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Can Environmental Regulation Enhance Green Total Factor Productivity?—Evidence from 107 Cities in the Yangtze River Economic Belt

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Abstract: Promoting green development has emerged as a pivotal approach to optimizing the ecological and economic structure, thereby fostering sustainable development. Whether the implementation of environmental regulations in the Yangtze River Economic Belt (YREB), an important economic corridor in China, has increased the green total factor productivity (GTFP) of cities remains to be investigated. This paper uses Chinese city panel data from 2007 to 2019 to calculate the green total factor productivity (GTFP) of 107 cities in the Yangtze River Economic Belt using the super-efficiency SBM (Slacks-Based Measure) model and the GML (Global Malmquist–Luenberger) index and measures the intensity of environmental regulations through textual analysis. Through empirical analyses, this paper finds that environmental regulation has an inverted U-shaped effect on green total factor productivity (GTFP), which is first promoted and then suppressed, and the inflection point of the inverted U-shaped curve is about 0.51. Mechanism analyses show that environmental regulation in the Yangtze River Economic Belt promotes the growth of GTFP by facilitating green technological innovation but does not improve GTFP by enhancing the level of industrial structure. Heterogeneity analyses show that the effect of environmental regulation on GTFP is more significant in the city clusters in the middle and upper reaches of the Yangtze River and in cities outside the city clusters. Therefore, when formulating environmental regulation policies, the relationship between economic development and environmental protection should be balanced, while focusing on regional heterogeneity and adapting to local conditions, to coordinate the environment and economic development of the whole Yangtze River basin.

Keywords: environmental regulation; green total factor productivity; Yangtze River Economic Belt

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1. Introduction

Green development is the key to implementing the new development concept and realizing high-quality development, especially since economic development has entered a new era, and the importance of accelerating green development has become more and more prominent as the global community has become increasingly concerned about environmental pollution, energy consumption, and carbon emissions. Promoting green development is also an inevitable requirement for sustainable development [1–3]. As an important indicator of green development, green total factor productivity (GTFP), compared with traditional total factor productivity (TFP), incorporates energy consumption and environmental pollution based on measuring technological change, which is more in line with the connotation of green development. Therefore, the realization of green TFP is not only a better reflection of the benefits of economic development but also an important manifestation of the enhancement of the capacity for sustainable development.

Since the externalities of environmental pollution can lead to market failure, solving environmental problems requires active government action. Environmental regulation is a key measure for governments to support green and sustainable development [4]. The need to improve the environment, tackle pollution and emissions, and promote green development has driven policies related to environmental regulation in China. The Yangtze River Economic Belt (YREB), a giant economy spanning China's east, middle, and west, has been experiencing acute conflicts between the development of the Yangtze River Basin and ecological safety for more than a decade, and ecological priority and green development have become inevitable strategic choices for the YREB. All provinces and cities in the Yangtze River Economic Belt have also introduced a series of environmental regulations to deal with environmental and developmental issues. So, what is the actual effect of environmental regulations on green total factor productivity (GTFP) in the Yangtze River Economic Belt? Additionally, what is the intrinsic mechanism of these elements? Does environmental regulation have a regionally heterogeneous impact on green total factor productivity?

Based on the above questions, this paper takes environmental regulation and green total factor productivity as the core variables and takes the panel data of cities in the Yangtze River Economic Belt from 2007 to 2019 as the analytical basis to test the above questions and explain the mechanism of environmental regulation on green total factor productivity to provide certain references for the formulation of environmental regulation policies, such as environmental governance and the "dual carbon" targets.

The three main innovations of this paper are as follows: (1) The innovative measurement of the level of environmental regulation. Most of the literature only focuses on a single environmental regulation policy, which cannot comprehensively reflect the government's environmental governance policy and environmental regulation intensity. By constructing an indicator system for environmental words and using Python to textually analyze government work reports, this paper derives the level of environmental regulation in the Yangtze River Economic Belt, which can more comprehensively reflect the environmental regulation intensity of local governments in that year. (2) It supplements the literature on the policy effects of environmental regulation in cities in the Yangtze River Economic Belt, providing new empirical evidence on the impact effects of environmental regulation in the Yangtze River Economic Belt. (3) Most of the existing studies have been conducted from the perspectives of industrial enterprises and the provincial level, and few of them have explored in depth the impact of environmental regulations on green total factor productivity at the city level. Our study provides a new perspective on the impact of environmental regulation in the Yangtze River Economic Belt from the perspective of green total factor productivity at the city level.

The ability of environmental regulation to improve green total factor productivity (GTFP) is crucial for alleviating environmental pollution problems and promoting sustainable social development. The existing literature on the impact of environmental regulation on total factor productivity can be categorized into the following three types depending on the viewpoint.

The first view is Porter's hypothesis: well-designed environmental regulations (ERs) can generate innovation compensation effects, improve production technology, partially or even completely offset the costs of environmental regulations, and promote GTFP [5]. Many scholars have supported this theory through research and empirical analyses [6–14]. For example, Jaffe and Palmer [10], Hamamoto [9], and Rassier and Earnhart [13] state that ER can stimulate firms' research and development (R & D) expenditures and further improve firm performance and total factor productivity (TFP). By investigating the European manufacturing sector, Rubashkina et al. [15] found that ER is positively correlated with innovation activity. In addition, ER has been shown to have a positive impact on total factor productivity in China [16]. Feng et al. [7] demonstrate that market-based ER can effectively enhance GTFP at the national level. Moreover, a rational industrial structure can enhance the contribution of ER to GTFP [17].

The second view is the inhibition hypothesis. This hypothesis argues that ER may increase production costs, crowd out investment, and deteriorate GTFP. for example, Gray [18] finds that environmental regulations may inhibit total factor productivity (TFP) enhancement in U.S. manufacturing firms, and Barbera and McConnell [19] demonstrate that overly stringent environmental regulations are detrimental to the TFP of industries. Environmental regulations increase firms' capital constraints and reduce their output, affecting their total factor productivity development [20]. Gray and Shadbegian [21] classified factories into integrated and non-integrated factories and found that there is a negative (non-significant) relationship between environmental regulations and total factor productivity in integrated (non-integrated) factories. Lanoie et al. [11] also observed a negative effect of environmental regulations on firm performance and that this negative effect is larger than the positive effect from R & D investments. In other words, the innovation compensation effect brought by environmental regulation can hardly compensate for the cost brought by environmental regulation, which ultimately leads to the deterioration of their green total factor productivity. Tang et al. [22] suggest that command-and-control environmental regulation can hardly realize the win–win policy objective of the total factor productivity growth of firms and environmental sustainability. In addition, Hou et al. [23] found that market-based environmental regulation, such as a carbon emission permit trading mechanism, may inhibit the enhancement of GTFP in China.

The third view is the uncertainty hypothesis, which argues that the impact of environmental regulation on total factor productivity is uncertain. With the gradual enrichment of research methods and diversification of research perspectives, scholars have found that the relationship between the two is not a simple facilitating or inhibiting relationship but a more complex one. For example, Becker [24], using a sample of U.S. manufacturing firms, found that the impact of environmental regulations on firms' total factor productivity may not be significant in regions with strict environmental regulations and relatively high environmental costs. Wang and Shen [25] found that there is an inverted U-shaped relationship between environmental regulations and China's environmental productivity, but that this inverted U-shaped relationship exists only in some sectors. Moreover, environmental regulation has also been shown to have an inverted U-shaped effect on green economy efficiency and regional economic development [26], which is facilitated and then inhibited. On the contrary, some scholars proposed the existence of a U-shaped relationship between green total factor productivity and environmental regulation [27,28]. In addition, Luo et al. [29] demonstrated that informal environmental regulation (market-based environmental regulation) and command-and-control environmental regulation have a dampening (facilitating) effect on green innovation. He et al. [30], on the other hand, concluded that the effect of environmental regulation on green total factor productivity is not significant.

In summary, the existing literature has the following shortcomings: First, as an important economic corridor in China, the Yangtze River Economic Belt has little literature on the impact of environmental regulation on green total factor productivity. Secondly, the studies on the measurement of green total factor productivity mainly use the traditional DEA model or the SBM model that considers the undesired outputs, and there is little literature on the measurement of green total factor productivity using the super-efficient SBM model that considers the undesired outputs. Thirdly, most of the existing studies analyze the policy effects of environmental regulation from a single perspective of environmental regulation, which cannot reflect the government's emphasis on environmental governance and the intensity of regulation from a global perspective.

Based on the existing studies and their shortcomings, this paper tries to expand from the following aspects: Firstly, using the SBM-GML model, the green total factor productivity of the Yangtze River Economic Belt (YREB) is measured, and the level and characteristics of the green total factor productivity of the YREB region are portrayed. Secondly, by constructing the indicator system of environmental protection words and applying the method of text analysis, the level of local environmental regulation was derived, which can reflect the environmental regulation strength of local governments in that year in a

more comprehensive way and measure the environmental regulation strength of each city in the Yangtze River Economic Belt. Once again, through the construction of a two-way fixed effect model, the goal of this study is to empirically test the effect of environmental regulation on green total factor productivity in the Yangtze River Economic Belt at the city level, and finally, based on the empirical findings, put forward policy recommendations to promote the coordinated development of green total factor productivity.

A review of the existing literature reveals that the effect of environmental regulation on green total factor productivity may have both positive and negative aspects.

On the one hand, environmental regulation can have an innovation compensation effect, i.e., there is the "Porter hypothesis". The Porter hypothesis was put forward by Harvard University professor Porter in 1991, who argued that environmental regulations can force enterprises to increase more R & D funding, thereby improving technological innovation. Improvements in technological innovation can increase firms' productivity and profits, thus compensating for the additional costs of environmental regulation [31,32]. Therefore, environmental regulations can contribute to the growth of GTFP.

On the other hand, environmental regulation has a "cost effect". Under the premise of the total amount of enterprise resources, to meet the requirements of environmental regulation, enterprises will invest part of the labor and capital production factors into the field of environmental management, which will increase the production and operation costs of enterprises from the total viewpoint (including the cost of environmental compliance and operating costs), and from the viewpoint of the cost structure, the proportion of R & D and production-oriented investment in the total ratio will decline, squeezing out part of the original expenditure on R & D and innovation and technology introduction. Therefore, while the negative externalities of environmental pollution are internalized, the productivity of enterprises is reduced, which inhibits the growth of GTFP.

The impact of environmental regulation on green total factor productivity is complex and cannot be simply defined as a facilitating or inhibiting effect, the impact of the effect of uncertainty, depending on the relative size of the "innovation compensation effect" and "cost effect". When the "innovation compensation effect" is greater than the "cost effect", environmental regulation can force enterprises to increase more R & D funds; to improve technological innovation, thereby improving enterprise productivity and increasing enterprise profits [33,34]; and to make up for the "cost effect" brought about by environmental regulation. The "cost effect" of environmental regulations can be compensated for by increasing the profitability of enterprises, thus enhancing green total factor productivity. When the "cost effect" is greater than the "innovation compensation effect", the benefits brought by the "innovation compensation effect" can hardly make up for the costs brought by environmental regulations, which ultimately leads to the deterioration of green total factor productivity. The total factor productivity of green is deteriorating.

At the same time, both the "innovation compensation effect" and the "cost effect" emphasize the importance of technological innovation, which is an important factor influencing the production efficiency of enterprises and the main source of total factor productivity growth. Technological innovation, especially green technological innovation, is an important way for environmental regulation to affect green total factor productivity.

Based on the above discussion, we propose the following hypotheses:

H1: *The impact of environmental regulation on green total factor productivity in cities in the Yangtze River Economic Belt is uncertain.*

H2: *Green technological innovation is an important mechanism through which environmental regulation affects green total factor productivity in cities in the Yangtze River Economic Belt.*

The service industry, which is characterized by low energy consumption, low pollution emissions, and high added value, has a contributing effect on the enhancement of green total factor productivity. The secondary industry, represented by industry, consumes

many natural resources and energy and produces many polluting emissions, which has a significant inhibiting effect on green total factor productivity. The primary industry is less polluting but accounts for a relatively small proportion of the total economy and has a limited role in promoting green total factor productivity. Therefore, increasing the proportion of tertiary industries such as the service industry can help optimize the industrial structure, promote the advanced industrial structure, reduce pollution emissions and energy consumption, and, thus, promote the increase in green total factor productivity; conversely, it may lead to the decline in green total factor productivity.

On the one hand, in the process of implementing the environmental regulation policy, with the banning of "small and messy" enterprises, the investment of enterprises may shift to the tertiary industry, which will increase the output value and proportion of the tertiary industry and promote the development of the industrial structure to the advanced level, thus promoting the improvement of the green total factor productivity.

On the other hand, however, the Yangtze River Economic Belt region is the main battlefield for China's industrial construction and development, as well as China's major industrial agglomeration and growth agglomeration area, with a good manufacturing industry foundation and a complete industrial system. The environmental regulation policy is more likely to reduce the backward production capacity in the secondary industry of the Yangtze River Economic Belt to be replaced by new environmentally friendly production capacity and to improve the capacity efficiency and output value of the secondary industry. At the same time, environmental regulation may promote green technological innovation, which improves energy efficiency and reduces production costs through iterative technological upgrading. According to cost theory, this will shift the production possibility boundary of enterprises outward, leading to an increase in product demand. To maximize profits, firms will increase factor inputs to expand production capacity, leading to an increase in output value in the secondary sector. Therefore, environmental regulation may not be able to enhance green total factor productivity through the path of industrial structure advancement by increasing the share of the tertiary industry.

Given this, the following research hypothesis is proposed:

H3: *Environmental regulation may not be able to enhance the green total factor productivity of cities in the Yangtze River Economic Belt through the path of industrial structure advancement.*

2. Materials and Methods

2.1. Model Establishment

Firstly, the fitted curve of environmental regulation and green total factor productivity is plotted using Stata 17.0, as shown in Figure 1; there is a nonlinear relationship between environmental regulation and green total factor productivity. Therefore, this paper refers to the existing literature [35] and adds the squared term of the explanatory variable environmental regulation to the equation to establish a nonlinear relationship model, as shown in the constructed bidirectional fixed effects model (1). To test the mechanism of the impact of environmental regulation on green total factor productivity, a mediated effects model is constructed, as shown in Equation (2).

$$GTFP_{it} = \alpha_0 + \beta_1 ER_{it} + \beta_2 ER2_{it} + \gamma controls_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (1)$$

$$M_{it} = b_0 + b_1 ER_{it} + b_2 ER2_{it} + \lambda controls_{it} + \varphi_i + \omega_t + \varepsilon_{it} \quad (2)$$

$GTFP_{it}$ represents the green total factor productivity of city i in year t; ER_{it} represents the environmental regulation intensity of city i in year t; $ER2_{it}$ represents the square of the environmental regulation intensity of city i in year t; and $controls_{it}$ represents the set of control variables. μ_i and θ_t are the individual and time-fixed effects and ε_{it} is the error term. β_1 and β_2 reflect the effect of environmental regulation on green total factor productivity, and the effect of government environmental regulation on green total factor productivity

is analyzed according to the magnitude, direction, and significance of β_1 and β_2. M_{it} in model (2) is the mediating variable, which is analyzed using green technology innovation (GTI) and industrial structure advanced (IS), respectively, b_1 and b_2 reflect the effect of environmental regulation on mediators, and $controls_{it}$ represents the set of control variables, φ_i and ω_t are individual and time-fixed effects, and ε_{it} is the error term.

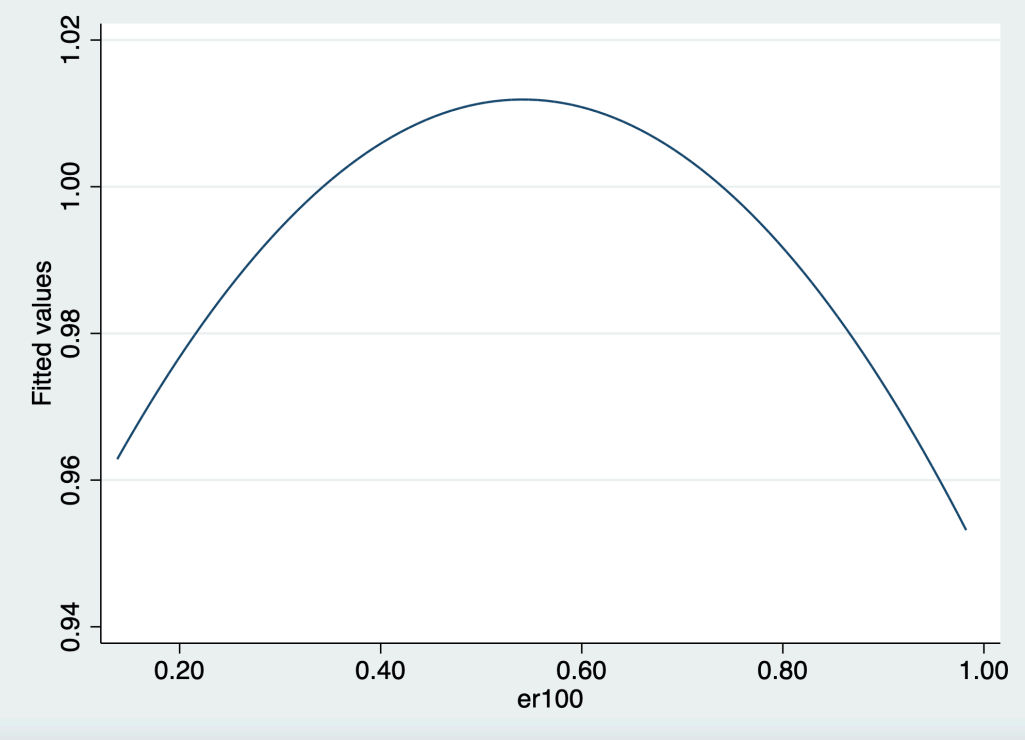


Figure 1. Fitted plot of environmental regulation and green total factor productivity.

2.2. Selection of Variables

2.2.1. Explained Variable

Explained variable: green total factor productivity (GTFP). This paper uses the SBM model including undesired output and GML index to measure GTFP. In this paper, we construct a super-efficient SBM model with undesired outputs and combine it with the Global Malmquist–Luenberger (GML) productivity index proposed by Pastor and Lovell [36] to measure green total factor productivity. The calculation process is as follows.

Assuming that there are n decision-making units (DMUs), each city is treated as a production decision-making unit (DMU), and each DMU uses p-factor inputs in period t. Define the matrix $X = [x_1, \ldots, x_n] \in R^{p \times n} > 0$, which produces good outputs, i.e., desired outputs; $Y^g = [{y^g}_1, \ldots, {y^g}_n] \in R^{se \times n} > 0$, which emits bad outputs, i.e., undesired outputs; and $Y^b = [{y^b}_1, \ldots, {y^b}_n] \in R^{su \times n} > 0$, which emits bad outputs, i.e., undesired outputs. If $\left(x_0, {y^g}_0, {y^b}_0\right)$ is valid, then there exists no other combination $\left(x, y^g, y^b\right)$ within the set of production possibilities that satisfies the following conditions: $x_0 \geq x$, ${y^g}_0 \leq y^g$, ${y^b}_0 \geq y^b$ and at least one of the conditions is a strict inequality sign. Accordingly, the solved SBM model is shown below:

$$E_c^G\left(x^t, y^{gt}, y^{bt}\right) = min \frac{1 - \frac{1}{p}\sum_{i=1}^{p} \frac{S_i^x}{x_{i0}}}{1 + \frac{1}{s_e + s_u}\left(\sum_{k=1}^{s_e} \frac{S_k^g}{y_{k0}^g} + \sum_{r=1}^{s_u} \frac{S_r^b}{y_{r0}^b}\right)} \tag{3}$$

$$s.t.x_{i0}^{t} = \sum_{t=1}^{T}\sum_{j=1}^{n}\lambda_j x_j^t + s_i^x \tag{4}$$

$$y_{k0}^{gt} = \sum_{t=1}^{T}\sum_{j=1}^{n}\lambda_j y_j^{gt} - s_k^{yg} \tag{5}$$

$$y_{i0}^{bt} = \sum_{t=1}^{T}\sum_{j=1}^{n}\lambda_j y_j^{bt} + s_r^{yb} \tag{6}$$

$$s_i^x \geq 0,\ s_k^{yg} \geq 0,\ s_r^{yb} \geq 0,\ \lambda_j \geq 0, \forall i, j, k, r \tag{7}$$

Based on the results of the SBM model solution, the GTFP index is calculated concerning the Global Malmquist–Luenberger (GML) index with undesired outputs derived by Pastor and Lovell [36], and the GTFP index is given by the following formula:

$$GTFP\left(x^t, y^{gt}, y^{bt}; x^{t+1}, y^{gt+1}, y^{bt+1}\right) = \frac{E_c^G\left(x^{t+1}, y^{gt+1}, y^{bt+1}\right)}{E_c^G\left(x^t, y^{gt}, y^{bt}\right)} \tag{8}$$

In the realm of indicator selection, this paper adheres to the methodology established in the extant literature [37,38] and selects input–output variables as depicted in Table 1.

Table 1. Green total factor productivity input–output indicators.

Variant	Indicator Type	Indicator Selection
Input Variables	Labor Inputs	Number of employees at the end of the year (10,000)
	Capital Inputs	Fixed capital stock (billion CNY)
	Energy inputs	Energy consumption of standard coal (tons)
Expected outputs	GDP	Real GDP (billions of USD)
Unexpected outputs	Wastewater emissions	Industrial wastewater emissions (tons)
	Sulfur dioxide emissions	Industrial sulfur dioxide emissions (tons)
	Fume and dust emissions	Industrial fume and dust emissions (tons)

2.2.2. Core Explanatory Variable

Explanatory Variable: environmental regulation (ER). This study employs Python to conduct a textual analysis of the work reports from provincial governments, deriving the frequency of environmental-related terms. These frequencies are then multiplied by the proportion of industrial-added value to GDP, serving as a measure of the intensity of environmental regulation by local governments. To facilitate the observation of data characteristics and empirical analysis, the data initially calculated are multiplied by 100 and converted into percentages. The environmental regulation (ER) index ranges from 0 to 1, with higher values indicating greater intensity of environmental regulation.

2.2.3. Mediating Variables

Mediating Variables: The analysis is conducted from two perspectives, green technology innovation (GTI) and Industrial Structure Sophistication (IS). Green technology innovation (GTI) is measured by the number of green invention patent applications filed in that city in the current year, where a higher number of green invention patent applications indicates a higher level of green technological innovation. Industrial Structure Sophistication (IS) is measured by the ratio of the value added by the tertiary sector to that of the secondary sector, with a higher ratio indicating a more advanced industrial structure.

2.2.4. Control Variables

Drawing upon existing scholarly research [37,39], this study selects the financial development level (FIN), human capital level (HC), degree of fiscal intervention (GOV),

level of openness to foreign trade (OPEN), and infrastructure level (ROAD) as control variables that influence urban green total factor productivity.

2.3. Data Sources

This study focuses on cities within the Yangtze River Economic Belt. The original sample was processed to exclude municipalities or autonomous prefectures with significant data gaps, as well as areas where data consistency was affected by administrative readjustments. Consequently, a final selection of 107 cities was made as the analytical sample. Table 2 provides a detailed list of the 11 provinces (cities) in the Yangtze River Economic Belt and the 107 cities they encompass. Furthermore, considering the completeness and comparability of the data, the research period is set from 2007 to 2019 to avoid the impact of the COVID-19 pandemic in 2020 on data integrity. Missing data were imputed using linear interpolation, and all price variables were deflated to the base year of 2006, and ultimately adjusted to form a balanced panel data set. Data sources primarily include government work reports, the "China City Statistical Yearbook", "China Energy Statistical Yearbook", "China Urban Construction Statistical Yearbook", and relevant provincial and municipal statistical yearbooks and bulletins. To mitigate the interference of extreme or outlier values, the data were winsorized at the 1% level. Table 3 provides the definitions and descriptive statistics for the sample data.

Table 2. List of provinces and cities in the Yangtze River Economic Belt.

Province	City
Shanghai	Shanghai
Chongqing	Chongqing
Yunnan	Baoshan; Kunming; Lijiang; Lincang; Qujing; Yuxi; Zhaotong
Jiangxi	Fuzhou; Ganzhou; Ji'an; Jingdezhen; Jiujiang; Nanchang; Pingxiang; Shangrao; Xinyu; Yichun; Yingtan
Jiangsu	Changzhou; Huai'an; Lianyungang; Nanjing; Nantong; Suzhou; Suqian; Taizhou; Wuxi; Xuzhou; Yancheng; Yangzhou; Zhenjiang
Sichuan	Bazhong; Chengdu; Dazhou; Deyang; Guang'an; Guangyuan; Leshan; Luzhou; Meishan; Mianyang; Nanchong; Neijiang; Panzhihua; Suining; Ya'an; Yibin; Ziyang; Zigong
Hubei	Ezhou; Huanggang; Huangshi; Jingmen; Jinzhou; Shiyan; Suizhou; Wuhan; Xiangyang; Xiaogan; Yichang
Anhui	Anqing; Bengbu; Bozhou; Chizhou; Chuzhou; Fuyang; Hefei; Huaihe; Huainan; Huaishan; Luan; Ma'anshan; Suzhou; Tongling; Wuhu; Xuancheng
Zhejiang	Hangzhou; Huzhou; Jiaxing; Jinhua; Lishui; Ningbo; Quzhou; Shaoxing; Taizhou; Wenzhou; Zhoushan
Hunan	Changde; Chenzhou; Hengyang; Huaihua; Loudi; Shaoyang; Xiangtan; Yiyang; Yongzhou; Yueyang; Zhangjiajie; Changsha; Zhuzhou
Guizhou	Anshun; Guiyang; Liupanshui; Zunyi

Table 3. Descriptive statistics and definitions.

Panel A Variable Description						
Variable	Description	N	Mean	SD	Min	Max
GTFP	Green total factor productivity	1391	1.001	0.132	0.574	1.558
ER	Environmental regulation	1391	0.463	0.172	0.138	0.982
FIN	Financial development	1391	2.226	0.913	0.956	5.647
HC	Human capital	1391	0.018	0.023	0.000	0.116
GOV	Fiscal intervention	1391	0.184	0.08	0.076	0.491
OPEN	Openness to the outside world	1391	0.17	0.241	0.003	1.312
ROAD	The level of infrastructure	1391	16.875	6.746	4.04	38.2
Panel B Variable Definitions						
Variable	Variable Definition					
GTFP	Measured using Matlab R2022b based on the SBM-GML model					
ER	Calculation of word frequency of environmental words using text analysis methods × (value added by industry/GDP)					
FIN	Year-end deposit and loan balances of financial institutions/GDP					
HC	Number of students enrolled in general higher education institutions/household population					
GOV	General budget expenditure/GDP					
OPEN	Total exports and imports/GDP					
ROAD	Road area per capita					

3. Results

3.1. Benchmark Regression Results

Table 4 presents the baseline regression results of the impact of environmental regulation on green total factor productivity in the Yangtze River Economic Belt. As shown in columns (1) and (2) of Table 4, the coefficient of the linear term of environmental regulation (ER) is significantly positive, while the coefficient of the quadratic term (ER2) is significantly negative. This indicates that at the current stage, the effect of the intensity of environmental regulation on green total factor productivity in the Yangtze River Economic Belt exhibits a significant inverse "U"-shaped relationship. After the inclusion of control variables, the significance and coefficient of the core explanatory variable have not undergone substantial changes. The regression results suggest that as the intensity of environmental regulation in the Yangtze River Economic Belt increases, its impact on green total factor productivity gradually shifts from a promoting effect to an inhibiting effect, thereby validating Hypothesis H1.

Table 4. Baseline regression analysis results.

VARIABLES	**(1)**	**(2)**
	GTFP	**GTFP**
ER	0.291 **	0.301 **
	(2.23)	(2.18)
ER2	−0.269 ***	−0.282 ***
	(−2.66)	(−2.69)
FIN		−0.032 *
		(−1.90)
HC		0.007
		(0.01)
GOV		0.017
		(0.12)

Table 4. *Cont.*

VARIABLES	(1)	(2)
	GTFP	GTFP
OPEN		0.015
		(0.26)
ROAD		0.000
		(0.01)
Constant	0.926 ***	0.976 ***
	(28.06)	(23.40)
Observations	1391	1391
R-squared	0.080	0.083
Number of cities	107	107
City FE	YES	YES
Year FE	YES	YES

Note: Valid t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.2. Robustness Tests

3.2.1. Utest Test

Although the regression coefficients of the explanatory variables ER and ER2 in the baseline regression results satisfy the conditions for an inverted "U"-shaped relationship, it does not necessarily mean that such a relationship exists. For example, when the inflection point does not fall within the interval of the variable, the point does not have economic significance. Based on this, the utest test is conducted on the model to test whether it satisfies the "U"-type relationship. The regression results are shown in Table 5, and the test results include the intervals, slopes, t-values, and *p*-values of the left and right sides of the inflection points and the overall extreme points, t-values, and *p*-values, with columns (1) and (2) being the results of the test of the left and right sides of the inflection points without control variables, and columns (3) and (4) being the results of the test of the left and right sides of the inflection points with the inclusion of the control variables. As can be seen from Table 5, the utest test is significant at the 1% and 5% level of significance when control variables are added and when no control variables are added, respectively; the extreme points are within the range of values of environmental regulation (ER); and the positive and negative slopes of the left and right sides of the inflection points are also in line with the hypothesis. It shows that environmental regulation (ER) and green total factor productivity (GTFP) have an inverted "U"-shaped relationship, which confirms the robustness of the results.

Table 5. Utest Test Results for the Inverted U-Shaped Relationship.

VARIABLES	(1)	(2)	(3)	(4)
	Left Side	Right Side	Left Side	Right Side
Interval	0.1380	0.9823	0.1380	0.9823
Slope	0.2167	−0.2373	0.2232	−0.2529
t-value	2.08	−2.8302	2.0216	−3.0180
$p > \|t\|$	0.0199	0.0027	0.0229	0.0016
Extreme point	0.5410		0.5339	
t-value	2.08		2.02	
$p > \|t\|$	0.0199		0.0229	

3.2.2. System GMM Model

To address potential endogeneity issues, this study utilizes a dynamic panel regression model for robustness checks, which includes a first-order lag of the explanatory variable GTFP in the equation. Subsequently, the model is estimated using the system GMM (Generalized Method of Moments) approach.

The Generalized Method of Moments (GMM) is a technique for constructing estimators. GMM assumes that random variables follow specific moments rather than making assumptions about the entire distribution, which are known as moment conditions. This characteristic makes GMM more robust. As a result, GMM models are commonly used to address panel data or models with endogeneity issues. The difference of the GMM model involves performing a first-order differencing on the basic model to eliminate the impact of fixed effects and then using lagged explanatory variables as instrumental variables for the corresponding variables in the difference equation. The system GMM model has evolved from the different GMM models. The system GMM estimator combines the difference equation and the level equation and adds a set of lagged differenced variables as the corresponding instruments for the level equation. The system GMM model has a smaller estimation bias and higher efficiency, making it widely applicable.

The construction of the dynamic panel model is as follows:

$$GTFP_{it} = \alpha_0 + \beta_1 GTFP_{i,t-1} + \beta_2 ER_{it} + \beta_3 ER2_{it} + \gamma controls_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (9)$$

L.GTFP represents the first-order lagged term of the explanatory variable GTFP. The results of the estimation using the system GMM are presented in column (1) of Table 6. In this column, the regression coefficients of L. GTFP, ER, and ER2 are found to be statistically significant at the 5%, 1%, and 1% levels of significance, respectively. The validity test indicates an inverted "U" relationship between the effect of environmental regulation (ER) and green total factor productivity (GTFP), with *p*-values of 0.000 and 0.307 for AR (1) and AR (2). This implies that the first-order differential autocorrelation of the perturbation term is satisfied, and the second-order differential autocorrelation does not exist. Additionally, the *p*-value for Hansen's test is 0.226, confirming that the instrumental variables are valid. The use of systematic GMM regression addresses the endogeneity problem in the model and provides further support for the robustness of the benchmark regression results.

Table 6. Regression results of the system GMM model and the results after the exclusion of outliers.

VARIABLES	(1)	(1)	(2)
	GTFP	GTFP	GTFP
L.GTFP	−0.109 **		
	(−2.17)		
ER	0.951 ***	0.228 *	0.240 *
	(2.83)	(1.85)	(1.84)
ER2	−0.845 ***	−0.221 **	−0.235 **
	(−3.16)	(−2.33)	(−2.38)
FIN	−0.000		−0.033 *
	(−0.04)		(−1.97)
HC	0.323 *		0.021
	(1.71)		(0.04)
GOV	0.068		0.023
	(0.63)		(0.15)
OPEN	0.039		0.024
	(1.36)		(0.40)
ROAD	−0.001		−0.000
	(−1.30)		(−0.00)
Constant	0.882 ***	0.949 ***	1.010 ***
	(6.12)	(26.33)	(22.02)
Observations	1284	1365	1365
R-squared	107	0.082	0.085
Number of cities	107	105	105
City FE	YES	YES	YES
Year FE	YES	YES	YES

Notes: Robust t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.2.3. Elimination of Outliers

The analysis in this paper focuses on 107 cities in the Yangtze River Economic Belt, except for the municipalities of Shanghai and Chongqing. Given that the administrative levels and city sizes of these two municipalities differ from the other cities, we have excluded the data from Chongqing and Shanghai to verify the reliability of the empirical findings. Subsequently, we re-conducted the regression analyses, and the results are presented in columns (2) and (3) of Table 6. It is worth noting that the regression coefficient of environmental regulation (ER) is significantly positive, whereas the regression coefficient of the squared term of environmental regulation (ER2) is significantly negative. These findings reveal a notable inverted "U"-shaped relationship between environmental regulations (ERs) and green total factor productivity (GTFP), thereby reinforcing the robustness of the initial regression results.

3.3. Mechanism Analysis

Based on the previous theoretical analyses and research hypotheses, this paper examines the impact mechanism of environmental regulation on green total factor productivity from the perspectives of green technological innovation (GTI) and industrial structure advancement (IS), respectively.

3.3.1. Green Technological Innovations (GTI)

The analysis of green technology innovation's mechanism is presented in columns (1) and (2) of Table 7. The results in column (1) indicate a significantly positive coefficient for the primary term of environmental regulation, suggesting that environmental regulation can effectively stimulate the level of green technological innovation. In column (2), the primary term's coefficient remains significantly positive, while the secondary term's coefficient is significantly negative. The inflection point, indicating the shift in the role of environmental regulation on green technological innovation from facilitation to inhibition, is approximately 0.74, well above the typical intensity of environmental regulation in most cities. Overall, these findings suggest that environmental regulation can bolster the level of green technological innovation, consequently boosting green total factor productivity and validating hypothesis H2. This underscores the importance of actively fostering green technological innovation as a crucial avenue for enhancing green total factor productivity in cities.

Table 7. Results of mechanism test.

VARIABLES	(1)	(2)	(3)	(4)
	GTI	GTI	IS	IS
ER	0.138 ***	0.362 ***	−0.233 ***	−0.972 ***
	(2.91)	(3.13)	(−3.99)	(−4.58)
ER2		−0.246 ***		0.671 ***
		(−2.81)		(4.27)
FIN		−0.069 ***	0.050	0.054 *
		(−3.20)	(1.63)	(1.76)
HC		0.742	−1.407	−1.454
		(0.60)	(−1.07)	(−1.15)
GOV		0.537 ***	−0.214	−0.202
		(2.77)	(−0.72)	(−0.70)
OPEN		0.452 ***	−0.267 *	−0.255 *
		(2.83)	(−1.69)	(−1.69)
ROAD		0.005 ***	−0.000	0.000
		(2.84)	(−0.08)	(0.08)
Constant	−0.071 ***	−0.227 ***	0.940 ***	1.089 ***

Table 7. *Cont.*

VARIABLES	(1)	(2)	(3)	(4)
	GTI	GTI	IS	IS
	(−4.33)	(−4.35)	(13.51)	(13.46)
Observations	1391	1391	1391	1391
R-squared	0.260	0.365	0.590	0.600
Number of cities	107	107	107	107
City FE	YES	YES	City FE	YES
Year FE	YES	YES	Year FE	YES

Note: Valid t-statistics in parentheses, *** $p < 0.01$, * $p < 0.1$.

3.3.2. Advanced Industrial Structure (IS)

The analysis of the advancement of industrial structure reveals compelling insights in columns (3) and (4) of Table 7. The results in column (3) indicate a significant negative coefficient for the primary term of environmental regulation, suggesting that environmental regulation leads to a decline in the value added of the tertiary industry compared to the secondary industry, hindering the advancement of the industrial structure. In column (4), the significantly negative coefficient of the primary term of environmental regulation, coupled with the significantly positive coefficient of the secondary term, suggests that as environmental regulation intensifies, it initially inhibits and then promotes the advancement of industrial structure. The inflection point for this transition is approximately 0.72, which exceeds the environmental regulation intensity of most cities in the Yangtze River Economic Belt. Consequently, environmental regulations have contributed to a decrease in the added value of the tertiary industry relative to the secondary industry, impeding the improvement of green total factor productivity. This indicates that the current level of environmental regulation in the Yangtze River Economic Belt does not significantly promote the increase in the added value of the tertiary industry and, thus, does not enhance its green total factor productivity through the mechanism of advanced industrial structure. This validates Hypothesis H3.

3.4. Heterogeneity Analysis

Due to the vast basin of the Yangtze River Economic Belt, different regions are heterogeneous in terms of ecological environment, economic base, and development. To further understand whether environmental regulations in the Yangtze River Economic Belt different impacts on its green total factor productivity have depending on the region and urban form, this paper divides the sample into the middle and upper reaches of the Yangtze River and the lower reaches of the Yangtze River, as well as into cities within urban agglomerations and cities outside of urban agglomerations and conducts heterogeneity analyses.

3.4.1. Heterogeneity Analysis between the Upper and Lower Reaches of the Yangtze River

The regression results are shown in columns (1) and (2) of Table 8. Among them, column (1) demonstrates the regression results for the middle and upper reaches of the Yangtze River Economic Belt, where the regression coefficient of environmental regulation (ER) is positive but insignificant, while the regression coefficient of the squared term of environmental regulation (ER2) is significantly negative. The test results show that the original hypothesis is rejected at the 10% significance level, i.e., there is an inverted U-shaped effect between environmental regulation on green total factor productivity (GTFP) in the middle and upper reaches of the Yangtze River. Column (2) shows the regression results for the downstream region of the Yangtze River Economic Belt, and the regression coefficients of ER and ER2 are not significant, indicating that there is no inverted U-shaped relationship in the downstream region of the Yangtze River.

Table 8. Results of heterogeneity analysis.

VARIABLES	(1)	(2)	(3)	(4)
	Up&Mid	**Down**	**Out_agg**	**In_agg**
ER	0.298	0.385	0.394 **	0.176
	(1.60)	(1.43)	(2.06)	(0.89)
ER2	−0.318 **	−0.277	−0.371 **	−0.164
	(−2.33)	(−1.16)	(−2.64)	(−1.10)
FIN	−0.035	−0.029	−0.023	−0.020
	(−1.34)	(−1.15)	(−1.18)	(−0.69)
HC	−0.494	−1.254	0.213	0.139
	(−0.77)	(−1.08)	(0.33)	(0.12)
GOV	−0.094	0.209	−0.191	0.026
	(−0.56)	(0.79)	(−0.88)	(0.16)
OPEN	−0.033	−0.039	0.258 **	−0.085
	(−0.32)	(−0.68)	(2.48)	(−1.58)
ROAD	0.000	0.001	−0.001	0.000
	(0.01)	(0.30)	(−0.36)	(0.33)
Constant	1.000 ***	0.969 ***	0.947 ***	1.019 ***
	(15.80)	(14.36)	(17.88)	(12.67)
Observations	858	533	637	754
R-squared	0.099	0.091	0.138	0.067
Number of cities	66	41	49	58
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Notes: Robust t-statistics in parentheses, *** $p < 0.01$, ** $p < 0.05$.

Compared with the downstream region, the middle and upper reaches of the Yangtze River are relatively backward in terms of economic strength, technological level, and industrial structure. The introduction of environmental regulations, on the one hand, promotes the inter-regional flow of various factors, improves the technological level of the middle and upper reaches of the Yangtze River, and improves technological innovation. The improvement of technological innovation can improve production efficiency and increase the profits of enterprises, thus compensating for the extra costs brought by environmental regulations and promoting the growth of GTFP, which is manifested as the innovation incentive effect.

On the other hand, the middle and upper reaches of the Yangtze River seized the opportunity for industrial transformation and upgrading in the downstream region, and actively undertook the transfer of labor-intensive and resource-intensive industries from the downstream region, which led to the improvement of industrial output value in the middle and lower reaches. The introduction and absorption of technology have upgraded the technological level of the middle and upper reaches of the Yangtze River, which can enhance and optimize the efficiency of energy use and reduce production costs. According to cost theory, this causes the production possibility frontier to shift outward, leading to an increase in the demand for products. To maximize profits, firms will increase factor inputs to expand production capacity, leading to an increase in energy demand, energy consumption, and carbon emissions, which in turn leads to a decline in green total factor productivity.

Therefore, when the intensity of environmental regulation is low, environmental regulation can promote green technological innovation in the middle and upper reaches of the region to compensate for the cost of environmental regulation when the impact of environmental regulation on green total factor productivity is shown as a promotional effect. However, with the strengthening of environmental regulations, environmental costs gradually increase, causing enterprises to compensate for the higher environmental costs, in the pursuit of maximum profits; they will continue to expand production so that the demand for energy, energy consumption, and carbon emissions growth, resulting in a decline in green total factor productivity. At this point, the impact of excessive environmental regulation on green total factor productivity is shown as a dampening effect.

Therefore, the inverted U-shaped relationship of environmental regulation intensity on green total factor productivity is more obvious in the middle and upper reaches of the Yangtze River.

3.4.2. Heterogeneity Analysis within and Outside Urban Agglomeration

Cities in the Yangtze River Economic Belt are divided into two groups: outside and inside city clusters. The effects of environmental regulations on the green total factor productivity of these two groups of cities are analyzed separately, and the results are shown in columns (3) and (4) of Table 8.

The results in column (3) show that for cities outside the city cluster, the regression coefficient for environmental regulation (ER) is significantly positive, while the regression coefficient for the squared term of environmental regulation (ER2) is significantly negative. The results of the U-shaped test indicate that the relationship between environmental regulation and green total factor productivity has an inverted U-shape at the 5-percent level of significance. For the sample within urban agglomerations, the coefficient for environmental regulation (ER) is positive but not significant, and its squared term (ER2) is also not significant. The results suggest that the inverted "U" shape of the impact of environmental regulations on green total factor productivity is more pronounced in cities outside the city cluster.

This difference may be related to the disparity in technology level and industrial structure between cities inside and outside the cluster. Cities outside the city clusters are less advanced in terms of technology level and industrial structure compared to those within the city clusters, and under the influence of environmental regulation, they adopt technology and undergo industrial transfers from cities within the city clusters.

The moderate intensity of environmental regulation can encourage cities outside the city cluster to accept technology transfer and engage in technological innovation. Technology transfer can introduce new technology and experience, promoting technological advancement in cities outside urban agglomerations. Such technological improvements can enhance production efficiency and corporate profits, thereby offsetting the additional costs of environmental regulation and contributing to the growth of GTFP.

However, environmental regulation may also lead cities outside the city cluster to undertake industrial transfers, such as labor-intensive and resource-intensive industries, which are not conducive to optimizing their industrial structure and hinder the improvement of green total factor productivity. Furthermore, as the intensity of environmental regulation increases, enterprises will augment factor inputs to expand production capacity to compensate for higher environmental costs and pursue profit maximization. This leads to an increase in energy demand, energy consumption, and carbon emissions, resulting in a decline in green total factor productivity.

Therefore, moderate environmental regulation can foster technological innovation in cities outside the city cluster, resulting in the "innovation compensation effect". However, as the intensity of environmental regulation increases, the "cost effect" outweighs the "innovation compensation effect", leading to a decline in green total factor productivity, and the impact of environmental regulation on green total factor productivity shifts from a facilitating to a dampening effect.

4. Discussion

This paper examines the impact of environmental regulations on green total factor productivity in the Yangtze River Economic Belt. Although existing studies have explored the impact of environmental regulations on total factor productivity, little literature has focused on the effects and mechanisms of environmental regulations on green total factor productivity at the city level in the Yangtze River Economic Belt. In this paper, we examine the effects of environmental regulations on green total factor productivity (GTFP) from 2007 to 2019 in 107 cities within the Yangtze River Economic Belt.

We find that the impact of environmental regulation on GTFP in the Yangtze River Economic Belt exhibits an inverted U-shape. As the intensity of environmental regulation increases, the effect on GTFP initially promotes and then turns to inhibit. Yan and Wang [28] also identify an "inverted U-shape" relationship between the degree of environmental regulation and environmental productivity in their study of the impact of environmental regulation on industrial productivity in China. Similarly, Wang and Shen [25] confirmed that environmental regulation (ER) has an inverted U-shaped effect on environmental productivity in China.

Although there have been studies with varying views on the impact of environmental regulation on total factor productivity, including promotion [15,40], inhibition [22,41], and uncertainty [24,42], these differences may be attributed to variations in research subjects, data, methods, and sample intervals.

Our results confirm the inverted "U"-shaped relationship between environmental regulation and green total factor productivity in the Yangtze River Economic Zone and identify a critical inflection point for the optimal intensity of environmental regulation, i.e., a critical value of 0.51. Until this threshold is reached, increasing the stringency of environmental regulation is advantageous, as mild environmental regulation can create an incentive to innovate, known as "Porter's hypothesis", compensating for the costs of environmental regulation and promoting GTFP. However, once the tipping point is exceeded, environmental regulation leads to a decline in GTFP. At this juncture, the cost of environmental regulation becomes too high, and to compensate for the environmental costs and maximize profits, enterprises leverage the high efficiency resulting from technological innovation and progress to increase factor inputs and expand production capacity. This results in increased energy demand, energy consumption, and carbon emissions, leading to a decline in GTFP. Thus, at higher intensities, environmental regulation has a dampening effect on green total factor productivity.

The results of the mechanism analysis show that environmental regulation in the Yangtze River Economic Belt is important for GTFP mainly through the pathway of green technological innovation, reaffirming the significance of technological innovation for enhancing total factor productivity [5,13], whereas the mechanism of industrial structure advancement is less apparent. This is related to the industrial structure and economic positioning of the Yangtze River Economic Belt. The region is China's primary area for industrial construction and development, as well as a main industrial and growth cluster, with a robust manufacturing industry base and a comprehensive industrial system. Environmental regulation policies are more likely to reduce outdated production capacity in the secondary industry and replace it with new environmentally friendly production capacity, thereby improving production efficiency and output value. Therefore, environmental regulation in the Yangtze River Economic Belt may not enhance GTFP through the advancement of industrial structure that increases the share of the tertiary industry.

In conclusion, the feasibility of environmental regulation policies must be carefully considered. The goal of policy should be to balance the stringency of environmental regulation to achieve optimal policy outcomes. When environmental regulation is maintained within an appropriate range, it can positively impact overall economic and environmental performance. However, the principle of "too much of a good thing can be harmful" applies to policymaking, and only by accurately gauging the "degree" can benefits be maximized. When formulating environmental regulatory policies, it is essential to balance ecological benefits with economic costs to ensure that economic losses remain manageable.

Furthermore, the factors influencing economic activities are complex, and it is challenging to accurately measure factor inputs and actual outputs with a few indicators. The input–output indicator system established in this paper to measure GTFP may not be comprehensive and could differ slightly from reality. Therefore, future research should revisit the measurement method of GTFP in a more in-depth and multifaceted manner to enhance our understanding. Additionally, from a city perspective, the industrial layout of different cities also affects the relationship between environmental regulation and GTFP [43], and the

impact of environmental regulation on productivity varies across industries [25]. Future studies will adopt an urban industry perspective to examine the differences in the effects of environmental regulation on GTFP between cities.

5. Conclusions

This paper takes 107 cities in the Yangtze River Economic Belt as the research object and employs the super-efficiency SBM (Slacks-Based Measure) model and the GML (Global Malmquist–Luenberger) index to measure green total factor productivity (GTFP). The intensity of environmental regulation is obtained through textual analysis, and the impact of this regulation on GTFP from 2007 to 2019 is explored. The following conclusions are drawn:

First, the impact of environmental regulation on GTFP in the Yangtze River Economic Belt follows an inverted U-shape. Before reaching a specific threshold (0.51), GTFP increases as the intensity of environmental regulation increases; however, after surpassing this inflection point, environmental regulation has a dampening effect on GTFP. Second, the mechanism analysis indicates that environmental regulation in the Yangtze River Economic Belt promotes GTFP by enhancing the level of green technology innovation but does not promote GTFP through the optimization of its industrial structure. Third, the impact of environmental regulation on GTFP is heterogeneous; the inverted "U" shape effect is more pronounced in the middle and upper reaches of the Yangtze River and non-urban agglomeration areas, whereas it is not significant in the lower reaches and within urban agglomerations.

Based on the empirical findings, this paper offers the following policy recommendations: (1) Given the inverted "U" shaped impact of environmental regulation on GTFP in the Yangtze River Economic Belt, an appropriate level of environmental regulation can enhance GTFP, while an excessively high level may lead to a decrease. Therefore, environmental regulation policies should consider the balance between economic efficiency and environmental protection, and carefully determine the "degree" of regulation. (2) When formulating environmental regulation policies, governments should consider the technological level and industrial structure of the region and the impact of environmental regulation on technological innovation and industrial structure, tailoring policies to local conditions. (3) Environmental regulatory policies must consider the unique characteristics of different regions, apply differentiated management strategies, foster green development, and achieve harmonious economic growth and environmental protection.

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