficiency. Industrial transformation from labor-based to technological-driven and from emissions-intensive to cleaner production restrict further development of emissions-intensive industries, thereby improve their production efficiency. Second, industrial structure reflects the rate of flow of production factors, including capital and labor among industries. If these factors turn to be environment-friendly then the level of green efficiency will be improved; otherwise, the green growth efficiency will be declined. Moreover, Xiong et al. (2019) claimed that industrial structure efficiency increases provincial industrial energy efficiency in China. Zhou et al. (2019) analyzed the impact of industrial structure on eco-efficiency across 48 cities in China. They stated that industrial structure transformation significantly increased eco-efficiency, but the indirect effect of the industrial structure is negative from a spatial perspective. Guo et al. (2020) used the data of 34 cities in China and confirmed that industrial structure is negatively
related to green growth. Other scholars investigated the effect of industrial structure on green economic efficiency from advanced and rationalized perspective. For example, Zhu et al. (2019a, b) found that industrial advancement and rationalization have streamlined China’s green economic development. Zhao et al. (2020b) pointed out that industrial structure advancement significantly improves the environmental performance in China. However, heavy reliance on fossil-fuel resources will not only impede the favorable effect of industrial restructuring but also adversely affect the economic development level. Zhao et al. (2021) found that industrial structure upgrading can improve green economic efficiency by reducing environmental pollution in China. Therefore, this study formulates hypothesis 3 as follows:

**H3: The industrial structure optimization can accelerate China’s green economic efficiency.**

From the existing literature, it is evident that scholars have rarely analyzed the heterogeneous effects of environmental regulations on green economic efficiency, especially with a focus on the mediating effect of industrial structure. To address these gaps, this study therefore contributes to the existing literature in the following manner. This study examines the heterogeneous impact mechanism of environmental regulations on green economic efficiency. Additionally, taking geographical and spatial heterogeneity into consideration, the dataset is divided into inland and coastal regions and 2003 ~ 2010 and 2011 ~ 2017 time periods for empirical analysis. Second, the industrial structure is further classified into advanced and rationalized industrial structure, and examined their differential effects on green economic efficiency. Third, based on mediation roles of advanced and rationalized industrial structure, the impact mechanism of environmental regulations on green economic efficiency is empirically explored.

**Theoretical basis and mechanism**

In this section, we discuss the mechanism through which environmental regulation affects the factor endowment of industry and its green economic efficiency.

**Innovative compensation theory**

The Porter hypothesis (PH) states that polluting firms can benefit from environmental policies, arguing that well-designed and stringent environmental regulation can stimulate innovations, which in turn increase the productivity of firms or the product value for end users (Porter 1991). Ambec et al. (2013) both theoretically and empirically found that environmental regulations encourage firms to increase technological innovation and accelerate their green economic efficiency. In the similar vein, Albrizio et al. (2017) argued that well-implemented environmental regulations enhance productivity of firms in a short-run in technologically developed countries. Yu et al. (2019) stated that environmental regulations have different effects on green economic efficiency of industries, that is, the forced effect of environmental regulation on green economic efficiency of firms is generally reflected in the private firms.

**Following the cost theory**

Several researchers began to determine the key reasons affecting economic development and empirically examined how environmental organizations influence industry’s green growth. Consequently, the design and importance of environmental regulations has considerably raised the production costs of firms and resulted in the reduction of corporate profits. Gollop and Roberts (1983) claimed that environmental regulations have significantly increased costs of production and considerably reduced productivity growth. The higher costs of production would adversely affect economic growth (Jorgenson and Wilcoxen 1990), which is not beneficial to the green economic efficiency. Gray (1987) found that environmental regulation and government supervision have partially increased firm’s production cost, resulting in lower productivity of manufacturing industry. Based on the cost theory, the impact of environmental regulations on production cost has been extensively explored in empirical research by using different datasets and research methods (Shuai and Fan, 2020).

**The uncertainty hypothesis**

Followers of this hypothesis state that the role of environmental regulations on economic growth is challenging to envisage. Kuosmanen et al. (2009) found that environmental regulations affect economic development in the short run, and the advantageous impacts of environmental regulations on the economic growth are challenging to determine, while in the long term, there are significant advantages. The variations in economic efficiency unavoidably affect green economic efficiency. It is also evident that different environmental regulations have different effects on green growth. For example, in the short run, market-incentive environmental regulations have stimulated green economic efficiency, but further stringency would adversely affect green economic efficiency (Yuan and Xiang, 2018). According to Wang et al. (2019), the effect of environmental regulations on green economic efficiency has nonlinear characteristics in China. In summary, in the light of the uncertainty hypothesis, studies have found that the upgrading and transformation of
industrial structure has influenced green economic efficiency. Because the effect of environmental regulations on green economic efficiency of industry is not obvious, the influence of industrial structure on green economic efficiency may be moderately obvious (Luo et al., 2021).

Methodology

DEA methodology

In the literature, the DEA methods have been extensively used for green economic estimation. However, the radial and angular DEA models do not consider relaxation variables and avoid several inputs or outputs, leading to biased estimation. To solve this problem, this study uses the directional distance function (DDF) model, which effectively addresses the measurement error by incorporating slack variables of inputs and outputs (Chung et al. 1997) and can be expressed as follows:

\[ \overline{D}_0(x, y, b) = \text{sup} \{ \beta : (y, b) + \beta x \in P(x) \} \]  
(1)

where \( x, y, b \) are inputs (labor, capital stock, and energy), good output (gross domestic product), and bad outputs (sulfur dioxide emissions, smoke (dust) emissions, and wastewater emissions) of decision-making units (DMUs), respectively. \( g \) is the directional vector, defined as \( (g_y, -g_b) \). \( \beta \) denotes the expansion or contraction ratio of good and bad outputs, and \( \overline{D}_0 \) indicates the increase in good outputs and decrease in bad outputs, simultaneously. \( P(x) \) is the production possibilities and defined as Eq. 2:

\[ P(x) = \{(x, y, b) : x \text{ produce } (y, b), x \in R^+_M, y \in R^+_N, b \in R^+_I \} \]  
(2)

where \( M, N, \) and \( I \) are respectively number of inputs, good outputs, and bad outputs.

Even though traditional DDF is widely adopted estimation technique to measure green productivity. However, it suffers from radial and guiding problems and the estimated green economic efficiency deviates from the actual one. Tone (2001) considered the shortcomings of traditional DDF and developed a nonradial, nonoriented SBM model based on the slack variable measurement. To solve the problem of deviation in efficiency estimation, Fukuyama and Weber (2009) combined the SBM method with the directional distance function and proposed the latest production efficiency measurement model—based on the slack-based measurement direction distance function (SBM-DDF). In this study, we measure China’s green economic efficiency through the following linear programing of the SBM-DDF model.

\[ \overline{D}_0(x, y, b, g^s, g^b) = \max \frac{1}{n} \sum_{i=1}^{M} x_m^i + \frac{1}{n} \sum_{i=1}^{N} y_m^i + \frac{1}{n} \sum_{i=1}^{I} b_m^i \]

s.t.

\[ \sum_{i=1}^{M} x_m^i + s_m^b = x_m^v, \forall m \]

\[ \sum_{i=1}^{N} y_m^i - s_m^g = y_m^v, \forall m \]

\[ \sum_{i=1}^{I} b_m^i + s_m^b = b_m^v, \forall i \]

\[ \sum_{i=1}^{I} \lambda_i = 1, \lambda_i \geq 0, \forall k \]

\[ s_m^b \geq 0, \forall m, s_m^g \geq 0, \forall m, s_m^b \geq 0, \forall i \]

where \( (x_m^b, y_m^b, b_m^b) \) indicate input–output vectors; \((g^s, g^b, g^b)\) is the direction vector; \((g_m^g, g_m^b, g_m^b)\) represent direction of \( n \)th input, \( n \)th good output, and \( i \)th bad output projected onto the technological frontier, respectively; \((s_m^b, s_m^g, s_m^b)\) is the slack vector of the input and output reaching the efficiency frontier; \( \lambda_i \) is the weight of period \( t \).

System GMM estimator

This study uses the system-GMM estimator developed by Blundell and Bond (1998) for empirical analysis. Unlike difference-GMM and horizontal GMM that have low accuracy and higher sample bias, the system-GMM considers the lagged differences of the explained variable as instruments for estimation at levels and also incorporates the lagged levels of the explanatory variables for calculation at first differences. In this study, we methodically demonstrate and discuss the differential effects of environmental regulations, industrial structure, and control variables (degree of opening, technical progress, government intervention, urbanization, and human capital) as an indicator of province’s green economic efficiency. This study therefore considers green economic efficiency as endogenous variable, while ER and control variables as exogenous variable.

System-GMM is robust to autocorrelation and heteroscedasticity. Therefore, it improves the estimation efficiency and provides relatively more robust and consistent results. Moreover, GMM estimators can be classified into two kinds of transformation approaches, known as first-difference transformation (one-step GMM) and second-order transformation (two-step GMM). However, the one-step GMM has some restrictions. For example, if a variable’s current value is missing, one-step GMM method (where a variable’s previous value is deducted from its current value) could lose many observations (Roodman, 2009). To overcome this problem, Arellano and Bover (1995) suggested the application of a two-step GMM estimator. Thus, in the case of a balanced panel dataset, the endogenous problem can be effectively solved by using a two-step system GMM model, and it can be outlined as follows:

\[ GEE_{it} = \alpha + \beta_i GEE_{it-1} + \beta_t ER_{it} + \lambda Z_{it} + \epsilon_{it} \]  
(4)

where \( i \) and \( t \) are the province and period, respectively. \( GEE_{it} \) and \( GEE_{it-1} \) indicate the green economic efficiency of the i
Mediating model

To accelerate green economic efficiency, the modernization of industrial structure is an effective and long-term strategy. In the new development stage, industrial structure optimization is the top priority of the Chinese government in a bid to promote sustainable development without jeopardizing the environment. Based on the classical mediating effect model developed by Baron and Kenny (1986), this study examines the mediating role of industrial pattern in environmental regulation affecting green economic efficiency. Referring to Preacher and Hayes (2008) and MacKinnon et al. (2002), this paper adopts multiple mediation models to test whether mediation effects of advanced and rationalized industrial structure are statistically significant. This effectively avoids the higher type I error rates and reduces biased estimates in the model. Integrating the time-lag terms of the explained variables, the mediating effect models can be expressed as follows:

\[
IS_{it} = \alpha_1 + \delta_1 IS_{i,t-1} + \delta_2 ER_{it} + \lambda Z_{it} + \epsilon_{it} \quad (5)
\]

\[
IR_{it} = \alpha_2 + \gamma_1 IR_{i,t-1} + \gamma_2 ER_{it} + \lambda Z_{it} + \epsilon_{it} \quad (6)
\]

\[
GEE_{it} = \alpha_3 + \theta_1 GEE_{i,t-1} + \theta_2 IS_{it} + \theta_3 IR_{it} + \theta_4 ER_{it} + \lambda Z_{it} + \epsilon_{it} \quad (7)
\]

where \(i\) and \(t\) are the province and time dimensions, respectively. \(IS_{it}, IR_{it},\) and \(GEE_{it}\) are respectively advanced industrial structure, industrial structure rationalization and green economic efficiency. \(\delta_1\) is the first-order lag variable coefficient of \(IS\) on \(IS\). \(\delta_2\) is the coefficient of \(ER\) on \(IS\). \(\gamma_1\) is the first-order lag variable coefficient of \(IR\) on \(IR\). \(\gamma_2\) is coefficient of \(ER\) on \(IR\). \(\theta_1, \theta_2, \theta_3\) are coefficients of \(IS\) and \(IR\) on \(GEE\), respectively. \(\lambda\) indicates the control variable coefficient.

Variable selection and data sources

Input–output variables

This study employs the classical input variables namely labor, capital stock, and energy consumption. For the labor, this paper selects the number of employees in each province at the end of the year Zhao et al., (2020a). Regarding energy input, this study converted the use of energy consumption of each province into standard coal (Wu et al., 2020). Since there was no statistical data on the provincial’s capital stock; this paper follows the study of Zhang et al. (2004) to measure the capital stock through “perpetual inventory method” as follows:

\[
K_{it} = K_{i,t-1} (1 - \delta_i) + I_{it} \quad (8)
\]

where \(K_{i,t-1}\) and \(K_{it}\) represent the capital stock of province \(i\) in year \(t-1\) and \(t\) years, respectively. Capital stock is the total fixed capital formation in the year 2000 divided by 10%. \(\delta_i\) represents the depreciation rate in year \(t\). \(\delta_i\) in this study is 9.6%. \(I_{it}\) denotes the investment amount represented by total fixed capital formation and deflated to the constant price following the base year 2000 based on the fixed asset investment price index.

This paper uses GDP to represent the expected output, deflated to the constant price as of the year 2000 consistent with the consumer price index. The undesired outputs include sulfur dioxide emissions, smoke (dust) emissions, and wastewater emissions (Guo et al. 2020).

Core independent variable

This study considers various types of environmental regulations as core explanatory variables. Among the three types, command-and-control environmental regulation is represented by the comprehensive index of environmental indicators—sulfur dioxide emissions, smoke (powder) dust emission, and total waste water discharge using entropy evaluation method (Li and Zou 2018; Tian and Hao 2020). Following Zhao et al. (2018), market-based environmental regulation is represented by logarithm of the investment in control of industrial pollution sources, which is deflated to the constant price as of the year 2000 in line with the consumer price index. Voluntary environmental regulation is represented by logarithm of the number of letters and personnel for the Environmental Letters and Visits Office (Ren et al. 2018).

Mediating variable

Consistent with Hung and Cuong (2018) and Sun et al. (2018), rationalized and advanced industrial structures are included as mediating variables in this study. The rationalization of the industrial structure is expressed by the reciprocal of the Theil index (Zhong et al., 2021). The Theil index considers the relative importance of the industry and avoids the estimation of the absolute values. The specific calculation method is defined as:
where $Y_{it}$, $L_{it}$, are GDP and number of employees of the $i$ province and the $s$ indicates the industrial area in the year $t$, respectively. $Y_{it}$ and $L_{it}$ indicate GDP and the number of employees of the $i$ province in year $t$, respectively. $IR_{it}$ is the industrial structure rationalization for the $ith$ province in year $t$. The higher $IR_{it}$ value indicates the unreasonable industrial structure.

An important feature of the advanced industrial pattern is the service-oriented economic structure (Gan et al. 2011), and the growth rate of the tertiary industry is higher than that of the secondary industry (Wu, 2006). Therefore, this study refers to Fu (2010) to define the advanced industrial structure, which can reflect whether the economic structure is changing in the direction of service and can be modeled as:

$$
\theta_j = \arccos \left( \frac{1}{\sum_{i=1}^{3} (x_i \cdot x_{i,j})} \right), \quad j = 1, 2, 3
$$

$$
IS = 3 \times \theta_1 + 2 \times \theta_2 + 1 \times \theta_3
$$

where $x_{i,j}$ denotes the proportion of $j$th industry in $ith$ province. $X_1 = (1,0,0)$, $X_2 = (0,1,0)$, $X_3 = (0,0,1)$ are the base vectors of industrial structure from low to high. $\theta_j$ is the angle of the $j$th industry. IS denotes advanced industrial structure. The larger $IS$ value implies the higher industrial structure advancement.

Control variables

1. Degree of opening (OPEN). Openness may either incur incalculable environmental cost alongside regional economic growth and hinder green economic efficiency or bring a green technological spillover effect of improving economic growth in the long run accompanied with an improved environmental performance, only when the degree of green technological is closely related to the stringency of environmental regulation of the host countries (Xie et al., 2017). This study employs the percentage of actually utilized foreign direct investment in GDP to measure the degree of outward economy.

2. Technical progress (TP). Green technical progress is the key driving force to promote environmentally sustainable economic growth (Salman et al., 2019d). This study uses logarithm of the number of domestic patent applications to represent technical progress (Salman et al., 2022b, 2022c).

3. Government intervention (GII). During the initial phase of economic growth, local governments prioritize economic expansion over environmental quality, and allocate low funds to protect the environment (Copeland and Taylor, 2004). However, as the per capita income increases, the environmental awareness of the people also increases. Therefore, environmental protection is the top priority of the local governments (Wang et al., 2021a). In this paper, we use logarithm of general budget expenditure of local finance to proxy the government intervention.

4. Urbanization (Urban). Urbanization may affect green economic efficiency in two ways. First, urbanization aids production accumulation which further contributes to green growth. Second, infrastructure development consumes extensive amount of energy and release more greenhouse gases which ultimately decelerate green economic efficiency (Du and Li, 2019). This paper uses the percentage of urban population to total population to measure urbanization level.

5. Human capital (HC). Innovation is essential for green economic growth in both developed and developing countries. One of the most important sources of innovation is human capital Zhang et al. (2020a). Number of students in regular institutions of higher learning per 10,000 people represents the human capital in this study (Fig. 1).

Data sources

This study uses the dataset of thirty provincial administrative regions in China over the period 2003–2017. We extract the data of command-and-control environmental regulation, degree of opening, government intervention, urbanization, and human capital from the China Statistical Yearbook for each year. The data on technical progress came from the China National Intellectual Property Administration (CNIPA). The data source on market-based environmental regulation is obtained from the China Environment Database. The data on voluntary environmental regulation is collected from the China Environmental Yearbook. The results of descriptive statistics are shown in Table 1.

Results

Spatiotemporal change of GEE

Figure 2 shows the temporal variation characteristics of GEE across national, coastal, and inland regions in China from 2003 to 2017. Clearly, GEE showed declining trend at national level with the decrease from 0.55 in 2003 to 0.37 in 2017. We further noticed that there was a fluctuant
The results documented that China’s green economic efficiency experienced a downward growth over the study period. The result can be explained by the fact that the economic benefit-oriented development mode has deteriorated environmental quality and impeded green economic efficiency. As elaborated by Zhao et al. (2020a), the prognosis for widespread attainment of green economic efficiency across different regions in China is quite bleak, since there are significant region-based differences in green economic development in China. They further argued that most of the economically developed provinces are located in coastal region, and they have modernized their industrial structure through stringent environmental regulations. Also, the local governments in coastal region have encouraged foreign enterprises to transfer cleaner production technologies and promote environmentally-friendly economic activities. On the other hand, majority of the provinces in inland region have entered in rapid phase of economic development, and the local governments prefer to improve their economies at the cost of environmental degradation. Additionally, foreign investment transfers their emission-intensive industries to the less-developed provinces of inland region. This has significantly affected regional green economic efficiency of inland region.

We then sketch in Fig. 3 the spatial variation in green economic efficiency for the whole sample in three different time horizons, i.e., 2003, 2010, and 2017. Based on our estimates, 60% of provinces had average GEE scores lower than 0.50 in 2003 with the Guizhou having the lowest GEE score of 0.213. In 2010, Beijing, Tianjin, Shanghai, and Guangdong had relatively higher GEE scores, while Qinghai (0.214)
achieved the lowest average green economic efficiency. In 2017, the green economic efficiency was higher in Beijing, Shanghai, and Guangdong, and the green economic efficiency was low in Qinghai. The overall green economic efficiency exhibited a decreasing pattern in the years of 2003, 2010, and 2017 with considerable regional differences. Additionally, the results showed that green economic efficiency was in a gradient decreasing pattern of “east–west.”

**Unit root and multicollinearity test**

Unit root is a serious issue when an econometric model includes many explanatory variables. If this issue is not addressed then the regression estimates may be biased and inconsistent (Salman et al., 2019b). Thus, this study conducts three unit root tests to check the stability of the variables (Table 2). Based on the results, the three unit root tests show that all the variables are stationary at 5% significance level and reject the null of non-stationary.

In the next step, we employed the variance inflation factor (VIF) to detect the multicollinearity issue in the data. If VIF > 10, it points out the presence of multicollinearity; otherwise, the model has no multicollinearity issue. The results demonstrate that the VIF values of all variables are less than 10, meaning that there is no multicollinearity problem in the model.

**Whole sample analysis**

The estimates of two-step system GMM shown in Table 3 found that adopting the dynamic model was appropriate, since the first-lag order of GEE is statistically significant and positive. The results further revealed that the command-and-control, market-based, and voluntary environmental regulation significantly promote green economic efficiency. Command and control regulation is a type of environmental regulation that allows policy makers to specifically regulate both the amount and the process by which a firm should maintain the quality of the environment. It sets specific limits for pollution emissions and/or mandates that specific pollution-control technologies that must be used. The results are line with the study of Cheng et al. (2017) who argued that command-and-control significantly reduced environmental pollution. The coefficients of MER and VER are statistically significant and positive, indicating that one per cent increase in MER and VER accelerate green economic efficiency by 3% and 4.5%, respectively. Our results are consistent with the study of Gao et al. (2021b). It is evident from Table 3 that the magnitude of the promotion effect of CER is relatively stronger than the other two types of environmental regulations. Command and control instruments involve a government issuing a command, which sets a standard and then controlling performance by monitoring and requiring adherence to that standard. It is most commonly applied to pollution issues, where a command might be that no facility will emit more than specific units of pollutant per measured output unit or measure. On the other hand, market-oriented environmental policies create incentives to allow firms some flexibility in reducing pollution. Therefore, MER exerts relatively a minor impact on enterprise production, and ultimately weakens its impact on green productivity (Jin et al., 2019).

Regarding control variables analysis, our estimates demonstrate that the degree of openness has positive significant effect on green economic efficiency. The positive effect of openness indicates that the Chinese government has prioritized the import of environmentally friendly technologies by tightening the environmental regulations. The result is in line with Gao et al. (2021a).
From the perspective of government intervention, the negative effect on green economic efficiency shows that the intervention of government in the achievement of green growth is not conducive. As Li et al. (2018) stated, officials tend to boost economy at the cost of environmental consequences during the initial and middle stages of industrialization. Under the pressure of officials’ promotion, which is up to the economy (Li and Zhou, 2005), they prefer to develop the economy.

From the perspective of urbanization and technical progress, the two variables have advantageous effects on the level of green economy. This implies that the process of urbanization influences regional green economic efficiency through the spillover effect of technological progress. The improvement of urbanization level not only accelerates green economic growth but also promotes the development of clean production technology. During the study period, the urbanization level of China has been steadily improved, and the level of green economic efficiency has also changed in the same direction. In the process of urbanization, the construction of a green economy and sustainable development has achieved great results. Our results are supported by the recent study of Sun and Huang (2020).

Regarding human capital, the negative effect on of HC on green economic efficiency suggests that an increase in human capital will deteriorate the level of green economic
efficiency. This result reveals that in order for a society to be sustainable, there needs to be an importance on education and the development of human capital. Moreover, the curriculum needs to be more focused on environmental sustainability and the improvement of society. As it is specified that human capital is comprised of knowledge and skills that help in mitigating environmental issues but in the case of the current study results, education along with skills does not merely fortify human capital in China. The result is in line with the study of Zia et al. (2021) which suggests that human capital significantly reduced the level of green economic growth by increasing ecological footprint in China.

### Heterogeneity analysis

#### Temporal heterogeneity

Environmental policy is not always static but keeps changing at different stages. According to the 11th Five-Year Plan, the study period is divided into two time horizons, 2003 ~ 2010 which is “before 2010” and 2011 ~ 2017 which is “after 2010.” We then analyzed the temporal heterogeneity effects of environmental regulations on green economic efficiency “before 2010” and “after 2010” periods, respectively (Table 4). Based on results of “before 2010,” we found that command-and-control and voluntary

#### Table 3 Impact of heterogeneity environmental regulations on GEE

| Variables | GEE   | GEE   | GEE   |
|-----------|-------|-------|-------|
| L.GEE     | 0.488*** | 0.511*** | 0.496*** |
| (42.60)   | (43.85) | (66.85) |
| CER       | 0.444*** |       |       |
| (10.23)   |       |       |       |
| MER       |       | 0.030*** |       |
| (12.97)   |       |       |       |
| VER       |       |       | 0.045*** |
| (28.07)   |       |       |       |
| OPEN      |       |       | 1.745*** |
| (9.38)    |       |       | (11.43) |
| TP        |       |       | 0.002   |
| (6.01)    |       |       | (0.48)  |
| GII       |       |       | 0.058*** |
| (−6.17)   |       |       | (−9.07) |
| URBAN     |       | 0.156*** | 0.229*** |
| (2.76)    |       |       | (4.26)  |
| HC        |       |       | 0.00003 |
| (−1.98)   |       |       | (0.19)  |
| AR(2)     |       |       | 1.025   |
|          |       |       | (−1.224) |
| Sargan    | 26.272 | 26.197 | 27.305 |

r statistics in parentheses

*p < 0.1; **p < 0.05; ***p < 0.01
environmental regulations significantly promoted green economic efficiency. However, the impact of market-based regulation on green economic efficiency was inhibiting. For the sub-period “after 2010,” the effects of the three types of environmental regulations on green economic efficiency were facilitating. These results are similar to the empirical results obtained for the whole time-period (2003–2017). The results found that the magnitude of the promotion effect of VER increased from 2.7% “before 2010” to 4.5% “after 2010,” and the effect of CER reduced from 2.89% “before 2010” to 11.3% “after 2010,” while the impact of MER turned from negative “before 2010” to positive “after 2010”.

Spatial heterogeneity

Keeping in mind the considerable regional variations in resource consumption efficiency, economic development level, and technological ability, we classified the 30 provinces into the coastal and inland parts. The empirical results are reported in Table 5. In coastal part, the coefficient of $L.GEE$ is statistically insignificant, which infers that there is no obvious “transfer effect” or the “transfer effect” is weak between the current green economic efficiency and the previous period. This outcome is consistent with the recent study of Ren (2020). Moreover, the results show that CER (insignificantly) inhibits green economic efficiency, while MER and VER promote (insignificantly) green economy. The level of economic development of coastal areas is relatively higher in China. With the change of time, the high cost of CER becomes increasingly prominent, while the source governance effect of MER has not yet appeared. Although VER promotes green economic efficiency, its influence is small. Moreover, most of the population in coastal areas are migrants, who pay little attention to the environment.

In inland provinces, the effects of CER and VER on green economic efficiency are facilitating, but the effect of MER is

| Variables | Before 2010 | After 2010 |
|-----------|-------------|------------|
| L.GEE     | 0.418***    | 0.440***   |
|           | (118.92)    | (139.06)   |
| CER       | 0.289***    | 0.113***   |
|           | (15.08)     | (3.12)     |
| MER       | –0.00008    | 0.049***   |
|           | (–0.06)     | (16.50)    |
| VER       | 2.618***    | 0.027***   |
|           | (21.20)     | (33.44)    |
| OPEN      | 0.128***    | –0.055***  |
|           | (49.13)     | (44.87)    |
| GEE       | –0.152***   | –0.091***  |
|           | (–38.97)    | (–47.89)   |
| TP        | 0.014***    | 1.013***   |
|           | (–2.95)     | (10.00)    |
| GII       | –0.00003    | 0.0004***  |
|           | (–7.86)     | (12.00)    |
| URBAN     | –0.093***   | –0.098***  |
|           | (–3.65)     | (–3.95)    |
| HC        | 27.517      | 27.932     |
| Sargan    | 27.932      | 27.694     |

$t$ statistics in parentheses

$p < 0.1; **p < 0.05; ***p < 0.01$
insignificantly inhibiting. With the implementation strategy of “revitalizing the east, rising the middle and developing the west,” a large number of industries are transferred to the inland provinces, which accelerate economic growth and environmental pollution in the same direction in the inland provinces. Meanwhile, the effectiveness of the three types of environmental regulations in inland provinces is more robust. Moreover, residents in inland areas comply with national environmental management standards.

**Mediating analysis**

The results of mediating effects of heterogeneous environmental regulations on green economic efficiency are presented in Table 6. Columns 1, 4, and 7 report the impacts of the command-and-control, market-based, and voluntary environmental regulation on GEE, respectively, while advanced and rationalized industrial structures are controlled. Columns 2, 5, and 8 show the impacts of command-and-control, market-based, and voluntary environmental regulation on the advanced industrial structure, respectively. The impacts of command-and-control, market-based, and voluntary environmental regulation on the rationalized industrial structure are given in columns 3, 6, and 9, respectively.

From the perspective of controlled advanced industrial structure and industrial structure rationalization, the three types of environmental regulations are conducive to green economic efficiency. CER promotes green economic efficiency through the development of advanced industrial structure. Command-and-control regulation forced some emissions-intensive enterprises to withdraw from the market due to high production cost. As a result, some cleaned-enterprises comply and modernize their industrial pattern through technological innovation. The impact of market-based regulation is conducive to green economic efficiency by improving the advanced and rationalized industrial structures. That indicates that MER not only optimize rationalized industrial structure, also accelerates the development of the tertiary industry. The implementation of voluntary-based regulation improves green economic efficiency by advanced industrial structure, but inhibits by rationalized industrial structure.

**Robustness analysis**

**Alternative indicator**

To verify the robustness of the results, this study replaces both environmental regulation and control variables to
estimate the parameters of the results (see Table 7). The results revealed that CER is represented by comprehensive utilization rate of industrial solid waste. We employed the logarithm of the proportion of investment in industrial pollution control to GDP to proxy MER. Following Luo et al. (2021), we use the logarithm of number of environmental proposals for NPC (the National People’s Congress) and CPPCC (the Chinese People’s Political Consultative Conference) to proxy voluntary-based regulation. We recruited infrastructure as an alternative control variable of urbanization. It is represented by the public transport vehicles in every 10,000 people. The results of robustness analysis showed that the sign and significance of the variables are similar to the results presented in the above sections; thus, the results of this paper are robust.

### Alternative estimation method

This study further uses an alternative approach that is based on the SBM model. The results are presented in Table 8. We found that the results derived from SBM model indicate that the sign and significance of the variables are consistent with the results presented in the previous sections. Overall, the robustness analysis verifies the reliability and rationality of the conclusions drawn in this study.

### Conclusions and policy recommendations

Environmental regulation is an important channel to promote green economic efficiency and streamline industrial structure. China’s environmental issues, the result of
### Table 7 Robustness test results of replacing explanatory and control variables

| Variables | CER | MER | VER |
|-----------|-----|-----|-----|
|           | GEE | GEE | IS  | IR | GEE | GEE | IS  | IR | GEE | GEE | IS  | IR |
| L.GEE     | 0.457*** | 0.379*** | 0.508*** | 0.371*** | 0.502*** | 0.401*** | (62.56) | (24.29) | (35.75) | (29.38) | (41.30) | (29.71) |
| L.IS      | 0.985*** | 0.984*** | (753.71) | (711.86) | (269.66) | (258.69) | (295.04) | (269.66) | (258.69) | (269.66) | (258.69) | (258.69) |
| L.IR      | 0.829*** | 0.833*** | (753.71) | (711.86) | (269.66) | (258.69) | (295.04) | (269.66) | (258.69) | (269.66) | (258.69) | (258.69) |
| CER       | 0.325*** | 0.325*** | 0.013 | 0.017 | 0.165*** | 0.165*** | 0.007*** | 0.007*** | 0.122*** | 0.122*** | 0.007*** | 0.007*** |
| MER       | 0.032*** | 0.032*** | 0.007*** | 0.007*** | 0.034*** | 0.034*** | 0.007*** | 0.007*** | 0.034*** | 0.034*** | 0.007*** | 0.007*** |
| VER       | 0.083*** | 0.093*** | 0.007*** | 0.007*** | 0.001*** | 0.001*** | 0.007*** | 0.007*** | 0.001*** | 0.001*** | 0.007*** | 0.007*** |
| IS        | 0.001*** | 0.003*** | 0.007*** | 0.007*** | 0.083*** | 0.083*** | 0.007*** | 0.007*** | 0.083*** | 0.083*** | 0.007*** | 0.007*** |
| IR        | (3.69) | (15.83) | (2.62) | (2.62) | (15.83) | (15.83) | (2.62) | (2.62) | (15.83) | (15.83) | (2.62) | (2.62) |
| OPEN      | 1.378*** | 0.322** | 0.067*** | 0.067*** | 1.866*** | 1.866*** | 0.593*** | 0.593*** | 1.925*** | 1.925*** | 0.593*** | 0.593*** |
| TP        | 0.050*** | 0.009 | 0.025*** | 0.025*** | 0.074*** | 0.074*** | 0.013* | 0.013* | 0.083*** | 0.083*** | 0.013* | 0.013* |
| GII       | −0.043*** | −0.091*** | −0.018*** | −0.018*** | −0.042*** | −0.042*** | −0.089*** | −0.089*** | −0.057*** | −0.057*** | −0.089*** | −0.089*** |
| INFRA     | −0.013*** | −0.008*** | −0.0003 | −0.0003 | −0.015*** | −0.015*** | −0.020*** | −0.020*** | −0.005*** | −0.005*** | −0.021*** | −0.021*** |
| HC        | −0.0004*** | 0.0001*** | −0.010*** | −0.010*** | 0.00002 | 0.00002 | 0.001*** | 0.001*** | 0.00005*** | 0.00005*** | 0.001*** | 0.001*** |
| AR(2)     | 0.191 | 0.191 | 0.024 | 0.024 | 0.101 | 0.101 | 0.082 | 0.082 | 0.105 | 0.105 | 0.084 | 0.084 |
| Sargan    | 27.384 | 28.794 | 27.715 | 27.715 | 25.906 | 25.906 | 26.253 | 26.253 | 24.568 | 24.568 | 28.521 | 28.521 |

\( t \) statistics in parentheses

\( *p < 0.1; **p < 0.05; ***p < 0.01 \)
| Variables | CER | | | | MER | | | | VER | | |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| GEE | GEE | IS | IR | GEE | GEE | IS | IR | GEE | GEE | IS | IR |
| L.GEE | 0.544*** | 0.445*** | | | 0.702*** | 0.457*** | | | 0.678*** | 0.474*** |
| (32.95) | (32.23) | | | | (36.83) | (23.61) | | | (37.28) | (23.57) |
| L.IS | | 0.983*** | | | | 0.985*** | | | | 0.985*** |
| (615.50) | | | | | | (734.11) | | | | (737.02) |
| L.IR | | | 0.768*** | | | | 0.764*** | | | | 0.760*** |
| (268.07) | | | | | | (403.59) | | | | (381.08) |
| CER | 0.824*** | 0.703*** | 0.038*** | 0.448 | 0.026*** | 0.031*** | 0.006*** | 0.162*** | 0.032*** | 0.024*** | 0.001** | −0.209*** |
| (37.90) | (18.33) | (3.40) | (1.10) | (5.30) | (4.80) | (5.99) | (7.11) | | (12.08) | (10.34) | (2.05) | (−17.51) |
| IS | 0.061*** | | | | 0.126*** | | | | 0.117*** |
| (5.31) | | | | | | (12.44) | | | | (24.21) |
| IR | 0.005*** | | | | 0.004*** | | | | 0.003*** |
| (11.79) | | | | | | (12.74) | | | | (9.27) |
| OPEN | 1.762*** | 1.391* | 0.054 | −0.307 | 2.457*** | 0.983** | 0.134 | −0.919 | 2.424*** | 0.915** | 0.075 | 6.688*** |
| (3.55) | (1.68) | (0.48) | (−0.12) | (4.31) | (2.12) | (1.57) | (−0.52) | (3.50) | (2.30) | (0.70) | (2.75) |
| TP | 0.038*** | −0.024** | 0.025*** | 0.590*** | −0.002 | −0.102*** | 0.021*** | 0.495*** | −0.037*** | −0.118*** | 0.024*** | 0.754*** |
| (6.01) | (−1.96) | (10.32) | (5.86) | (−0.28) | (8.24) | (8.56) | (3.30) | (−7.80) | (−10.41) | (11.92) | (5.06) |
| GII | −0.088*** | −0.061*** | −0.019*** | −0.888*** | 0.022*** | −0.005 | −0.016*** | −0.762*** | 0.026*** | −0.007 | −0.019*** | −0.745*** |
| (−10.41) | (−6.55) | (−5.52) | (−8.23) | (2.82) | (3.08) | (−4.53) | (−4.71) | (2.86) | (−0.49) | (−5.65) | (−5.09) |
| INFRA | 0.888*** | 0.630*** | −0.002 | 14.170*** | 0.604*** | 0.497*** | 0.0006 | 14.270*** | 0.551*** | 0.474*** | −0.002 | 14.250*** |
| (18.56) | (8.18) | (−0.31) | (45.42) | (13.26) | (16.18) | (0.10) | (50.00) | (16.29) | (13.11) | (−0.31) | (61.73) |
| HC | −0.001*** | −0.001** | 0.0002** | −0.020*** | −0.002*** | −0.00005 | 0.001*** | −0.021*** | −0.002*** | 0.0004** | 0.0002** | −0.024*** |
| (−8.91) | (−2.20) | (2.49) | (−15.38) | (−12.28) | (−0.22) | (2.78) | (−20.40) | (−8.99) | (2.45) | (2.32) | (−20.79) |
| AR(2) | 0.749 | 0.643 | 0.021 | −1.029 | 0.649 | 0.715 | −0.133 | −1.031 | 1.128 | 1.012 | 0.045 | −1.023 |
| Sargan | 28.136 | 28.001 | 28.089 | 26.254 | 28.614 | 28.823 | 28.514 | 25.650 | 28.972 | 27.473 | 28.364 | 26.781 |

* $t$ statistics in parentheses
** $p < 0.1$; *** $p < 0.05$; **** $p < 0.01$
decades of rapid industrialization, not only threaten public health but also impede green economic efficiency. Its energy-intensive industries have caused additional environmental problems. In response, China has implemented policies to accelerate green economic efficiency and optimize industrial structure. Scholars have presented some different views on the effects of environmental regulation on green economic efficiency and industrial structure upgrading. While some researchers believe that China’s green economic efficiency has increased in recent years (Wang et al. 2021b), others argue that China has experienced decline in its green economic efficiency due to considerable regional heterogeneity Zhao et al. (2020a).

This study attempts to empirically explore the different effects of the three types of environmental regulations (command-and-control, market-based, and voluntary environmental regulations) on green economic efficiency using slacks-based direction distance function (SBM-DDF) model. Meanwhile, this study incorporates the mediating role of industrial structure (advanced and rationalized) in the model. We adopted a two-step system GMM estimator to estimate the differential effects of environmental regulations on green economic efficiency under the mediating role of industrial structure. The results show that three types of environmental regulations are conducive to green economic efficiency in China over the period 2003–2017. The results demonstrated that control-and-command regulation has relatively more profound effect on green economic efficiency, while the effect of market-based regulation was less profound. The results of temporal heterogeneity analysis showed that the positive effect of control-and-command regulation was decreasing, while the positive effect of voluntary-based regulation was increasing. The market-based regulation had both negative and positive effects on green economic efficiency. The spatial heterogeneity analysis suggested that there was an evidence of statistically significant and positive effects of control-and-command regulation and voluntary-based regulation on green economic efficiency in inland provinces, but the three types of environmental regulations had statistically insignificant effects in coastal provinces. The mediation analysis found that control-and-command regulation improved green economic efficiency through the development of advanced industrial structure, market-based regulation promoted green economic efficiency through advanced industrial structure and industrial structure rationalization. Voluntary-based regulation accelerated green economic efficiency through advanced industrial structure and hindered through industrial structure rationalization.

Based on the above results, this study formulates several important policy implications. First, industrial heterogeneity should be primarily considered in environmental regulations. To effectively apply the environmental regulations, it is imperative to take into account the industrial heterogeneity in green economic efficiency and environmental regulations.

Keeping in view the overall scenario of the industrial sectors, a single approach of environmental regulation plan may not only result in regulatory failures to date as realizing “win–win” objectives for the economy and environment, but may also discourage the willingness of companies to innovate in compensation. Second, improve the environmental regulatory capacity of the middle-polluting industry. The recent environmental success story in China is mainly attributed to the efficient execution of a “low-hanging fruit” environmental strategy for high-polluting industries. The middle-polluting industrial sector has the same emission intensity as the high-polluting industries, should place sufficient attention in order to address these low-hanging fruits. Finally, the three types of environmental regulations should be harmonized. The environmental regulation system in China still relies on government for policy design and macro-control. However, there is a considerable potential in the public participation and the market. Therefore, it is essential to fully reflect the features of various environmental regulations to jointly develop an environmental regulation framework, and to learn from each other in order to achieve optimum coordination.

Even though this study presented some insightful results, there are few limitations. First, this paper only studies the influence of heterogeneous environmental regulations on GEE from the perspective of provincial level. In future, prefecture-city level data can be used for further investigation. Second, although the SYS-GMM method employed in this study can overcome the endogenous problem to a certain extent, it cannot judge empirically whether there may be endogenous problems in environmental regulation and industrial structure. The above shortcomings provide directions for our future research work.

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Data availability The data and materials are available upon request.

Declarations

Ethical approval We testify that this study is our original research with all data acquired by our examination and there is no plagiarism in it. We also affirm that this study has not been published elsewhere and is not under consideration by another journal.
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