Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

Pol. J. Environ. Stud. Vol. 33, No. X (2024), 1-16
DOI: *10.15244/pjoes/187118* ONLINE PUBLICATION DATE:

Original Research

The Impact of Environmental Regulation on the Regional Cross-Border E-Commerce Green Innovation: Based on System GMM and Threshold Effects Modeling

Liqin Wen[1], Shenglin Ma[1*], Gongmin Zhao[1], Huifang Liu[2]

[1]School of Economics and Management, North University of China, Taiyuan, China
[2]Shandong Youth University of Political Science, China

Received: 20 February 2024
Accepted: 13 April 2024

Abstract

Environmental regulation is an important way to address the negative externalities of environmental governance and to advance regional green innovation efficiency. This paper takes the panel data of 30 provinces and municipalities from 2011 to 2021 as the research object, adopts Super-SBM to measure the regional cross-border e-commerce green innovation efficiency (EGIE) in each region, utilizes the system GMM method to test the impact effect of environmental regulation on EGIE and the mechanism of its action, and carves out the dynamic evolution and spatial differentiation in terms of the time series of the spatial and temporal evolution of EGIE. The results show that environmental regulation significantly promotes the enhancement of EGIE at the 1% level ($\beta = 0.105$). In terms of the impact mechanism, environmental regulations increase EGIE by improving the level of industrial structure upgrading, and intellectual property protection negatively regulates the relationship between environmental regulations and EGIE (β=-0.270). Threshold analysis finds that there is a significant double threshold effect of industrial agglomeration on environmental regulations to promote EGIE growth. When the industrial agglomeration value (AGG≤0.0072) is active, it will promote the green innovation efficiency of cross-border e-commerce, but exceeding the threshold value of industrial agglomeration (AGG=0.0202) will weaken the promotion effect of environmental regulation on EGIE. The purpose of this paper is to study the impact effect of environmental regulation in addressing the relationship between environmental pollution control and promoting EGIE, with a view to providing a decision-making basis for the coordinated development of regional cross-border e-commerce and the environment.

Keywords: green innovation efficiency, environmental regulation, upgrading of industrial structure, intellectual property protection, system GMM

e-mail: sz202209002@st.nuc.edu.cn
Tel: +86 18660435547

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

Introduction

Green innovation efficiency is an evaluation index formed on the basis of green innovation research combined with traditional technical efficiency theory. It reflects the production efficiency of green innovation products through the measurement of green resource input and output to achieve value maximization and environmental optimization, and its essence is the allocation efficiency of green innovation resources. The theory of environmental regulation suggests that governments can effectively solve the problem of "market failure" caused by green technological innovation through environmental policies [1]. The reason is that the uncertainty of the impact of environmental policy on the institutional factors of green technological innovation will lead to the reconfiguration of the innovation factors of enterprises and changes in the direction, focus, and scale of innovation [2]. It can be seen that the government implements environmental regulation policies as a public means to inhibit and constrain the negative externalities of environmental resource use, and support policies for enterprises are implemented to correct the positive externalities arising from the enterprises' green technological innovations and to incentivize their green R&D investment [3]. Previously, the 20th CPC National Congress made a specific deployment of "promoting green development", emphasizing the need to "improve the scientific and technological innovation system", "accelerate the research and development of advanced energy-saving and carbon-reducing technologies and their popularization and application", and "strengthen the role of green technology in green and low-carbon development". On the other hand, environmental regulation is an environmental tool for the government to achieve energy savings and emission reduction by heavily subsidizing enterprises through environmental protection expenditures and providing support for environmental protection R&D costs. Environmental regulation can effectively internalize the negative externality problems of the innovation subject, optimize the innovation division of labor, and build a green innovation cooperation space with complementary resource elements and gradient division of labor. It can also optimize the division of labor and cooperation in innovation, build a green innovation cooperation space with complementary resource elements and gradient division of labor and cooperation, and realize the improvement of regional green innovation efficiency.

At present, cross-border e-commerce comprehensive pilot zones have achieved full coverage of the province, highlighting institutional innovation, technological innovation, and service innovation, and strengthening guidance and support in the construction of cross-border e-commerce parks, the improvement of supply chain systems, business incubation, and talent training to achieve the efficiency of cross-border e-commerce green innovation in all regions. It is necessary to comprehensively analyze whether environmental regulation can effectively enhance the development of regional cross-border e-commerce green innovation efficiency, as well as the mediating factors that affect the transmission of environmental regulation to regional cross-border e-commerce green innovation efficiency under the premise of reducing energy emissions and realizing the management of ecological pollution, so as to excavate the "black box" in the process of green innovation from inputs to outputs and to provide the theoretical basis and practical support for the construction of regional green innovation systems.

According to previous studies, a large number of empirical studies have been conducted on government-type environmental regulation, with manufacturing enterprises and industrial economic zones as the main objects of study. Most of them study the impact of command-type environmental regulation and market incentive-type environmental regulation on regional green innovation efficiency, and fewer of them explore the impact on green innovation efficiency from the perspective of government subsidies. Therefore, this paper first adopts Super-SBM to measure the EGIE at the macro level in light of China's reality on the green innovation efficiency of cross-border e-commerce with green attributes in the first place. Secondly, considering the endogeneity of regional green innovation efficiency, we establish a systematic generalized moments model to empirically analyze the influence effect of environmental regulation in solving the relationship between environmental pollution governance and promoting regional green innovation efficiency. Then the threshold regression model is used to systematically study the impact of industrial agglomeration on regional green innovation efficiency. Finally, the spatio-temporal evolution characteristics of EGIE are portrayed in terms of time-series dynamic evolution and spatial differentiation, with a view to providing a decision-making basis for the improvement of regional cross-border e-commerce green innovation efficiency and the coordinated development of the environment.

The main innovations of this paper are: First, there is little literature on measuring regional EGIE from the perspective of inputs and outputs, and this paper further validates Porter's hypothesis by exploring the role of environmental regulation in influencing EGIE. Second, we examine the regulatory impact of the level of intellectual property on EGIE, which will provide a reference for the government to formulate scientific and differentiated environmental regulatory policies in the future. Third, it proposes the existence of a threshold effect of industrial agglomeration in the impact of environmental regulation on EGIE, which enriches the theoretical research to find out the optimal scale value of industrial agglomeration and provides theoretical reference for the future agglomeration of cross-border e-commerce enterprises. Fourth, while previous studies seldom studied green innovation efficiency from the perspective of spatial and temporal evolution,

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

the present paper describes the characteristics of evolution in terms of temporal dynamic evolution and spatial differentiation and intuitively portrays the development trends of EGIE in terms of geographic trends.

Material and Methods

The Impact of Environmental Regulation on EGIE

The theory of environmental regulation suggests that governmental environmental regulatory policies are an effective means of addressing market failures in green technological innovation. The existing literature has gradually developed two different views in the process of studying the impact of environmental regulation on the efficiency of green innovation: the pollution paradise hypothesis and Porter's hypothesis.

From a static point of view, the neoclassical economic school believes that strict environmental regulation policies will increase the production costs of enterprises and form a pollution paradise in regions with low environmental regulation, so environmental regulation cannot effectively promote regional green innovation efficiency. Some studies have found that due to the decentralized governance structure and performance appraisal mechanism, the government tends to give up the idea of long-term green economic growth in order to achieve short-term economic development, i.e., the existence of race-to-the-bottom at all levels of local governments, which then leads to the spatial spillover of environmental pollution. Around this view, Zhang et al. [4] point out that local governments often reduce the "compliance cost" of local enterprises by weakening the intensity of environmental regulation to achieve the goal of promoting economic growth, so even if the region's environmental regulatory policies are very strict, the benefits of environmental governance inputs may be very limited. Baumeister et al. decomposed the environmental regulation stringency index, the OECD regulatory indicators, and the green total factor productivity growth index using 19 EU countries as examples [5]. The empirical results found that market-based environmental regulations have a negative impact on the pure and scale efficiency indices of green total factor productivity. Guo et al. argued that the scale of taxes on environmental protection in environmental regulatory instruments is too small to incentivize firms to invest in green eco-innovation [6]. Jin and Shen find that the interaction of environmental regulation enforcement in geographically neighboring municipalities exhibits asymmetry, with a race to the bottom and a race to the top co-existing, forcing less productive polluting firms to relocate between municipalities [7]. These observations support the existence of a "cost effect" of environmental regulations on the efficiency of green innovation. Li &Yang pointed out that the strengthening of environmental regulations makes the government and enterprises increase the cost of environmental protection and pollution control, which inhibits the output performance of enterprises and economic development [8].

The Porter hypothesis [9] posits the dynamic view that strict environmental regulation policies can actually have a net positive impact on the innovation capacity of regulated firms [5-9]. As the policy promotes cost cutting and higher levels of efficiency, which in turn reduces or completely offsets the costs of environmental regulation and facilitates the application of innovation in new technologies, it can help firms achieve international technological leadership. Sterlacchini et al. [10] empirically found that the stringency of market-incentivized environmental regulatory instruments in the EU region had a more positive facilitating effect on green innovation patents in 19 OECD countries. Li found that environmental regulation and government R&D funding have a positive impact on enterprises' green technology innovation, and the coupling of the two has a stronger effect on green technology innovation [11]. Bao and Chai [12] empirically found that environmental regulation is positively correlated with regional green innovation efficiency, and the government improves the efficiency of green innovation by improving the allocation of financial resources [10-12]. Therefore, the study of Porter's hypothesis further proves that there is an "innovation effect" on the impact of environmental regulation on green technology.

In summary, there is no consensus on the impact of environmental regulation on the efficiency of green innovation. Generally speaking, environmental regulation acts on enterprises' green innovation activities mainly through two mechanisms: the negative "compliance cost effect" and the positive "innovation compensation effect". Some scholars believe that the technological innovation effect of environmental regulation is sufficient to offset the cost of environmental governance and has a facilitating effect on the improvement of green development efficiency. However, some scholars hold the opposite view that the "cost compliance effect" of environmental regulation is greater than the "innovation incentive effect", thus inhibiting urban green development. Some scholars hold the opposite view that the "cost compliance effect" of environmental regulation is greater than the "innovation incentive effect", thus inhibiting urban green development. Based on the above analysis, the following hypotheses are proposed:

H1: Environmental regulation has a facilitating effect on regional cross-border e-commerce green innovation efficiency.

The Intermediary Effect of Industrial Structural Upgrading

Environmental regulation has a direct impact on green technology innovation efficiency, but it also has an indirect impact through certain factors.

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

To study the impact of industrial structure upgrading on environmental regulation on the green innovation efficiency of regional cross-border e-commerce, we mainly analyze two aspects: one is the role of environmental regulation on the impact of industrial structure upgrading, and the other is the role of industrial structure upgrading on the green innovation efficiency of regional cross-border e-commerce.

(1) The impact of environmental regulation on industrial structure upgrading. As one of the economic tools used by regional managers to control environmental pollution, the impact of environmental regulation on the upgrading of regional industrial structure needs to be realized through the two paths of advancement of industrial structure and rationalization of industrial structure. Based on the development trend of industrial green transformation, many scholars have studied the impact of environmental regulation on industrial structure upgrading at different scales, such as national, city cluster, watershed economy, specific industries, micro enterprises, etc., and their research conclusions are inconsistent. Some scholars hold the "promotion theory" on the impact of environmental regulation on industrial structure upgrading, believing that environmental regulation can play the "innovation compensation effect", enhance the overall competitive advantage of the industry, and promote industrial structure upgrading. Some scholars hold the "inhibition theory", believing that the "cost of compliance effect" of environmental regulation increases the burden of enterprises, raises the entry barriers of the industry, and inhibits the upgrading of industrial structures. Another scholar holds the "uncertainty theory" and believes that the impact of environmental regulation on industrial structure upgrading is related to the size of the "innovation compensation effect" and the "cost of compliance effect". In addition, most scholars start from the supply perspective and believe that environmental regulation mainly promotes industrial structure upgrading by stimulating technological innovation in enterprises, attracting foreign direct investment, and facilitating factor mobility. Some scholars also pay attention to the demand side and take the growth of social demand as an important way for environmental regulation to affect industrial structure upgrading. Huang [13] argued that environmental regulation helps to stimulate the rationalization of industrial structure by improving the efficiency of factor replacement and also helps to enhance the advancement through industrial structure of factor upgrading [6, 10, 13].

(2) In terms of the impact of industrial structure upgrading on regional green innovation efficiency. Local governments should formulate industrial policies according to the industrial structure, factor endowment, and green transformation development strategy of different regions. Through the agreement on the division of labor and cooperation of green products and green technologies, green technology diffusion and inter-provincial green knowledge spillover can be realized so as to promote the spatial concentration of green innovation activities in the region. This not only reduces the uncertainty and risk of green innovation activities, but also lowers the cost of green science and technology research and development and the transformation of green results, which ultimately brings about a change in regional green innovation efficiency. In addition, as the industrial structure tends to be advanced, the production factors are transferred from the low-efficiency industrial sectors to the high-efficiency industrial sectors, and the spatial reset of innovation resources in this process will inevitably have an impact on the performance of green technological innovation. Green leading industries with high green production efficiency will drive the growth of other emerging industries, thus promoting the innovation of upstream and downstream industries, expanding the scale of regional green innovation, and promoting the enhancement of regional green innovation capacity and green innovation efficiency. Scholar She et al. empirically found that low-carbon pilot policies indirectly enhance the green total factor productivity of low-carbon pilot cities through the channel of promoting industrial upgrading [14]. Lu et al. used a finite mixture model to empirically analyze that industrial structure upgrading and technological innovation have a significant promotional effect on regional green total factor productivity and that there are obvious "leading-type", "catching-up-type" and "lagging-type" green total factor productivity [15, 16]. Based on the above analysis, the following hypothesis is proposed:

H2: Environmental regulation promotes industrial structure upgrading, thereby improving regional cross-border e-commerce green innovation efficiency.

The Regulatory Effect of Intellectual Property Protection

In dealing with the contradiction between environmental protection and economic growth, it is necessary for the government to take the lead in adopting binding instruments for environmental control. At the same time, it is also necessary to adopt incentives and utilize intellectual property rights to protect the results of innovations in order to maintain and increase the incentives of enterprises to innovate.

Weak awareness of intellectual property protection in cross-border e-commerce transactions, negligence, and insufficient supervision by the relevant departments have led to numerous cases of intellectual property infringement in cross-border e-commerce, violating the interests and intellectual property rights of the relevant people, destroying the good business environment, and hindering the innovative development of cross-border e-commerce. In China's theoretical research, the issue of intellectual property protection in e-commerce has also attracted more and more attention from the academic community. For example, Cui [17] believes that the current intellectual property rules have many problems, such as incomplete rules and unclear infringement

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

liability, especially in the current e-commerce legal system in China, which is mainly based on internet information as the object of control and lacks a specification of the commercial activities of the platform concerned. Luo [18] believes that intellectual property rights are the driving force for enterprises to develop cross-border e-commerce businesses. Intellectual property is at the core of the development of cross-border e-commerce businesses, which is particularly important in the era of the knowledge economy, and the legal protection of intellectual property should be strengthened to improve the legal system of cross-border e-commerce [17, 18].

As an important institutional arrangement to encourage the production of new knowledge, intellectual property protection policy has attracted extensive attention from scholars. Zheng and Sun [19] found that the incentive effect of the establishment of intellectual property courts on the quality of firms' innovation was more significant for state-owned enterprises and enterprises in the Pearl River Delta Economic Circle, but not for private enterprises [15, 17, 19]. While some scholars are against it, Zhang et al. found that strengthening Intellectual Property Rights protection would inhibit international technology spillovers, which in turn would have a negative impact on technological innovation [20]. Based on the above analysis, the hypothesis is formulated:

H3: The interaction of environmental regulation and intellectual property protection has a negative moderating effect on regional cross-border e-commerce green innovation efficiency.

The Threshold Effect of Industrial Agglomeration

Industrial agglomeration is the main manifestation and means of realizing industrial allocation, and at the same time, it is also a necessary condition for guaranteeing the green development of the region. The impact of industrial agglomeration on green innovation efficiency can be analyzed in terms of the "industrial synergy effect" and the "pollution transfer effect".

(1) Industrial synergy. Geospatial agglomeration is conducive to the transmission of information, and with the deepening of the division of labor and cooperation among enterprises, a complete industrial chain is gradually formed, and enterprises in the agglomeration area can share information, infrastructure, labor markets, and specialized services, so as to be able to effectively control production costs. Therefore, under a certain level of industrial agglomeration, environmental regulation can promote the spillover and dissemination of green knowledge and promote green technological innovation.

(2) Pollution transfer effect. When the scale of industrial agglomeration reaches a certain level, problems such as environmental degradation, insufficient resources, population congestion, traffic congestion, and other problems gradually appear, the advantages of the agglomeration gradually dissipate, and the scale effect of the agglomeration area is no longer significant. Therefore, industrial enterprises with low green technology content and high pollution emissions will gradually shift to adjacent areas due to the early loss of comparative advantages, and the negative environmental effects of adjacent areas will continue to increase, which will hinder the green development of the region.

Accordingly, this paper formulates the hypothesis:

H4: There is a threshold effect of environmental regulation on regional cross-border e-commerce green innovation efficiency under different levels of industrial agglomeration.

System GMM Model Settings

The most commonly used estimation methods for panel data models are the fixed effects model and the random effects model, but there is an endogeneity problem in the model when the lagged terms of the explanatory variables are introduced as explanatory variables in the regression model, making the model dynamically explanatory. Therefore, Arellano et al. proposed the so-called Generalized Moment Method (GMM), and the GMM estimation method of the dynamic panel data model was divided into DIF-GMM and SYS-GMM [21]. Roodman argued that although the differential GMM method reduces the impact of endogeneity on model estimation, it suffers from a serious "weak instrumental variables" problem under limited sample conditions, which leads to poor accuracy of coefficient estimation results [22]. For this reason, Blundell et al. proposed a GMM estimation method to solve the problems of autocorrelation, heteroskedasticity, endogeneity, and weak instrumental variables [23]. Meanwhile, Roodman pointed out that the necessary condition for applying the system GMM model was that the number of cross sections should be larger than the time dimension. As the number of periods increases, the system GMM generates by default a large number of instrumental variables that may outweigh the endogenous variables and weaken the model setting test [7, 15, 21]. Therefore, to make the results more reliable, we prefer a two-step system GMM approach for estimating panel data.

In this paper, we take regional cross-border e-commerce green innovation efficiency as an explained variable and introduce the first-order lag term of green innovation efficiency and environmental regulation as a core explanatory variable to satisfy the condition setting that the explained variables are dynamic and not all explanatory variables are strictly exogenous. At the same time, the individual and temporal double fixed effects are also controlled to satisfy the conditions for the use of the system GMM model. In addition, there are many factors affecting green innovation efficiency, so other factors affecting green innovation efficiency are introduced as control variables. Among them, the control variables include level of economic development

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

(AGDP), level of urbanization (UR), foreign direct investment (FDI), energy consumption structure (ECS), and level of human capital (HCL). In the equation, i denotes the industry individual, t denotes the year, and ε denotes the error term. Meanwhile, the model also controls the region fixed effect δ, year fixed effect μ, and εi as the random error term, β_0 is a constant, and β_i is the regression coefficient of the corresponding variable. Considering that the transformation of regional cross-border e-commerce green innovation efficiency results requires a time cycle, the green innovation efficiency of the current year not only depends on the performance of the current period, but is also affected by the green innovation efficiency stock of previous years. Therefore, the green innovation efficiency ($EGIE_{it-1}$) with a lag of one period is added to the model to control its own inherent shocks. The resulting dynamic panel regression model is shown below:

$$\ln EGIE_{i,t} = \beta_0 + \beta_1 \ln EGIE_{i,t-1} + \beta_2 \ln GSER_{i,t} + \beta_3 \ln AGDP_{i,t} + \beta_4 \ln UR_{i,t} + \beta_5 \ln FDI_{i,t} + \beta_6 \ln ECS_{i,t} + \beta_7 \ln HCL_{i,t} + \delta_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

In the process of analyzing the impact of environmental regulation on regional cross-border e-commerce green innovation efficiency, the interaction between environmental regulation and intellectual property protection should be considered at the same time as a measure of the circular cumulative effect caused by the impact of knowledge protection behaviors other than environmental regulation. Therefore, the moderating effect model is:

$$\ln EGIE_{i,t} = \beta_0 + \beta_1 \ln EGIE_{i,t-1} + \beta_2 \ln GSER_{i,t} + \beta_3 \ln GSER_{i,t} \times \ln INTEL_{i,t} + \beta_4 \ln INTEL_{i,t} + \beta_5 \ln AGDP_{i,t} + \beta_6 \ln UR_{i,t} + \beta_7 \ln FDI_{i,t} + \beta_8 \ln ECS_{i,t} + \beta_9 \ln HCL_{i,t} + \delta_i + \mu_t + \varepsilon_{i,t} \quad (2)$$

Selection of Variables

The Explained Variable (EGIE)

The measurement of green innovation efficiency mainly adopts principal component analysis, projection tracing evaluation model, particle swarm optimization algorithm, stochastic frontier analysis represented by parametric technology, and data envelopment analysis represented by non-parametric technology. The data envelopment method is adopted by many scholars because it can avoid the problem of weight setting, is convenient to deal with the innovation efficiency measurement of multiple inputs and multiple outputs, and does not need to set a specific form of production function in advance, which is more in line with the analysis of the actual problems in the complex economic environment. So in this paper, we use a non-radial and non-angle Super-SBM model that can solve the problem of non-desired output and non-zero relaxation to measure the regional green innovation efficiency of cross-border e-commerce in 30 provinces (municipalities and autonomous regions) in China from 2011 to 2021. Xiao proposed a Super-SBM model with the following formula [24]:

$$\min\rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{z_i^-}{x_{ik}}}{1+\frac{1}{p_1+p_2}\left(\sum_{r=1}^{p_1}\frac{z_r^+}{y_{rk}}+\sum_{t=1}^{p_2}\frac{z_t^{h-}}{h_{rk}}\right)}$$

$$\text{s.t.} \begin{cases} \sum_{j=1,j\neq k}^{n} x_{rj}\lambda_j - z_i^- \leqslant x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{ij}\lambda_j + z_i^- \geqslant y_{rk} \\ \sum_{j=1,j\neq k}^{n} h_{tj}\lambda_j - z_i^{h-} \leqslant h_{tk} \\ \lambda, z^-, z^+, z^{h-} \geqslant 0 \end{cases}$$

$$i = 1,2,\cdots,m; r = 1,2,\cdots,p_1; t = 1,2,\cdots,p_2; j = 1,2,\cdots,n(j \neq k) \quad (3)$$

There are m inputs, p1 desired outputs, p2 non-desired outputs, λ representing the weight vector and $z = \left(z_i^-, z_r^+, z_t^{h-}\right)$ representing the relaxation of inputs (xi), desired outputs (yr), and non-desired outputs (hr). Drawing on the Huang and Wu (2020) approach, the green innovation efficiency evaluation index system is constructed from the input and output dimensions, and the specific indexes are selected as shown in Table 1.

(1) Input factors. The input factor consists of three indicators: the labor input factor, the capital input factor, and the energy input factor. Cross-border e-commerce relies on the Internet and modern communication technology for business operations, so the labor input in this paper is expressed by the full-time equivalent of regional R&D personnel and the number of employees in the information service industry. Regional capital is measured by the internal expenditure on R&D activities and the output value of the information service industry based on a precise viewpoint. Energy input is an important factor to be considered for green innovation, and since cross-border e-commerce is a commercial service activity carried out online in the form of electronic transactions, its proxy variable is selected as the proportion of regional electricity consumption in the total electricity consumption of the country.

(2) Desired output. The ultimate goal of green innovation is to achieve regional energy savings, emission reduction for technological innovation growth, and green economic optimization. For this reason, this paper selects regional green patent applications and regional technology market transaction contract amount as proxy variables, representing the regional green technology development trend and the embodiment of green innovation results into market economic benefits, respectively. In this paper, regional express delivery revenue, new product sales revenue, and the number of cross-border e-commerce pilot zones are added to evaluate regional cross-border e-commerce output.

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

(3) Non-desired outputs. During the operation of cross-border e-commerce, the region is bound to produce environmental pollutant emissions. In terms of non-desired outputs, some scholars take the absolute amount of pollutant emissions as a measure. Nowadays, scholars mostly use the three wastes to measure undesired outputs. The "three wastes" emissions comprehensive index for measurement shows that the larger the value of the variable, the greater the environmental damage. The entropy method is applied to standardize the three pollutant indicators, and the weights of the indicators and the comprehensive index of regional environmental non-desired output are calculated according to the information entropy.

The Explanatory Variable (GSER)

There are more existing indicators around the measurement of governmental environmental regulation, and most of the existing studies have used indicators such as investment in environmental management of pollution and collection of sewage charges to measure governmental environmental regulation. This paper draws on Bao and Chai to use the share of government environmental protection expenditure in fiscal expenditure to measure environmental regulation [12].

Control Variables

Drawing on Wang [3] and Sun et al. [25] related studies on industrial green development efficiency, this paper mainly considers five control variables (as shown in Table 1).

The Intermediary Variables (INDUSTRY)

The indicator of advanced industrial structure (AIS) can reflect the gradual evolution of the regional industrial structure from low level to high level, especially the absorption process of technological innovation in the regional dominant industrial sector. Its direction is the process of regional dominant industry shifting from primary industry to secondary industry and continuing to develop to tertiary industry,

Table 1. Measurement of relevant indicators.

Level 1 indicators	Level 2 indicators	Basic indicators
Input indicators	Labor inputs	Number of employees in the information services industry (ten thousand people)
		Full-time equivalent of R&D personnel (person-years)
	Capital inputs	Output value of the information service industry (billions of yuan)
		Expenditures on internal funding for R&D activities (ten thousand yuan)
	Energy inputs	Regional electricity consumption as a percentage of total national electricity consumption (%)
Output indicators	Desired outputs	Number of patents granted (pieces)
		Technology market turnover (billions of yuan)
		Revenue from express delivery operations (ten thousand yuan)
		Revenue from sales of new products (billions of yuan)
		Cross-border e-commerce comprehensive pilot zone (number of individuals)
	Non-desired outputs	Industrial wastewater discharges (10^4 tons)
		Industrial sulfur dioxide emissions (10^4 tons)
		Industrial fume (dust) emissions (10^4 tons)
Indicators for the measurement of control variables	Level of economic development (AGDP)	GDP per capita (yuan/person)
	Level of urbanization (UR)	Share of urban population in total population at the end of the year (%)
	Foreign direct investment (FDI)	(Total FDI* US Dollar to RMB exchange rate) / Gross regional product (%)
	Energy consumption structure (ECS)	Regional electricity consumption /Total national electricity consumption (%)
	Level of human capital (HCL)	Number of students enrolled in higher education /Total population (%)

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

which reflects the characteristics of regional industrial structure changing to knowledge-intensive industry and high value-added service industry. Therefore, this paper adopts the ratio of the added value of the tertiary industry to the added value of the secondary industry to measure the advanced industrial structure. The rationalization of industrial structure (RIS) indicator can reflect the allocation of regional factor resources in the industry, and the optimization degree of the proportionality between the regional industrial structure, i.e., the quality of inter-industry aggregation, is high [26-29]. In order to reflect the quality of regional inter-industry aggregation and the utilization of resource endowment, scholars have adopted "Theil's index" to characterize the rationalization of industrial structure. Among them, the Theil formula is:

$$\text{Theil}_{i,t} = \sum_{m=1}^{3} y_{i,m,t} \ln\left(\frac{y_{i,m,t}}{l_{i,m,t}}\right) \quad (4)$$

In Equation (4), m represents the three major industries, with values of 1, 2, and 3; $y_{i,m,t}$ represents the proportion of industry m in the GDP of city i in period t; and $l_{i,m,t}$ is the proportion of the mth industry of city i in the total number of employed people in period t. The value of this index is between 0 and 1, and the closer to 0, the closer to the equilibrium level of industrial structure. Finally, the entropy value method is used to synthesize the comprehensive index of industrial structure to characterize the upgrading level of industrial structure by rationalization and advanced industrial structure.

Threshold Variables (AGG)

Industrial agglomeration is the main manifestation and means of realizing industrial allocation, and at the same time, it is also a necessary condition for guaranteeing the green development of the region [28-30]. In this paper, the employment density (number of employed persons/ area of administrative division) is used to measure the level of regional industrial agglomeration. The higher the employment density of a region, the higher the industrial agglomeration level of the region.

The Regulatory Variable (INTEL)

Intellectual property protection depends not only on nominal protection, such as a country's intellectual property legislation, but also on the level of administrative enforcement of intellectual property rights in the region as well as the level of justice (i.e., actual protection). This paper mainly draws on the idea of Li et al., using the average of the number of intellectual property infringement cases divided by the total population and the number of regional lawyers divided by the total population in each region to characterize the level of regional intellectual property protection [19, 23, 25].

The Instrumental Variable (VC)

In order to avoid the impact of carbon emissions caused by natural factors, this paper chooses the air circulation coefficient (VC) as an instrumental variable for apparently exogenous environmental policies, so that the influential role of regional green innovation efficiency is realized only through environmental regulation to better address the endogeneity problem. Drawing on Liu's approach, the air circulation coefficient (VC) was obtained as the product of wind speed at 10 m height and the height of the atmospheric boundary layer using ArcGIS software with a 0.125-degree raster [26, 27].

Data Sources

Due to the lack of data for Hong Kong, Macao, Taiwan, and Tibet, as well as the availability of the sample, panel data for 30 provinces (municipalities and autonomous regions) in China were used for the analysis from 2011-2021, with a sample observation of 330. The data come from the China Urban Statistical Yearbook, the China Financial Yearbook, the China Science and Technology Statistical Yearbook, the China Statistical Yearbook, the China Energy Statistics Yearbook, and the statistical yearbooks of prefectural-level municipalities. Based on the fact that the outliers in the sample years may cause the regression results to be less robust, this paper adopts the "shrinking method" to shrink the data samples by the upper and lower 1%. All data are logarithmically processed for each variable to ensure the robustness of the variable data, and some of the missing data is filled in by linear interpolation. The descriptive statistics of each indicator are shown in Table 2.

Results and Discussion

Pre-Testing and Data Transformations

We use the panel unit root test to determine that the continuous variables used in the regression model are stationary. The unit root test proposed by Maddala and Wu [28] uses the Fisher's test, which defines the null, and alternative hypotheses of this test are defined as:

H0: All panels contain unit roots;

H1: At least one panel is stationary.

The results of the panel unit root test on the relevant variables are reported in Table 3. As can be readily seen, Table 3 shows that for the variables except HCL, the null hypothesis that all panels contain unit roots is strongly rejected by the test. The null hypothesis of unit root is rejected for the other tested panel variables. However, the null hypothesis was not rejected for the variable HCL, and we performed a second difference before rejecting the null hypothesis.

The Pearson correlation matrix and variance impact factor between the study variables were then utilized

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

Table 2. Descriptive statistics of variables.

Variables	Obs	Mean	Std. Dev.	Min	Max
EGIE	330	1.063	0.244	0.333	2.092
GSER	330	0.0190	0.00300	0.013	0.0260
AGDP	330	12758	8076	5125	48075
UR	330	0.596	0.121	0.350	0.896
FDI	330	0.0190	0.0150	0.0001	0.0800
ECS	330	0.0330	0.0230	0.004	0.0950
HCL	330	0.0200	0.00600	0.008	0.0420
INDUSTRY	330	0.1025	0.1307	0.0053	0.7167
FC	330	0.952	0.415	0.370	2.583
AGG	330	0.026	0.039	0.0003	0.217
VC	330	1315	453.7	452.4	2578

Table 3. Results of the panel unit root test.

Variable Name	Level		Second Difference		Integration (degree)	VIF
	Statistics	P-value	Statistics	P-value		
EGIE	-6.5114	＜0.001	- - -	- - -	I (0)	——
GSER	-7.6770	＜0.001	- - -	- - -	I (0)	1.33
UR	-5.7716	＜0.001	- - -	- - -	I (0)	6.05
DIL	-0.4207	0.3370	-5.0176	＜0.001	I (1)	3.74
AGDP	-7.1779	＜0.001	- - -	- - -	I (0)	4.01
FDI	-6.3699	＜0.001	- - -	- - -	I (0)	1.65
ECS	-11.8953	＜0.001	- - -	- - -	I (0)	1.22
HCL	-9.7600	＜0.001	- - -	- - -	I (0)	2.17
INTEL	-2.4270	0.0076	- - -	- - -	I (0)	——
INDUSTRY	-4.8567	＜0.001	- - -	- - -	I (0)	——

to check for multicollinearity between the independent variables. As shown in Table 3, the VIF values of all variables except variable UR are less than 5, indicating that the problem of multicollinearity among variables is limited. Therefore, we can continue to estimate the panel model.

Main Effect and Regulatory Effect Regression Analysis

The results of model regression are shown in models (1) and (2) in Table 4. The use of system GMM needs to determine the instrumental variables validity over-identification test. The Hansen test of the P-value is greater than 0.1 and does not reject the original hypothesis, indicating that the selection of instrumental variables in the system GMM model is valid and there is no over-identification problem. In addition, the system GMM model needs to utilize the Arellano-Bond test for the autocorrelation of the random perturbation term, and the P-values of the AR (1) test of the model are all less than 0.1; the P-values of the AR (2) test are all greater than 0.1, which indicates that there is no problem of second-order autocorrelation of the residual term in the system GMM model. Therefore, the model setting of environmental regulation on regional cross-border e-commerce green innovation efficiency is reasonable and effective.

Table 4 Model (1) shows the effect of environmental regulation on regional cross-border e-commerce green innovation efficiency after considering the first-order lag term of green innovation efficiency. According to model (1), the first-order lagged term of the explained variable has a significant promotion effect on the current green innovation efficiency at the 1% level, with an impact coefficient of 0.179, which indicates that the regional

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

cross-border e-commerce green innovation efficiency has inertia with a significant cumulative growth effect, and it is necessary to continuously accumulate green innovation technology and take green innovation capacity building as the focus of regional strategic development. The effect of environmental regulation on green innovation efficiency is significantly positive at the 1% level, with a coefficient of 0.105, and hypothesis H1 is verified. This indicates that under the facilitating effect of environmental regulation, the innovation main body in the region achieves greater effectiveness in energy saving, emission reduction, and green production technology, which significantly and positively guides and promotes the generation of regional green innovation efficiency.

Model (2) in Table 4 shows the regulatory effect of intellectual property protection in environmental regulation on regional cross-border e-commerce green innovation efficiency. Among them, the regression coefficient of the cross-multiplier term of intellectual property protection and environmental regulation negatively affects the regional cross-border e-commerce green innovation efficiency at the 1% significance level, with a coefficient of -0.270, which indicates that the stronger the intellectual property protection is, the more obvious is the inhibiting effect of environmental regulation on the regional cross-border e-commerce green innovation efficiency, and the H3b hypothesis is verified. The reason may be that when the intensity of intellectual property protection is too high, in order to avoid higher innovation risks and costs, enterprises will choose to carry out non-environmentally friendly technological innovations with low technological difficulty and fast returns to ensure a certain level of returns. This will largely crowd out the government's R&D investment in environmental regulation innovation, forming a crowding-out effect on the enterprise's green innovation capacity, which is not conducive to green technological innovation.

Table 4. Regression analysis of main, regulatory, and intermediary effects.

Variables	Model (1) lnegie	Models (2) lnegie	Model (3) lnegie	Model (4) lnindustry	Model (5) lnegie
lngser	0.105*** (2.829)	1.172*** (3.889)	0.1820** (2.2635)	0.1538* (1.9461)	0.1735** (2.2630)
lnfc					0.1581*** (3.0034)
L. lnegie	0.179*** (9.405)	0.230*** (3.112)			
lnur	0.505*** (4.823)	-0.115 (-0.441)	-1.0566*** (-2.6431)	0.1356 (0.3340)	-0.1082 (-0.2971)
lnagdp	0.041 (0.937)	0.400*** (4.599)	-0.0885 (-0.6993)	-0.1013 (-0.7989)	0.2627** (2.3799)
lnfdi	-0.014*** (-2.729)	-0.082*** (-2.718)	-0.0161 (-0.7198)	-0.0030 (-0.1335)	-0.0615*** (-3.2111)
lnecs	-0.046*** (-3.117)	0.003 (0.119)	0.0686 (0.5728)	0.2488** (2.0573)	-0.1118 (-1.1788)
lnhcl	-0.346*** (-6.662)	-0.044 (-0.330)	0.4652** (2.4695)	-0.5297*** (-2.7921)	0.0849 (0.5053)
lnintel		0.763*** (2.609)			
lngser_lnintel		-0.270*** (-2.737)			
Constant	2.314*** (11.189)	-2.758* (-2.341)	7.6203*** (5.0874)	-2.2440 (-1.4946)	2.8740** (2.1907)
AR(1)	0.038	0.019			
AR(2)	0.402	0.938			
Hansen	0.498	0.659			
Observations	300	300	330	330	330
Number	30	30	30	30	30

Note: The *, **, *** of this document represent significant at the 10%, 5%, 1% levels, respectively, and are omitted from the following notes.

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

Regression Analysis of Intermediary Effects

In order to explore the role of environmental regulation on the path of industrial structure upgrading, this paper constructs the mediation effect model in the following equation: Industry is the intermediary variable, representing industrial upgrading. The c is the total effect coefficient of environmental regulation affecting the efficiency of green innovation. The a is the coefficient of environmental regulation on the mediator variable. The b is the coefficient of the mediator variable's effect on the efficiency of green innovation, and the c′ is the coefficient of the direct effect of environmental regulation affecting the efficiency of green innovation, formula (5).

$$\begin{aligned} &ln\,EGIE_{i,t} = c\,ln\,GSER_{i,t} + \beta \mathrm{control}_{it} + \mu_i + v_t + \varepsilon_{it} \\ &lnINDUSTRY_{it} = a\,ln\,GSER_{i,t} + \beta \mathrm{control}_{it} + \mu_i + v_t + \varepsilon_{it} \\ &ln\,EGIE_{i,t} = bM_{it} + c'\,ln\,GSER_{i,t} + \beta \mathrm{control}_{it} + \mu_i + v_t + \varepsilon_{it} \end{aligned} \tag{5}$$

In the mechanism of industrial structure upgrading shown in Table 4, the coefficients c, a, and b are 0.1820, 0.1538, and 0.1581, respectively, all of which pass the test of significance at least 90% confidence level, and the coefficient c′ is also significant, which suggests that industrial structure upgrading has a partially mediating effect on the influence of environmental regulation on green innovation efficiency. Model (4) shows that environmental regulation has a significant positive effect on industrial structure upgrading (coefficient = 0.1538), and model (5) shows that industrial structure upgrading also has a significant positive effect on the green innovation efficiency of cross-border e-commerce (coefficient=0.1581). Combined with the theoretical analysis, it can be seen that the impact of environmental regulation on regional cross-border e-commerce green innovation efficiency can be realized through the path of empowering industrial structure upgrading, which supports hypothesis H2.

Threshold Regression

This paper draws on the new method of threshold regression proposed by Hansen [30] to verify whether there is a threshold effect of government subsidy-based environmental regulation on regional cross-border e-commerce green innovation efficiency and constructs a threshold model as in Equation (6):

$$\begin{aligned} EGIE_{it} = \beta_1 + \beta_2 GSER \times I(AGG_i \leqslant \gamma_1) + \beta_3 GSER \\ \times I(\gamma_2 < AGG_i \leqslant \gamma_3) + \beta_4 GSER \times I(AGG_i > \gamma_3) \\ + \beta_5\ \mathrm{control} + \varepsilon_i \end{aligned} \tag{6}$$

Where I () is the indicator function, AGGi is the three threshold variables, respectively, and γi is the threshold value, when the values of the threshold variables in parentheses satisfy the conditions, the indicator function takes the value of 1, and 0 anyway. Table 5 shows the number of thresholds and the threshold values obtained by repeated sampling 300 times using bootstrap. The results show that the current stage of industrial agglomeration passes the single threshold and double threshold tests at 1% significance, so the double threshold test is used to analyze it. The LR trend is shown in Fig. 1, and the LR values corresponding to the first and second thresholds of 0.0072 and 0.0202 fall below the critical value of 5% and tend to be close to 0, i.e., the estimated thresholds are equal to the real thresholds, and the industrial agglomeration can be more accurately classified as three stages.

The results of the parameter estimation of the double-threshold model are shown in Table 5. Environmental regulation has a positive effect on regional cross-border e-commerce green innovation efficiency. When the level of financial agglomeration is lower than the threshold (AGG≤0.0072), the influence coefficient of industrial agglomeration on green innovation efficiency is 0.2891, and the significance test of 1% indicates that industrial agglomeration has a positive significant impact on green innovation efficiency under this condition. When the level of industrial agglomeration is greater than the threshold (AGG>0.0202), the effect of industrial agglomeration at the 1% level on the promotion of green innovation efficiency decreases significantly (coefficient = 0.1277). Therefore, industrial agglomeration has different effects on the regional cross-border e-commerce green innovation efficiency at different levels. When the level of industrial agglomeration increases, the industrial ecological environment and the corresponding supporting facilities in the region where it is located are also significantly improved, and the positive externality of industrial agglomeration takes the advantage. When the scale of industrial agglomeration exceeds the threshold, environmental degradation, lack of resources, population congestion, traffic jams, and other problems gradually appear, the scale effect of the agglomeration area is no longer significant. Thus, industrial enterprises with lower green technology content and higher pollution emissions will lose their comparative advantages due to earlier losses, which in turn hinders the green development of the region.

Characterization of Spatial Differentiation

In order to realize China's goal of crossing into the ranks of innovative countries, the Ministry of Science and Technology issued a circular in April 2016 on the guidelines for the construction of innovative provinces, with Jiangsu, Sichuan, Anhui, Hunan, Fujian, Shaanxi, Zhejiang, Hubei, Guangdong, Shandong, and Jilin as pilot innovative provinces [31]. In addition, Beijing, Shanghai, Chongqing, and Tianjin are considered pilot innovative municipalities. This paper explores the impact of environmental regulation on the regional cross-border e-commerce green innovation efficiency

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

Table 5. Threshold effect test results.

Threshold variable	Number of thresholds	Threshold value	F-value	P-value	95% confidence interval
Industrial agglomeration	Single threshold	0.0072	36.88***	0.003	[0.0072,0.0073]
	Double threshold	0.0202	39.36***	0.003	[0.0199,0.0203]
Explanatory variable		Model (6)		P-value	
GSER (AGG ≤ 0.0072)		0.2891*** (3.67)		0.001	
GSER (0.0072 < AGG ≤ 0.0202)		0.1277* (1.80)		0.082	
GSER (AGG > 0.0202)		-0.0161 (-0.19)		0.853	

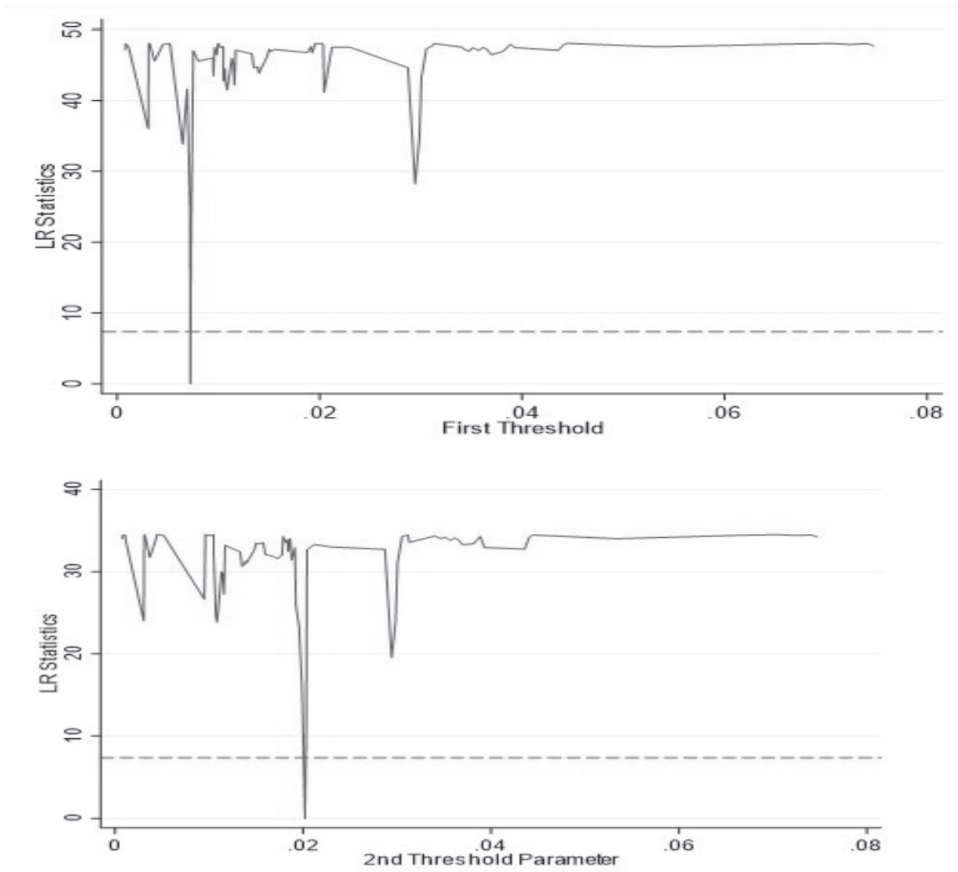

Fig. 1. Trend in LR for double-threshold estimates.

based on the innovative province and municipality pilots as the differentiation condition [2, 32, 33]. Among the innovative provinces and municipalities, eight eastern regions, four central regions, and three western regions are included.

Clarifying the spatial trend change of the regional cross-border e-commerce green innovation efficiency helps to grasp the process and mechanism of cross-border e-commerce development evolution as a whole. In this paper, with the help of the ArcGIS 10.8 software trend analysis tool, the spatial trend maps of 30 provinces and municipalities in 2011, 2016, and 2021 are drawn, and the results of the trend surface fitting are shown in Fig. 2. From the trend surface, it can be seen that in the north-south direction, the green innovation efficiency shows a U-shaped pattern, indicating that the green innovation efficiency in the north-south region is higher than that in the central region during the sample period, and the north-south region is almost at the same level over time. In the east-west direction, the green innovation efficiency shows an "inverted U" pattern, characterized by high in the middle and low on both sides, indicating that the green development efficiency of the eastern and western regions is lower than that of the

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

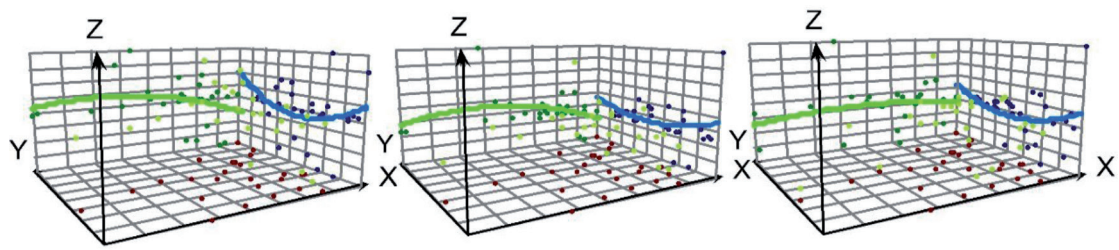

Fig. 2. Trend surface analysis of EGIE.

central region during the sample period. Over time, the trend curve rises from west to east, the green innovation efficiency of the eastern region increases significantly, and the trend curve evolves from an "inverted U" to a "zigzag pattern", indicating that the gap between the central region and the northern and southern regions gradually decreases. During the study period, the transition of the trend surface in the north-south direction is steeper, while the transition of the trend surface in the east-west direction tends to flatten out, which means that the divergence of green innovation efficiency in the north-south direction is more obvious and strong. It is found that the regional cross-border e-commerce green innovation efficiency, as an important manifestation of the attractiveness and competitiveness of "Internet e-commerce + manufacturing" in each region, is highly consistent with the spatial configuration of the regional economic development level and the abundance of industrial clusters.

Robustness Tests

The model replacement method is used to examine the stability of the evaluation methods and indicators, and if the same results can be obtained, it indicates that the data conclusions are stable and reliable, so this paper utilizes the differential GMM model to test the stability of the data in the robustness type test. As shown in Table 6, the regression coefficients and significance of the first-order lag terms of regional cross-border e-commerce green innovation efficiency, environmental regulation, and the cross-multiplier terms of environmental regulation and financial agglomeration in Models (7) and (8) are consistent with Models (1) and (2) in Table 4, which proves that the results of the main effects test are stable.

Heterogeneity Analysis

Model (9) is the sub-sample regression of non-innovative provinces (municipalities) regions, and model (10) is the sub-sample regression of innovative provinces (municipalities) regions. As shown in Table 6, the first-order lagged terms of the regional cross-border e-commerce green innovation efficiency are positively correlated with the current green innovation efficiency at the 1% significance level.

The environmental regulation in innovative provinces (municipalities) has a promotional effect on the regional cross-border e-commerce green innovation

Table 6. Robustness and heterogeneity test of the replacement regression analysis model.

Variables	Model (7) lnegie	Model (8) lnegie	Model (9) lnegie	Model (10) lnegie
lngser	0.143*** (4.679)	1.172*** (3.889)	0.071 (0.547)	0.060*** (2.624)
L. lnegie	0.184*** (2.998)	0.230*** (3.112)	0.297*** (3.098)	0.649*** (9.741)
lnintel		0.763*** (2.609)		
lngser_lnintel		-0.270*** (-2.737)		
Control variable	Yes	Yes	Yes	Yes
AR(1)	0.028	0.033	0.077	0.050
AR(2)	0.777	0.392	0.427	0.746
Hansen	0.833	0.411	0.654	0.984
Observations	270	270	150	150
Number of IDs	30	30	15	15

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

efficiency at the 1% significance level, with a coefficient of 0.060, which is consistent with the conclusion of the main effect test. The environmental regulations in non-innovative provinces (municipalities) have a promotional effect on the regional cross-border e-commerce green innovation efficiency, but there is no significant relationship. This may be due to the fact that the 15 non-innovative provinces (municipalities) include 12 provinces in the central and western regions, which have a relatively low degree of economic development and lag behind in the application of environmental regulations compared with the eastern regions, resulting in the weak ability to transform the results of green innovation and high-tech and the failure to form the competitiveness of green technological innovation [34, 35].

Conclusions

In this paper, in order to effectively control the problems of heteroskedasticity and endogeneity in the regression analysis, a two-step systematic GMM model is used as the main effect regression model to empirically analyze the effect of environmental regulation on regional cross-border e-commerce green innovation efficiency. It is found through empirical analysis:

(1) Environmental regulation has a significant promotional effect on regional cross-border e-commerce green innovation efficiency. For every 1% increase in the level of environmental regulation, the green innovation efficiency of cross-border e-commerce increases by 0.105%.

(2) Intellectual property protection has a negative regulating role in the effect of environmental regulation on regional cross-border e-commerce green innovation efficiency. This indicates that the stronger the government's protection of intellectual property rights, the more obvious the inhibitory effect of environmental regulation on the green innovation efficiency of cross-border e-commerce. For every 1% increase in the level of IPR protection, the green innovation efficiency of cross-border e-commerce decreases by 0.270%.

(3) In order to unveil the "black box" of the research on environmental regulations and the regional cross-border e-commerce green innovation efficiency, the step-by-step method confirms that financial agglomeration has a mediating and facilitating effect on the impact of environmental regulations on the regional cross-border e-commerce green innovation efficiency. Environmental regulation improves the efficiency of green innovation in cross-border e-commerce by empowering the upgrading of the regional industrial structure, which in turn improves the efficiency of green innovation in cross-border e-commerce.

(4) There is a double-threshold effect between environmental regulation and regional cross-border e-commerce green innovation efficiency. Industrial agglomeration passes the double-threshold test, and on the whole, the promotion effect of environmental regulation on green innovation efficiency decreases as the level of industrial agglomeration increases. When the level of industrial agglomeration is less than 0.0072, for every 1% increase in the level of industrial agglomeration, the green innovation efficiency of cross-border e-commerce will increase by 0.2891%. When the level of industrial agglomeration is greater than 0.0202, the green innovation efficiency of cross-border e-commerce increases by 0.1277% for every 1% increase in the level of industrial agglomeration. Different levels of industrial agglomeration have different promotional effects on the green innovation efficiency of cross-border e-commerce.

(5) Due to the vastness of China, the resource endowment of each region and its economic development situation are different. This paper, through sub-sample regression, found that innovative provinces and cities in the use of environmental regulation with non-innovative provinces and municipalities in the pilot region is different, so each region needs to carry out the depth and breadth of environmental regulation tools according to local conditions.

Based on the findings of the above study, the following takeaways are proposed:

(1) From the dimension of region, there is significant spatial heterogeneity in the impacts of environmental regulations on green innovation efficiency in pilot provinces and municipalities of innovative provinces and pilot provinces and municipalities of non-innovative provinces. Therefore, the government needs to progressively promote the intensity of environmental regulation in different provinces and implement locally tailored environmental regulation tools in different regions.

(2) Regional governments need to aim at industrial structure optimization and provide endogenous impetus for the development of green industries through the construction of a rationalized and advanced industrial structure in order to enhance the efficiency of regional green innovation. In the construction of industrial structure rationalization, local administrators strengthen environmental special subsidies, support, and R&D investment and provide the necessary green project investment funds, technology, and intellectual support for the transfer to knowledge-based, service-oriented, and green energy industries. In the construction of an advanced industrial structure, through the incentive and constraint effect of environmental regulation, promote the primary industry to increase production and reduce pollution, pay attention to the secondary industry's low-carbon and intensive utilization of high-carbon resources and alternative uses, promote the development of key technologies in low-carbon treatment of high-emission industries such as electric power, coal chemical industry, and oil and gas industry, and intensify the transformation and upgrading of the relevant industries.

(3) Formulate scientific and differentiated environmental regulatory policies based on different

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

intensities of intellectual property protection. Intellectual property protection intensity is constantly changing dynamically, and government departments at all levels should effectively consider the intensity range of local intellectual property protection levels in the process of driving green technological innovation with the help of environmental regulatory tools.

(4) Based on the advantages of industrial agglomeration, each region builds strategic alliances, regional cooperation, and innovation networks in agglomeration areas to promote the green innovation efficiency of cross-border e-commerce enterprises in the region. The agglomeration area should accelerate the cultivation and improvement of the industrial chain, integrate the innovation chain into the industrial chain, and fully realize the integration and synergy between the innovation chain and the industrial chain, so as to improve the effectiveness of innovation activities in the agglomeration area.

(5) Sound environmental protection mechanisms should give full play to the supply optimization and demand pulling effects of environmental regulation. The study shows that local governments should, on the one hand, innovate environmental regulatory means and, at the same time, cooperate with more active and open talent introduction and tax incentives to enhance the attractiveness of skilled labor, improve the investment environment of enterprises, and realize the industrial structure upgrading in the process of promoting the factor upgrading. On the other hand, they should increase subsidies for enterprises to introduce high-quality talents and advanced technologies and also make use of market competition and price mechanisms to stimulate enterprises to establish long-term, cleaner production mechanisms through technological innovation.

Funding

This work was supported by the Shanxi Provincial Office of Philosophy and Social Science Planning grant number 2022YK029] & Research on science and technology strategy in Shanxi Province [grant number 202204031401002] & The 19th graduate science and technology project of North University of China [grant number 20231945] & the Shanxi Federation of Humanities and Social Sciences [grant number SSKLZDKT2023052].

Acknowledgments

Thanks to the editors and reviewers for the revision suggestions during the paper review.

Conflict of Interest

The authors declare no conflict of interest.

References

1. KRIECHEL B., ZIESEMER T. The environmental Porter hypothesis: theory, evidence, and a model of timing of adoption. Economics of Innovation and New Technology, **18** (3), 267, **2009**.
2. ZHANG J.Y., TENG L., MA Q. Analysis of threshold effect of financial agglomeration on urban green economy efficiency-based on statistics of nine national central municipalities in China. Research on Technical Economics and Management, (03), 98, **2011**.
3. WANG J.M., QIU D.S., JIANG Q.Y., ZHANG M. Research on the Measurement and Enhancement Path of Industrial Green Development Efficiency in the Yangtze River Economic Belt. Science and Technology Management Research, (12), 46, **2019**.
4. ZHANG H. A study of strategic interactions of interregional environmental regulation an explanation for the non-exhaustive enforcement universality of environmental regulation. China Industrial Economics, (07), 74, **2016**.
5. BARON R.M., KENNY D.A. The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. Journal of Personality and Social Psychology, **51** (6), 1173, **1986**.
6. GUO J., YANG L.C. Impacts of environmental regulation and government R&D funding on green technology innovation - an empirical analysis based on provincial-level data in mainland China. Science and Technology Progress and Countermeasures, (10), 37, **2020**.
7. JIN G., SHEN K.R. Beggar-thy-neighbor or neighborly? – Environmental regulation enforcement interactions and urban productivity growth. Management World, (12), 43, **2018**.
8. LI R.J., YANG Y. Environmental regulation, financial resource allocation and green development efficiency. Ecological Economy, **36** (5), 147, **2020**.
9. PORTER M.E., VAN DER LINDE C. "Green and Competitive: Breaking the Stalemate". Harvard Business Review, September-October, **1995**.
10. STERLACCHINI A. Trends and determinants of energy innovations: patents, environmental policies and oil prices. Journal of Economic Policy Reform, 1, **2019**.
11. LI X.N., LI H. A study on the evolution of spatio-temporal pattern and path of green development of China's manufacturing industry. Regional Economic Review, (04), 64, **2021**.
12. BAO Q.L., CHAI H.Q. Environmental regulation, financial resource allocation, and regional green technology innovation efficiency. Discrete Dynamics in Nature and Society, **2022**, 1, **2022**.
13. HUANG L. Does industrial agglomeration enhance the efficiency of industrial green development in municipalities of the Yangtze River Economic Belt? Journal of Hubei University, (Philosophy and Social Science Edition) (01), 115, **2021**.
14. SHE S., WANG Q., ZHANG A.C. Technological innovation, industrial structure and green total factor productivity in cities: A channel test of impacts based on the pilot program of national low-carbon Cities. Economic and Management Research, **41** (8), 44, **2020**.
15. LU J., LI T.T. Industrial structure upgrading, technological innovation and green total factor productivity: a study based on heterogeneity. China Population Science, (4), 86, **2021**.

Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy • Author Copy

16. SUN J.H., TANG D.C., KONG H.J. Impact of industrial structure upgrading on green total factor productivity in the Yangtze river economic belt. International Journal of Environmental Research and Public Health, **19** (6), 3718, **2022**.
17. CUI C.C. On the adjustment object and application scope of e-commerce law. Journal of Soochow University (Philosophy and Social Science Edition), (01), **2019**.
18. LUO J. Analysis of techniques to prevent customer disputes under B2C conditions of cross-border e-commerce – taking Alibaba's global smar tone platform as an example. Foreign Economic and Trade Practice, (08), 67, **2017**.
19. ZHENG Y., SUN J. Can the strengthening of the rule of law contribute to improving the quality of corporate innovation? – Evidence from the establishment of intellectual property courts. Southern Finance, **2023**.
20. ZHANG J.Q., YU H.C., FAN F., TIAN J. Research on the threshold effect of environmental heterogeneity on innovation performance in the Yangtze river economic belt. China Science and Technology Forum, (01), 65, **2021**.
21. ARELLANO M., BOVER O. Another look at the instrumental variable estimation of error-components model. Journal of Econometrics, **68** (1), 29, **1995**.
22. ROODMAN D. How to doxtabond2: An introduction to difference and system GMM in Stata. The Stata Journal, **9**(1), 86, **2009**.
23. BLUNDELL R., BONDS S. Initial conditions and moment restrictions in dynamic panel data models. Journal of Econometrics, **87**, 115, **1998**.
24. XIAO Z.H., LI Y.Y. Green technology innovation model, environmental regulation and industry-university-research collaborative green innovation. Journal of Management Engineering (04), 16, **2023**.
25. SUN Z.Q., LI H.H., LIU B.L. Reserve, efficiency and influencing factors of industrial green development under carbon trading in China. East China Economic Management (12), 57, **2020**.
26. LI J.Q., MIAP E.-S. Intellectual property protection and firms' export technological complexity under incomplete contracts. China Industrial Economics, (12), 115, **2018**.
27. LIU C.M. Research on the effect of environmental regulation on the efficiency of green development (Doctoral dissertation, Central University of Finance and Economics), **2021**.
28. MADDALA G.S., WU S.A comparative study of unit root tests with panel data and a new simple test. Oxford Bulletin of Economics and Statistics, **61** (S1), 631, **1999**.
29. WU X.X. Research on the evolutionary trajectory and formation mechanism of regional green innovation efficiency in China. Science and Technology Progress and Countermeasures, (23), 36, **2019**.
30. HANSEN B.E. Threshold effects in non-dynamic panels: Estimation, testing, and inference. Journal of Econometrics, **93** (2), 345, **1999**.
31. CHUANG W.H., ZHANG W.T. Does strengthening judicial protection of intellectual property help enterprises innovate – evidence from the establishment of intellectual property courts. Contemporary Finance and Economics, **12** (9), **2020**.
32. WEN L., MA S., LYU S. The influence of internet celebrity anchors' reputation on consumers' purchase intention in the context of digital economy: from the perspective of consumers' initial trust. Applied Economics, 1, **2024**.
33. XIE Q.X. Environmental regulation, green finance development and corporate technological innovation. Research Management, (06), 65, **2021**.
34. ZHENG Z.Y., XU Y.B. Carbon emission trading mechanism, family control and green innovation efficiency. China Environmental Management, (05), 53, **2023**.
35. SONG Z.X., GE X.Y. Financial agglomeration, government intervention, opening up and regional economic development. Statistics and Decision Making, (19), 150, **2022**.