Bridging the gap: Environmental regulation and carbon productivity in the textile industry amid dual carbon targets

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XILIN ZHANG
HUIFANG LIU
JIE XU
HONGJUN ZENG
SHENGLIN MA

ABSTRACT – REZUMAT

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This research assessed the carbon productivity within the textile industry and utilised spatial Durbin and threshold regression models to empirically examine the relationship between environmental regulation and carbon productivity in this sector. The findings demonstrate that, at the national level, environmental regulation has generally enhanced the carbon productivity of China's textile industry. However, the local impact and spatial spillover effects of environmental regulation exhibit significant differences. At the regional level, environmental regulation has had a more substantial positive effect on the carbon productivity of the textile industry in the eastern and central regions, while it has hindered the improvement of carbon productivity in the western region. Additionally, the local and spatial spillover effects of environmental regulation vary greatly across different regions. The threshold effect analysis indicates that the impact of environmental regulation on the carbon productivity of the textile industry is contingent upon the level of textile technology. In provinces where the threshold value of textile technology has not been met, strengthening environmental regulation may impede the improvement of carbon productivity in the textile industry. Environmental regulation can boost the carbon productivity of the textile industry through two pathways: attracting foreign direct investment and optimising the energy structure.

Keywords: *textile technology, environmental regulation, carbon productivity, FDI, energy structure*

Reducerea decalajului: reglementările de mediu și productivitatea carbonului în industria textilă în contextul obiectivelor duble privind emisiile de carbon

Această cercetare a evaluat productivitatea carbonului în industria textilă și a utilizat modele spațiale Durbin și de regresie prag pentru a examina empiric relația dintre reglementările de mediu și productivitatea carbonului în acest sector. Rezultatele demonstrează că, la nivel național, reglementările de mediu au îmbunătățit în general productivitatea carbonului în industria textilă din China. Cu toate acestea, impactul local și efectele de propagare spațială ale reglementărilor de mediu prezintă diferențe semnificative. La nivel regional, reglementările de mediu au avut un efect pozitiv mai substanțial asupra productivității carbonului în industria textilă din regiunile estice și centrale, în timp ce au împiedicat îmbunătățirea productivității carbonului în regiunea vestică. În plus, efectele locale și spațiale ale reglementărilor de mediu variază foarte mult de la o regiune la alta. Analiza efectului de prag indică faptul că impactul reglementărilor de mediu asupra productivității carbonului în industria textilă depinde de nivelul tehnologiei textile. În provinciile în care valoarea pragului tehnologiei textile nu a fost atinsă, consolidarea reglementărilor de mediu poate împiedica îmbunătățirea productivității carbonului în industria textilă. Reglementările de mediu pot stimula productivitatea carbonului în industria textilă prin două căi: atragerea investițiilor străine directe și optimizarea structurii energetice.

Cuvinte-cheie*: tehnologia textilă, reglementări de mediu, productivitatea carbonului, investiții străine directe, structura energetică*

INTRODUCTION

The global textile industry faces unprecedented environmental challenges as international climate commitments intensify. The Paris Agreement's goal of limiting global warming to 1.5°C above pre-industrial levels has prompted nations worldwide to adopt ambitious carbon reduction targets. The European Union's Green Deal aims for climate neutrality by 2050, while the United States has committed to achieving net-zero emissions by 2050. These international frameworks have created a global imperative for industries to fundamentally transform their production models, with the textile sector, responsible for approximately 10% of global carbon emissions, under particular scrutiny.

The textile industry's environmental impact extends far beyond carbon emissions, encompassing water consumption (20% of global industrial water pollution), chemical usage, and waste generation. Major textile-producing countries, including India, Bangladesh, Vietnam, and Türkiye, are implementing increasingly stringent environmental regulations, creating a global competitive landscape where carbon productivity becomes a critical determinant of industrial competitiveness. The Ellen MacArthur Foundation's Make Fashion Circular initiative and the United Nations' Sustainable Development Goals have further elevated the urgency of sustainable textile production on the global agenda.

Within this global context, China has set ambitious goals to achieve peak carbon emissions before 2030 and carbon neutrality by 2060. The introduction of these dual carbon goals has had a profound impact on the textile industry, presenting both significant challenges and substantial development opportunities. Under the dual carbon framework, it is essential to vigorously promote new textile methods characterised by greening, intelligentisation, and industrialisation to facilitate the green development of the textile industry [1]. As a pillar industry of the national economy, the textile sector has driven rapid economic growth while causing severe environmental degradation [2]. In response, the government has implemented a series of environmental regulations to constrain corporate pollution emissions.

With the increasing severity of climate change and environmental pollution, China has been committed to advancing green development and pursuing a low-carbon, sustainable development path [3]. A low-carbon economy represents an economic model that achieves low-carbon development by balancing economic growth with carbon dioxide emission reduction targets [4]. The textile industry, as a foundational and pillar sector of economic development, consumes a large amount of energy and generates significant carbon dioxide emissions [5]. According to the Intergovernmental Panel on Climate Change (IPCC), the textile industry accounts for 36% of total carbon emissions, making reducing emissions from this sector an urgent priority. Current approaches to emission reduction include either reducing absolute carbon emissions or improving carbon productivity. The former approach, which sacrifices economic development, is inconsistent with the principles of sustainable development. In contrast, the latter approach, which is central to a low-carbon economy, represents a crucial pathway for sustainable carbon reduction [6].

China's position as the world's largest textile producer and exporter, accounting for over 50% of global textile production, makes its environmental regulatory effectiveness crucial for global sustainability goals. The country's textile industry not only serves domestic markets but also supplies major international brands, creating ripple effects throughout global supply chains. As international buyers increasingly demand sustainable production practices and implement supplier environmental standards, Chinese textile manufacturers face mounting pressure to improve their carbon productivity while maintaining competitive advantages.

In fact, the Chinese government has implemented a range of environmentally restrictive measures to protect the environment. These measures include regional joint prevention and control, as well as air pollution prevention and control plans aimed at reducing carbon emissions. The goal is to enhance carbon productivity and improve environmental quality through environmental regulation [7]. Given that the textile industry accounts for one-third of China's total industrial emissions, it is essential to determine whether environmental regulation has improved the carbon productivity of the domestic textile industry and its spillover effects on adjacent regions. Furthermore, it is necessary to explore whether a threshold value exists for the impact of environmental regulation on carbon productivity and whether other factors may constrain this relationship. Understanding how environmental regulation affects carbon productivity in the textile industry is crucial. This study addresses these questions by measuring the carbon productivity of the textile industry and analysing the relationship between environmental regulation and carbon productivity using spatial econometric and threshold regression models. This research is significant for informing region-specific environmental regulation policies and enhancing the carbon productivity of China's textile industry.

While existing literature has not specifically focused on the relationship between environmental regulation and carbon productivity in the textile industry, several studies have examined the broader relationship between environmental regulation and carbon productivity [8]. Cheng and Kong used provincial industrial data from China to explore the relationship between environmental regulation, industrial structural changes, and carbon productivity, concluding that increased environmental regulation intensity is beneficial for improving industrial carbon productivity [9]. Zhang et al. analysed the relationship between environmental regulation, economic growth, and regional carbon productivity in China, arguing that environmental regulation currently inhibits the improvement of carbon productivity [10]. Li et al. examined the non-linear impact of environmental regulation on regional carbon productivity under local government competition, suggesting that the effect of environmental regulation on carbon productivity can change with factors such as technological innovation [11]. These studies provide a theoretical foundation for further research on the relationship between environmental regulation and carbon productivity in the textile industry. However, several gaps remain: First, there is a lack of examination of the spillover effects of carbon productivity. As inter-regional competition and cooperation deepen, it is necessary to analyse the spatial spillover effects of carbon productivity. Second, there is insufficient research at the industry and regional levels. In addition to industry differences, regional disparities are also prevalent in China.

In light of these gaps, this study makes the following contributions based on provincial panel data from China between 2004 and 2022:

(1) Pioneering analysis of spatial spillover effects in textile manufacturing. This study was the first to systematically explore the spillover effects of environmental regulation on regional carbon productivity, specifically within the textile industry. Using spatial econometric models, the analysis captured interdependencies among textile-producing provinces and examined how environmental regulations in one textile hub affected carbon productivity in neighbouring textile regions. This addressed pollution haven effects commonly observed in labour-intensive manufacturing and provided insights for coordinated regional policy design through identification of textile technology diffusion, production facility relocation, and competitive spillover mechanisms across China's textile manufacturing belt.

(2) Multi-level comprehensive impact assessment of textile industry dynamics. The study conducted a comprehensive examination of overall, local, and spatial spillover effects at both national and regional levels within China's textile sector. The multi-dimensional framework differentiated between direct effects (within textile clusters), indirect effects (cross-regional textile supply chain spillovers), and total effects, providing granular insights into environmental regulation effectiveness across different textile manufacturing regions. Decomposition techniques separated local textile production effects from inter-regional spillover effects, enabling precise quantification of impact sources within the textile industry ecosystem.

(3) Advanced threshold effect analysis with textile technology interaction. The investigation explored non-linear relationships between environmental regulation and carbon productivity in textile manufacturing, identifying critical regulatory intensity levels where marginal effects on textile production efficiency changed dramatically. Incorporating textile-specific technology levels (including automation, clean production technologies, and energy-efficient machinery) as threshold variables revealed how regulation effectiveness varied across different stages of textile technological development. This dual-threshold approach employed Hansen's (1999) methodology with bootstrap procedures, contributing to the non-linear environmental economics literature whilst providing practical guidance for calibrating regulatory stringency in textile manufacturing contexts.

(4) Comprehensive transmission mechanism analysis for textile industry transformation. The study explored transmission mechanisms through which environmental regulation affected carbon productivity in textile manufacturing via multiple industry-specific channels: innovation (R&D stimulation in clean textile technologies), industrial restructuring (textile firm entry/exit dynamics and value chain reorganisation), scale effects (compliance costs impact on textile production capacity), competition (market dynamics alteration within textile segments), and investment reallocation (capital shifts toward energy-efficient textile machinery and sustainable production processes). Multi-mechanism analysis employed structural equation modelling and instrumental variables to establish causal relationships specific to textile industry transformation patterns.

(5) Methodological innovation and robustness in textile industry analysis. The study advanced methodological frontiers through: developing textile industry-specific carbon productivity measurement frameworks that accounted for fibre processing, dyeing, and finishing processes; combining spatial Durbin models with threshold regression techniques tailored to textile manufacturing characteristics; and implementing multiple robustness checks, including alternative spatial weight matrices reflecting textile supply chain linkages and instrumental variable approaches using textile-specific instruments. The framework could be adapted for other labour-intensive manufacturing industries, contributing to the spatial environmental analysis literature.

(6) Policy-relevant insights for global textile sustainability. The research generated actionable policy insights extending beyond China's textile industry through the identification of optimal regulatory intensity levels for textile manufacturing, spatial coordination requirements among textile-producing regions, and technology-conditional policy design principles for sustainable textile production. Findings contributed to international textile industry sustainability discussions and climate policy debates, offering evidence-based recommendations for balancing carbon reduction goals with textile industry competitiveness in developing economies, whilst supporting global textile supply chain decarbonisation efforts.

THEORETICAL ANALYSIS AND HYPOTHESIS DEVELOPMENT

Current academic research on the impact of environmental regulation on carbon productivity is primarily based on two theories: the Compliance Cost Theory [12] and the Innovation Compensation Theory [13]. The former argues that environmental regulation increases managerial complexity, pollution fees, and environmental investments, thereby reducing profitable production investments and capital returns. This ultimately has a negative impact on carbon productivity. In contrast, the latter, represented by the "Porter Hypothesis", posits that appropriate environmental regulation can drive technological progress in enterprises by reducing waste, pollution, and input costs. This, in turn, improves product quality and production efficiency, thereby compensating for and even exceeding compliance costs through innovation spillovers. Whether the impact of environmental regulation on carbon productivity is dominated by compliance costs or innovation compensation depends on the net effect of local effects (direct effects) and spatial spillover effects (indirect effects) [14].

In the context of the textile industry, carbon emissions consist of both direct emissions from textile activities and indirect emissions from the production of related materials, with the latter accounting for approximately 80% of total emissions [15]. Therefore, carbon emissions in the textile industry must consider not only emissions from textile activities but also those from the production of textile materials [16]. Given the currently high level of carbon emissions in the textile industry and the lack of significant technological breakthroughs [17], the innovation spillover effect of environmental regulation within a region is not pronounced [18]. Moreover, stringent environmental regulation in a region can lead to reduced output and increased costs for local textile material manufacturers, thereby increasing demand for textile materials from neighbouring regions [19]. This, in turn, promotes the development of textile material producers in neighbouring regions, particularly those with advanced technologies and broader market coverage. These enterprises can achieve economies of scale, improve production efficiency, and enhance carbon productivity in the textile industry in adjacent areas. Based on this analysis, the following hypothesis is proposed:

H1: Environmental regulation improves carbon productivity in the textile industry in Chinese regions.

The above analysis assumes homogeneity in macroeconomic factors such as economic levels. However, in China, there are significant differences in factor endowments, economic development levels, and geographical locations. Therefore, regional differences cannot be ignored when examining the impact of environmental regulation on carbon productivity in the textile industry. The eastern region, with its concentration of high-tech industries and higher economic development levels, also benefits from advanced technologies in textile-related auxiliary industries and textile material manufacturing [20]. This context is conducive to leveraging the innovation compensation effect of environmental regulation to improve local carbon productivity in the textile industry [21]. In contrast, the central and western regions, despite rapid development in the textile industry, still lag behind the eastern region in terms of economic and technological levels. Strengthening environmental regulation in these regions may inhibit industry expansion and result in significant compliance costs, thereby negatively impacting carbon productivity [22]. Based on these considerations, the following hypothesis is proposed:

H2: The impact of environmental regulation on carbon productivity in the textile industry varies across regions.

Existing studies have shown that the effect of environmental regulation on carbon productivity is also influenced by technological levels. When technological levels are high, environmental regulation can effectively promote innovation spillovers and enhance carbon productivity. In the textile industry, increased mechanisation and automation can improve energy efficiency. Currently, the production technology in China's textile industry is relatively mature. The key to effectively leveraging innovation compensation lies in the accumulation of incremental technological innovations [23]. Therefore, the impact of environmental regulation on carbon productivity in the textile industry is constrained by a technological threshold. Only when the technological level in the textile industry reaches this threshold can environmental regulation effectively promote improvements in carbon productivity. Based on this reasoning, the following hypothesis is proposed:

H3: The technological level in the textile industry acts as a threshold in the relationship between environmental regulation and carbon productivity.

Environmental regulation not only directly affects carbon productivity in the textile industry but also indirectly influences it through various channels. The "Pollution Haven Hypothesis" suggests that developed countries, in pursuit of profit maximisation, tend to shift pollution-intensive industries to developing countries with weaker environmental regulations [24]. Consequently, on one hand, stringent environmental regulation can deter some foreign direct investment (FDI) and increase pollution control costs for foreign enterprises. This may lead to a crowding-out effect on research and development (R&D) and management investments, weakening local firms' ability to absorb management knowledge and advanced technologies from foreign firms and thereby impeding the spillover effects of FDI. On the other hand, strict environmental regulation helps to screen out environmentally friendly firms and prevent the entry of pollution-intensive enterprises, which is conducive to the sustainable development of the textile industry [25]. Thus, environmental regulation can influence carbon productivity in the textile industry through the screening effect of FDI.

Reducing coal consumption and increasing the proportion of clean energy are important pathways to establishing a green production model in the textile industry [26]. The implementation of environmental regulation can encourage firms to reduce their demand for high-carbon energy sources such as coal and oil and increase the use of clean energy sources such as wind, solar, and geothermal energy. This guides firms towards establishing rational energy consumption patterns, which is particularly important for the sustainable development of the textile industry. Therefore, environmental regulation can improve carbon productivity in the textile industry by optimising the energy structure. Based on this analysis, the following hypothesis is proposed:

H4: Environmental regulation improves carbon productivity in the textile industry by increasing foreign direct investment and optimising the energy structure.

The theoretical framework diagram of the research in this paper is shown in figure 1.

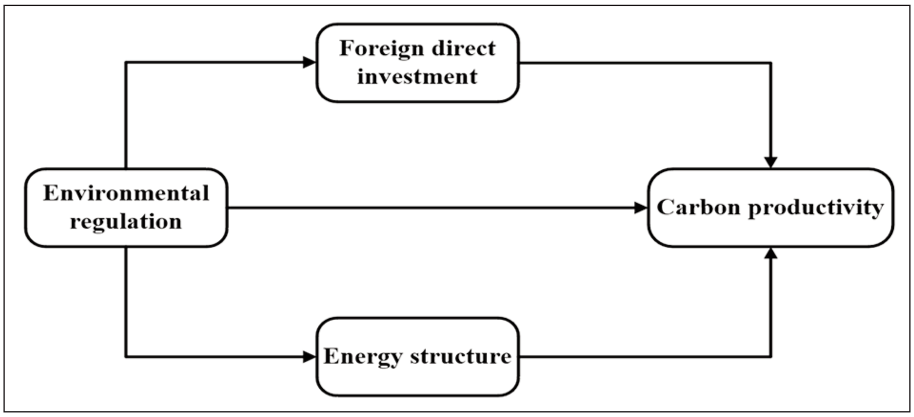

Fig. 1. Theoretical framework diagram

MODEL TEXTILE AND VARIABLE DESIGN

Model textile

Spatial Durbin Model (SDM)

Spatial econometric models mainly include the Spatial Lag Model (SLM), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM). The SLM and SEM are used to analyse spatial spillover effects on the dependent variable and spatial impacts of error shocks, respectively. The SDM is more general and incorporates both the SLM and SEM. Therefore, this study employs the SDM. The specific form is as follows:

$$\ln CP_{it} = \delta \sum_{j=1}^{n} w_{ij} \ln CP_{jt} + \beta \ln ER_{it} + \sigma \sum_{j=1}^{n} w_{ij} \ln ER_{jt} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where CP_{it} is an explanatory variable indicating the carbon productivity of the textile industry in province i in year t, ER_{it} is a core explanatory variable indicating the intensity of environmental regulation in province i in year t, w_{ij} is a weight matrix, X_{it} is a control variable, and δ, β, σ and γ are parameters to be estimated.

Threshold effect model

To further examine whether there is a threshold effect on the impact of environmental regulation on carbon productivity in the textile industry, this paper selects environmental regulation and the level of science and technology in the textile industry as the threshold variables, respectively, and analyses them by using a nonlinear panel threshold model, which is set as follows:

$$\ln CP_{it} = \alpha_0 + \alpha_1 \ln ER_{it} \cdot I(\ln T_{it} \leq \gamma) + \alpha_2 \ln ER_{it} \cdot I(\ln T_{it} > \gamma) + \beta X_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

where T is the threshold variable, γ – the threshold to be estimated, and $I(\cdot)$ denotes the indicator function.

Mechanism effect model

Meanwhile, in order to measure the indirect effect of environmental regulation on the carbon production efficiency of the textile industry, the following model is constructed.

$$\ln CP_{it} = \delta \sum_{j=1}^{n} w_{ij} \ln CP_{jt} + \beta_1 \ln ER_{it} + \beta_2 \ln ER_{it} \times \ln fdi_{it} + \beta_3 \ln ER_{it} \times \ln ener_{it} + \sigma \sum_{j=1}^{n} w_{ij} \ln ER_{jt} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

where $\ln ER_{it} \times \ln fdi_{it}$, $\ln ER_{it} \times \ln ener_{it}$ denote the interaction terms of environmental regulation with FDI and energy structure, respectively.

Indicator selection

Carbon productivity

Carbon productivity refers to the economic output generated per unit of carbon emissions, encompassing both economic growth and carbon dioxide emissions [27]. Based on this concept, this study first estimated the carbon emissions of the textile industry and then calculated its carbon productivity.

Existing methods for estimating carbon emissions in the textile industry primarily employ the material balance approach. Li et al. introduced the concept of associated carbon emissions in the textile industry, which includes both direct and indirect emissions [28]. They further specified the scope of carbon dioxide emissions in the textile industry as those directly generated by textile activities and those arising from the production of five major textile materials: steel, aluminium, glass, timber, and cement. Drawing on this approach, this study categorised textile industry carbon emissions into three types: (i) emissions from the consumption of 15 types of fossil fuels, including raw coal, washed coal, crude oil, and gasoline, during the textile process; (ii) emissions from electricity and heat consumption; and (iii) emissions from the production of five major textile materials, including cement and steel. Using the associated carbon emissions method, a model for estimating carbon emissions in the textile industry was established as follows:

$$E = E_1 + E_2 = 12/44 \times \left[\sum \alpha_i C_i + \sum \beta_i (1 - \delta_i) M_j\right] \quad (4)$$

where E is the total carbon emission from the textile industry, E_1 – the direct carbon emission, E_2 – the indirect carbon emission, and C – the corresponding energy consumption, α – the carbon emission coefficient of the corresponding energy source; M – the material usage, β – the carbon emission coefficient of the textile materials, and δ – the recycling coefficient of the corresponding textile materials. The coefficient 12/44 represents the molecular weight conversion factor from CO_2 to carbon. This conversion is necessary because: Molecular composition: Carbon dioxide (CO_2) has a molecular weight of 44 atomic mass units (carbon = 12, oxygen = 16 × 2 = 32, total = 44), whilst pure carbon has a molecular weight of 12 atomic mass units. Conversion rationale: Energy consumption data and emission coefficients typically measure CO_2 emissions. However, to calculate pure carbon emissions for carbon productivity analysis, the CO_2 values must be converted to their carbon equivalent by multiplying by 12/44 (≈ 0.273).

After estimating the carbon emissions of the textile industry in each province based on equation 4, the carbon productivity of the textile industry was calculated using GDP data adjusted to the base year of 2004. Carbon productivity was defined as the ratio of economic output to carbon emissions.

Environmental regulation intensity. Existing literature has identified three main approaches to measuring environmental regulation intensity: (i) using environmental policies as a proxy; (ii) estimating it based on pollutant emissions; and (iii) measuring it as the proportion of pollution control investment to relevant industrial output [29]. Since environmental policies are not always aligned with the growth of carbon emissions in the textile industry [30], and technological progress is a significant factor in reducing pollutant emissions, emissions data alone cannot accurately reflect the intensity of environmental regulation [31]. Therefore, this study adopted the third approach, measuring environmental regulation intensity as the ratio of pollution control costs to industrial output. Drawing on the method proposed by Azam et al., the study adjusted pollution control costs by the proportion of industrial output in the gross national product and used the adjusted value relative to the proportion of industrial output in the regional gross domestic product as the indicator of environmental regulation intensity [32].

Control variables

Given the multiple factors influencing carbon productivity in the textile industry, this study selected the following control variables based on relevant research: technological level in the textile industry, development level of the textile industry, development level of supporting industries, energy consumption structure of the textile industry, and openness of the textile industry to foreign investment. The technological level in the textile industry, as reflected in its mechanisation and automation, enhances resource utilisation efficiency [33]. In regions with a more developed textile industry, effective market competition promotes the rational allocation of production factors and improves industry productivity. The development of supporting industries, such as surveying and design, encourages the rationalisation of design plans and the adoption of new materials, thereby conserving resources [34]. The energy consumption structure significantly affects energy efficiency, with a higher proportion of primary energy sources, such as coal, reducing overall energy efficiency. Foreign investment in developing countries can introduce advanced management practices and technologies, generating demonstration and spillover effects that enhance domestic production efficiency.

The raw data used in this study were sourced from the *China Textile Industry Statistical Yearbook*, *China Energy Statistical Yearbook*, and *China Statistical Yearbook*. Due to significant data gaps for Tibet and the Hong Kong, Macao, and Taiwan regions, these areas were excluded from the analysis. Descriptive statistics for the variables are presented in table 1.

Table 1

STATISTICAL DESCRIPTION OF VARIABLES

Variable name	Variable explanation	Mean	SD	Min	Max
Carbon productivity in textile (CP)	Gross National Product/Carbon Emissions from textiles	4.215	2.103	0.850	9.880
Intensity of environmental regulation (ER)	Industrial Pollution Control Costs/Industrial Output Value	1.851	0.920	0.210	4.501
Level of technology in the textile industry (TL)	Technical equipment rate of the textile industry	8.450	3.200	2.100	18.500
Degree of development of the textile industry (CD)	Gross output value of the textile industry/Gross national economic output value	4.250	2.850	0.150	12.500
Degree of development of the ancillary Industries (AD)	Number of employees in the survey and design/Number of employees in the textile industry	2.150	1.120	0.350	5.200
Structure of energy consumption in the textile industry (EC)	Coal consumption converted to standard coal in the textile industry/Energy consumption in the textile industry	52.340	14.800	18.200	85.500
Level of opening up of the textile industry to the outside world (OL)	Gross output value of foreign investment in the textile industry/GDP of the textile industry	0.420	0.310	0.010	1.850

EMPIRICAL ANALYSIS

Spatial econometric estimation results and analysis

Before conducting a spatial econometric analysis, it is necessary to examine the spatial correlation in carbon productivity in the textile industry. This study employed Moran's I index to assess spatial autocorrelation using three matrices: an adjacency matrix, a distance matrix, and a spatial weights matrix. The results of Moran's I index were consistent across all three matrices. Therefore, only the results based on the adjacency matrix are presented in this study, as shown in table 2. The Moran's I index for carbon productivity in the textile industry from 2004 to 2022 was greater than zero and statistically significant, indicating positive spatial correlation. This result confirms that carbon productivity in the textile industry exhibits spatial dependence, justifying the use of spatial econometric models for further analysis.

Full sample estimation. In accordance with the selection rules for spatial econometric models, the study first conducted Lagrange Multiplier (LM) and robustness tests. When the LM-lag test was significant compared to the LM-error test, and the robust LM-lag test was significant while the robust LM-error test was not, the Spatial Autoregressive (SAR) model was preferred. Conversely, the Spatial Error Model (SEM) was selected if the LM-error test was more significant. The Spatial Durbin Model (SDM) was chosen based on further Wald and Likelihood Ratio (LR) tests to determine the final model. The Hausman test yielded a Z-value of 51.39 (P=0.000), significantly rejecting the null hypothesis and indicating the use of a fixed-effects model. Subsequent Wald and LR tests (P=0.006) rejected the null hypotheses of degeneration into SAR or SEM models, supporting the selection of the SDM model. To mitigate potential heteroscedasticity, all variables were transformed using logarithms. For statistical variables expressed in current prices, adjustments were made based on corresponding price indices. Given that ordinary least squares estimation in the SDM model may produce biased results, this study employed maximum likelihood estimation.

The estimation results in table 3 indicate the following: (1) Environmental regulation intensity passed the 5% significance test, showing a positive effect on the carbon productivity of the textile industry in adjacent regions but a negative effect in the local region, highlighting the prominence of compliance costs. Overall, environmental regulation contributed to the improvement of carbon productivity in China's textile industry to some extent. (2) The technological level of the textile industry had a positive effect on carbon productivity in both local and adjacent regions at the 1% significance level, confirming its importance in enhancing carbon productivity. (3) The energy consumption structure of the textile industry had significant positive direct and indirect effects on carbon productivity, indicating that a clean energy-oriented consumption pattern is a key factor in improving carbon productivity. Environmental regulation has effectively promoted

Table 2

MORAN'S I INDEX FOR CARBON PRODUCTIVITY IN THE TEXTILE INDUSTRY, 2004–2022

Index	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
I-value	0.321	0.345	0.378	0.364	0.346	0.333	0.320	0.317	0.346	0.355
P-value	0.002	0.001	0.000	0.001	0.000	0.004	0.001	0.002	0.001	0.008
Index	2014	2015	2016	2017	2018	2019	2020	2021	2022	-
I-value	0.358	0.352	0.363	0.365	0.371	0.378	0.382	0.390	0.388	-
P-value	0.001	0.005	0.001	0.000	0.002	0.001	0.000	0.001	0.004	-

Table 3

ESTIMATED RESULTS OF THE SAMPLE SPATIAL MEASUREMENT MODEL

Explanatory variable	Direct effect		Indirect effect		Total effect	
	Estimated value	Z value	Estimated value	Z value	Estimated value	Z value
ER	–0.021**	–1.979	0.045**	–2.105	0.024**	–2.178
TL	0.205***	3.120	0.337***	3.672	0.542***	3.594
CD	–0.222	–1.447	–0.175	–1.234	–0.397	–1.149
AD	0.529***	3.122	0.569***	3.455	1.099***	3.566
EC	0.044**	2.096	0.128**	2.001	0.172**	1.980
OL	0.005	0.878	–0.038	–1.234	–0.034	–1.143
R^2	0.567					
logL	167.789					

Note: The superscripts ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively. The same applies to the following tables.

carbon emission reductions through the low-carbon transformation of the energy consumption structure. The negative indirect effect of the energy consumption structure, which did not pass the significance test, suggests that its spillover effect on carbon productivity in the textile industry is not significant. (4) The development level of the textile industry had a positive effect at the 1% significance level, indicating that higher industry development levels enhance carbon productivity in the textile industry and drive improvements in adjacent regions. (5) The development level of supporting industries had positive direct and indirect effects at the 5% significance level, suggesting that rationalised surveying and design practices effectively reduce resource wastage and improve carbon productivity in the textile industry. (6) The openness of the textile industry to foreign investment had no significant effect on carbon productivity in China's textile industry and did not pass the significance test. This result is attributed to the continuous improvement of domestic textile technology and management practices, which have diminished the impact of foreign investment on the industry. Hypothesis 1 was thus validated.

Regional spatial econometric model estimation. To mitigate the impact of regional spatial development imbalances and reveal the regional characteristics of the effect of environmental regulation on carbon productivity in the textile industry, this study divided the 30 provinces into eastern, central, and western regions [35]. The estimation results are presented in table 4. As shown in table 4, in the eastern region, the direct and indirect effects of environmental regulation intensity on carbon productivity in the textile industry were positive. In contrast, in the central and western regions, the direct effects of environmental regulation intensity were negative, while the indirect effects were opposite, with a positive effect in the central region and a negative effect in the western region. This finding confirms the theoretical analysis that the impact of environmental regulation on carbon productivity in the textile industry exhibits regional heterogeneity. Regarding the control variables, the technological level of the textile industry, the development level of the textile industry, and the development level of supporting industries had positive direct and indirect effects on carbon productivity across all regions. Meanwhile, the energy consumption structure had negative direct and indirect effects on carbon productivity in all regions, consistent with the overall sample estimation results. The openness of the textile industry to foreign investment had negative direct and indirect effects on carbon productivity in the eastern and central regions, but did not pass the significance test. In the western region, however, the openness of the textile industry had positive direct and indirect effects on carbon productivity. This is primarily because the textile industry in the western region is relatively underdeveloped, and foreign investment in the textile sector can generate demonstration effects that enhance domestic productivity and improve carbon productivity. Hypothesis 2 was thus validated.

Threshold effect regression results and analysis

The empirical analysis in the preceding section primarily examined the impact of explanatory variables on carbon productivity in the textile industry. Subsequently, this study further investigated whether environmental regulation has a threshold effect on carbon productivity in the textile industry by separately selecting the intensity of environmental regulation and the technological level of the textile industry as threshold variables. Before the threshold effect analysis, it was necessary to examine the corresponding number and values of thresholds for the

Table 4

REGIONAL SPATIAL ECONOMETRIC MODEL ESTIMATION RESULTS

Explanatory variable	Eastern			Central			Western		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	0.023** (2.110)	0.039** (2.223)	0.062*** (3.078)	–0.039*** (–3.444)	0.091*** (3.879)	0.052* (1.782)	–0.041** (–2.101)	–0.198** (–2.326)	–0.239*** (–3.227)
TL	0.044*** (2.789)	0.118** (2.117)	0.162*** (3.332)	0.210 (1.270)	0.456** (2.054)	0.666*** (3.468)	0.037 (1.112)	0.151* (1.876)	0.188** (2.325)
CD	–0.218** (–2.102)	–0.276** (–2.054)	–0.494*** (–3.487)	–0.350** (–2.110)	–0.912* (–1.875)	–1.263*** (–3.565)	–0.051*** (–3.780)	–0.049 (–1.291)	–0.101** (–2.222)
AD	0.665* (1.770)	0.541** (2.183)	1.206*** (3.399)	1.048* (1.823)	1.110 (1.308)	2.158** (2.055)	1.032** (2.118)	0.611** (2.355)	1.643*** (3.448)
EC	0.004*** (2.987)	0.039** (2.116)	0.043*** (3.119)	0.002 (1.083)	0.009* (1.778)	0.011** (2.234)	0.156** (2.158)	0.006* (1.766)	0.162** (2.085)
OL	–0.014** (–1.988)	–0.114** (–2.221)	–0. 128*** (–3.356)	–0.015** (–2.067)	–0.056** (–2.011)	–0.071** (–2.232)	0.018* (1.870)	0.033** (2.039)	0.051*** (3.867)
R^2	0.763			0.509			0.688		
logL	123.782			56.905			85.149		

threshold variables. Table 5 presents the threshold values for the intensity of environmental regulation and the technological level of the textile industry obtained using the BS bootstrap sampling method. The results indicate that the threshold tests for the intensity of environmental regulation were not significant. That is, when the intensity of environmental regulation is used as a threshold variable, there is no significant threshold effect between environmental regulation and carbon productivity in the textile industry. This suggests that, at present, environmental regulation still has considerable potential to enhance carbon productivity in the textile industry. In contrast, the F-statistic for the single threshold of the technological level of the textile industry passed the 1% significance test, while the double and triple thresholds were not significant. Therefore, when the technological level of the textile industry is used as a threshold variable, a single threshold effect exists in the relationship between environmental regulation and carbon productivity.

Based on the threshold effect tests described above, this study employed a single-threshold panel model with the technological level of the textile industry as the threshold variable. The estimation results are presented in table 6. The results show that when the technological level of the textile industry is used as a threshold variable, the impact of environmental regulation on carbon productivity in the textile industry exhibits a V-shaped pattern. Specifically, when the technological level of the textile industry exceeds the threshold value, environmental regulation has a positive effect on improving carbon productivity. Conversely, when the technological level is below the threshold value, environmental regulation inhibits the improvement of carbon productivity. This indicates that in the textile industry, the innovation compensation effect of environmental regulation can only be effectively realised when the technological level reaches a certain standard. This effect not only offsets the compliance costs incurred by enterprises but also enhances carbon productivity. Further, based on the threshold value, the sample was divided into two groups: provinces with relatively high and relatively low technological levels in the textile industry, as shown in table 6. Provinces with technological levels below the threshold value have relatively low technological capabilities in the textile industry, which are not conducive to the realisation of innovation compensation effects. As a result, environmental regulation cannot effectively promote improvements in carbon productivity. Hypothesis 3 was thus validated.

Mechanism regression tests

To further investigate the indirect effects of heterogeneous environmental regulation on carbon productivity in the textile industry, interaction terms between environmental regulation and various mediating variables were introduced. The results are presented in table 7.

The interaction term between environmental regulation and foreign direct investment (ER×FDI) was positive, indicating that environmental regulation can exert a screening effect through foreign direct investment by attracting clean and environmentally friendly

Table 5

THRESHOLD EFFECT TESTS

Threshold variable	Number of thresholds	Threshold value	F value	P value	BS times	Threshold value		
						10%	5%	1%
Intensity of environmental regulation	Single threshold	0.456	2.982	0.672	500	8.234	10.789	15.110
	Double threshold	0.411 0.456	4.110	0.588	500	11.345	10.789	15.110
	Triple threshold	2.980	12.255	0.387	500	10.882	16.587	27.145
Level of science and technology	Single threshold	2.455***	29.107	0.000	500	18.565	22.909	29.816
	Double threshold	2.619 3.011	18.998	0.333	500	17.448	21.785	28.222
	Triple threshold	2.989	7.374	0.456	500	31.204	40.666	59.188

Table 6

SAMPLE GROUPING RESULTS OF TEXTILE INDUSTRY TECHNOLOGY LEVEL THRESHOLDS

Threshold variable	Threshold value	Coefficient	Equivalent provinces
Level of technology in the textile industry	TL≤2.455	–0.275**	Hebei, Liaoning, Anhui, Fujian, Jiangsu, Zhejiang Jiang, Jiangxi, Shandong, Henan, Hubei, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shanxi, Ningxia
	TL>2.455	0.467***	Beijing, Tianjin, Shanghai, Inner Mongolia, Jilin, Heilongjiang, Hunan, Guangdong, Qinghai

Table 7

ESTIMATION RESULTS OF THE INDIRECT EFFECTS OF ENVIRONMENTAL REGULATION ON CARBON PRODUCTIVITY IN THE TEXTILE INDUSTRY						
Explanatory variable	**Direct effect**	**Indirect effect**	**Total effect**	**Direct effect**	**Indirect effect**	**Total effect**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
ER	0.002* (1.786)	0.011*** (3.283)	0.073** (2.190)	0.023** (2.110)	0.039** (2.223)	0.062*** (3.078)
ER×FDI	0.111* (1.877)	0.203** (2.122)	0.128*** (3.589)	0.178** (2.113)	0.211** (2.089)	0.389*** (3.025)
ER×ENER	0.088* (1.783)	0.030** (2.29)	0.128*** (3.766)	0.110* (1.879)	0.166 (1.234)	0.276** (2.117)
TL	-	-	-	0.056** (2.111)	0.110* (1.887)	0.166*** (3.155)
CD	-	-	-	–0.134* (–1.812)	–0.211** (–2.149)	–0.345** (–2.147)
AD	-	-	-	0.459* (1.825)	0.446 (1.218)	0.905 (1.399)
EC	-	-	-	0.014*** (3.015)	0.023* (1.719)	0.037*** (3.230)
OL	-	-	-	–0.022* (–1.780)	–0.099** (–2.115)	–0. 120*** (–3.226)
R^2	0.673			0.666		
logL	123.45			110.255		

enterprises, thereby accelerating the green development of the textile industry. From the perspective of environmental regulation, this finding may be attributed to the fact that China's market mechanisms are not yet fully developed, necessitating the implementation of effective market incentive policies [36].

The interaction term between environmental regulation and energy structure (ER×ENER) was also positive, suggesting that environmental regulation can enhance carbon productivity in the textile industry by promoting the use of clean energy through the optimisation of the energy structure. From the perspective of environmental regulation, this outcome may be primarily driven by policy requirements and market guidance, with minimal influence from public preferences [37]. Hypothesis 4 was thus validated.

CONCLUSIONS AND POLICY IMPLICATIONS

This study estimated the direct and indirect effects of environmental regulation on carbon productivity in the textile industry at both the national and regional levels, based on provincial panel data from 2004 to 2022. Using spatial panel Durbin models and threshold panel models, the study also explored the threshold variables and values influencing the relationship between environmental regulation and carbon productivity in the textile industry. The results demonstrate the following:

(1) At the national level, environmental regulation has an overall positive effect on improving carbon productivity in China's textile industry. However, the local effect and spatial spillover effect differ significantly. While local environmental regulation has a significant positive spatial spillover effect on the carbon productivity of adjacent regions, its impact within the local region is less pronounced due to the compliance costs incurred by enterprises. Additionally, technological level, development level of the textile industry, and the development level of supporting industries positively influence carbon productivity. In contrast, a coal-dominated energy consumption structure hampers improvements in carbon productivity.

(2) Regionally, environmental regulation in the eastern and central regions has a more pronounced positive effect on carbon productivity in the textile industry. In contrast, environmental regulation in the western region inhibits improvements in carbon productivity. Significant differences exist in the local and spatial spillover effects of environmental regulation across regions. In the eastern region, both local and spatial spillover effects are positive, while in the central and western regions, the local effects are negative. The spatial spillover effects are opposite, with a positive effect in the central region and a negative effect in the western region. However, increased openness to foreign investment in the textile industry can promote improvements in carbon productivity in the western region.

(3) Regarding threshold effects, no significant nonlinear threshold relationship was found between environmental regulation and carbon productivity when environmental regulation intensity was used as the threshold variable. However, when the technological level of the textile industry was used as the threshold variable, a single V-shaped threshold effect was observed. That is, when the technological level exceeds the threshold value, the innovation spillover

effect of environmental regulation can offset the negative impact of compliance costs and enhance carbon productivity. Two-thirds of the provinces did not meet the technological threshold value, indicating substantial room for improvement in the technological level of the textile industry.

(4) Environmental regulation can improve carbon productivity in the textile industry through foreign direct investment and the optimisation of the energy structure.

The conclusions of this study offer the following policy implications:

- First, further promotion of the development and implementation of environmental regulation policies, particularly those related to the textile industry, is necessary to enhance the overall level of carbon productivity nationwide. Strengthening inter-regional coordination in the implementation of environmental regulations can prevent local textile industries in regions with stricter regulations from losing opportunities due to avoidance behaviours related to investment activities. This approach also protects the enthusiasm of local governments in implementing energy-saving and emission-reduction measures.
- Second, considering the varying development needs of the textile industry and environmental urgency across regions, region-specific measures should be adopted to balance ecological protection and economic development. The eastern region should focus on the scientific formulation and effective implementation of textile industry environmental regulations. In contrast, the central and western regions should prioritise improving the development level of the textile industry while gradually implementing environmental regulations.

  Encouraging foreign textile enterprises and high-tech textile firms from the eastern region to invest in the western region can enhance carbon productivity in the textile industry through technology spillovers and demonstration effects.
- Third, aligning environmental regulation with the technological level of the textile industry is essential to fully leverage the innovation compensation effect of environmental regulation. The improvement in carbon productivity driven by innovation compensation aligns with China's requirements for high-quality and regional innovative development. Therefore, in addition to implementing reasonable environmental regulation measures, regions should continuously enhance the technological level of the textile industry, especially in provinces that have not yet reached the threshold value. Optimising the energy consumption structure of the textile industry and related sectors, reducing the use of inefficient energy sources such as coal, and increasing the proportion of green energy consumption are also critical steps.

RESEARCH LIMITATIONS AND FUTURE RESEARCH PROSPECTS

Research limitations

Although this study utilised comprehensive provincial panel data spanning from 2004 to 2022, several data limitations were encountered. Firstly, the provincial-level aggregated data may have masked firm-level heterogeneous responses and variations in carbon productivity performance. Secondly, whilst the temporal scope was substantial, it may not have fully captured the long-term dynamic effects of environmental regulations.

The study employed spatial econometric and threshold regression techniques; however, certain methodological constraints remained. The construction of the spatial weight matrix was based on geographical proximity, which may not have comprehensively reflected the complex economic linkages between provinces. The threshold identification method assumed that threshold effects remained consistent across all provinces and time periods, potentially overlooking temporal variations and inter-provincial heterogeneity.

Future research prospects

Future research should extend to firm-level data to analyse the heterogeneous responses of different types of textile enterprises to environmental regulations, thereby providing a foundation for precise policy design.

The analytical framework should be expanded to include other major textile-producing countries, such as India, Bangladesh, Vietnam, and Turkey, to enhance the generalisability of the research findings. The effectiveness of different regulatory instruments (command-and-control versus market-based mechanisms) should be investigated, exploring the optimal design of policy combinations including carbon pricing, environmental taxes, and emissions trading systems.

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Authors:

XILIN ZHANG[1], HUIFANG LIU[2], JIE XU[3], HONGJUN ZENG[4], SHENGLIN MA[3]

[1]Shandong Huayu University of Technology, Dezhou, China

[2]School of Economics and Management, Shandong Youth University of Political Science, Jinan, China

[3]School of Economics and Management, North University of China, Jinan, China

[4]Department of Finance, College of Finance, Nanjing Agricultural University,
1 Weigang, Xuanwu District, Nanjing, 210095, Jiangsu, China

Corresponding author:

SHENGLIN MA
e-mail: sz202209002@st.nuc.edu.cn