



## The Impact of Environmental Regulation on Green Total Factor Productivity in the Construction Industry and Mechanism Testing: From the Perspective of Technological Innovation Moderation

Xiaozhuang Yang<sup>1</sup> and Xin Wang<sup>2,\*</sup>

<sup>1</sup> School of Energy and Architectural Engineering, Harbin University of Commerce, Harbin, 150028, Heilongjiang, China

<sup>2</sup> School of Management, Harbin University of Commerce, Harbin, 150028, Heilongjiang, China

**SUMMARY:** *Promoting the green transformation of the construction industry is to achieve the "dual carbon" goals, and environmental regulations are a typical policy tool that needs to be explored in more detail for its effects and underlying mechanisms. Carry out empirical studies to investigate the impact of environmental regulations on the construction industry in China on green total factor productivity (GTFP) and determine whether technological innovation moderates this effect. Provincial panel data in China are used for this study, and a two-way fixed-effects model is employed in the baseline regression; at the same time, to address endogeneity problems, methods such as stepwise regression and lagged variables are also used to ensure the robustness and reliability of the estimation results. Research shows that (1) Regulations on the environment positively and significantly affect the total factor productivity of the construction industry. The above tests have failed to establish endogeneity; therefore, it can be concluded that reasonable environmental regulations can promote the development of a green and efficient economy in the industry. (2) Mechanism analysis has also revealed that technological innovation has a negative moderating effect on the relationship between environmental regulation and GTFP, contrary to previous expectations. Therefore, although environmental regulations promote GTFP in a direct way, they also induce particular types of technological innovation that reduce the overall benefit of the regulations. According to the above analysis, the reason for this is that current technological innovation in the construction industry still has a prominent "end-of-pipe treatment" feature. Behaviors such as purchasing environmental protection equipment have relatively high compliance costs but do not promote the "innovation compensation" effect effectively. Therefore, rather than amplifying the positive impact of environmental regulation predicted by the traditional "Porter Hypothesis", technological innovation is taking the form of an indirect "cost-effect" offset mechanism. It provides a theoretical basis and policy guidance for the government to optimize the design of environmental policies and promote the construction industry to reduce sources and improve processes.*

**KEYWORDS:** *Environmental regulation; Green total factor productivity; Construction industry; Technological innovation*

\*wx2923813837@163.com

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# 1 Introduction

Based on data from the China Statistical Yearbook, in 2023, the total output value of the construction industry in China was 26.4 trillion yuan and accounted for 25.88% of the gross domestic product (GDP). From 2005 to 2021, the final energy consumption of the construction industry increased at an average rate of 6% per year, and its CO<sub>2</sub> emissions rose at an average rate of 5.84% per year. An extended-scale production model has caused considerable environmental damage. Therefore, the construction industry in China needs to update its green industrial policies and make the transition to a green economy. Industrial green transformation refers to the process of making an industrial sector more resource- and energy-efficient, reducing pollution emissions, and promoting high-quality sustainable development.

With the emergence of serious environmental pollution problems, many new environmental regulations and policies have been introduced in recent years to deal with these problems at the source. Gradually, through continuous reforms and adjustments, the environmental regulatory system in China has begun to introduce both command-and-control and market-based instruments. With the development of environmental policy construction, the system of market-oriented environmental regulations has begun to appear gradually. Therefore, the enforcement of the environment will have certain economic costs and production disturbances. Previous studies often use innovation to measure the technological impact of environmental regulations, but this index cannot reflect the change in efficiency accurately because it does not show such a shift. In recent years, with the development of new technologies, modern society and the economy have shown remarkable progress. Since the introduction of total factor productivity (TFP) theory, it has been regarded as an all-encompassing index of technological progress, optimisation of management mode, improvement in production quality, and industrial structural reform. Therefore, green total factor productivity (GTFP) has gradually drawn more attention, and since sustainable development requires that environmental and energy endowments be regarded as important constraints on economic growth.

## 2 Literature Review

Academic research has built a rich and dynamically changing cognitive system for understanding the complicated interconnections among environmental regulation, green technological innovation and green total factor productivity. China's construction industry has been selected as the subject of this study, and a comprehensive academic background of the relevant issues will be systematically organised; by tracing the evolution from macro-level consensus to micro-level mechanisms, from linear relationships to non-linear interactions, and finally from isolated analyses to spatial correlations, the current boundaries and future directions for further research will be precisely identified.

Most of the previous studies have focused on examining how environmental regulations affect the bottom-up level of green total factor productivity. There are several types of conclusions under the theoretical tension of "compliance cost" and "innovation compensation". Scholars have generally agreed that GTFP, which includes resource consumption and pollution emissions in its analysis, is the main reference standard for measuring the quality of green transformation [1, 2]. At the same time, with the continuous development of measurement methods, both radial DEA and non-radial SBM have been used; furthermore, hybrid models combining the strengths of both have also emerged, such as the Epsilon-Based

Measure (EBM) model [1], the Super-EBM model [3], and Directional Distance Functions (DDF). The above development has provided the basis for the accurate measurement of performance [4]. Research has progressively found that, in terms of impact, linear promotion and linear inhibition are relatively rare, and non-linear relationships, such as U-shaped [5, 6], inverted U-shaped [7-9], or complex threshold effects [10, 11], are more frequent. Therefore, it can be seen that the relationship between the strength of environmental regulation and a company's green total factor productivity is not necessarily an increasing trend, and there may be an optimal level of regulation strength.

With the deepening of understanding, research has moved away from the initial assessment of general effects and is now focused on the details of several transmission pathways and a gradual dismantling of the "black box" mechanism. Scholars are no longer satisfied with knowing whether the regulations have been effective but continuously investigate how this effectiveness is achieved. At the same time, the pathways for boosting Green Total Factor Productivity (GTFP) have also been identified; these include direct shifts in the production frontier, as well as indirect impacts through various channels: either by acting as "push" factors to stimulate the development and rationalisation of green technological innovation [5, 10, 12], or by influencing structural changes in the economy [1, 13], or by optimising the scale and structure of energy consumption [3]. At this time, technological innovation has been regarded as an index for determining whether the regulations have achieved the goals of green development, and is thus considered a key link in this process.

Theoretical studies have also not stopped. New research has recently shown that the situation is more complicated; that is to say, the function of green technological innovation is no longer that of a simple, passive "transmission bridge", but can also serve as a necessary contextual factor and actively modify the actual impact of environmental regulations in a systematic way to reduce them. This is the start of the period when the field has moved from "conditional" to "interactive" analysis. The intervention of government R&D subsidies complicates the above: non-linear moderation has been observed in the path of environmental regulation's impact on industrial GTFP [5], and a firm's own GTFP baseline can enhance the effectiveness of environmental judiciary in pollution control [14]. A specific finding is that the level of regional green technological innovation serves as a key threshold and a moderating variable for the effect of clean technology on industrial GTFP, and this effect shows completely opposite directions in the eastern, central and western regions of China. As shown above, innovation compensation and factor crowding-out occur simultaneously in different areas [11]. In addition, other external factors that impact the effectiveness of the "Porter effect" for regulatory policies in this study include the development of green finance and public environmental awareness [1], the level of intellectual property protection, and the extent of regional financial deepening [3]. These context-setting conditions affect both the strength and the direction of the regulatory effect, and generally have different threshold effects and complex spatial heterogeneity in how they modify this effect.

The story is not a mediation effect. Recent frontier research has found that the function of green technological innovation is relatively loose and active; it can provide the key context conditions for the entire process of environmental regulation and, at the same time, reduce the negative impact of regulations. Therefore, this study has reached a new level of "conditional" analysis. Many studies have shown that R&D subsidies are not linearly related to the effect of environmental regulations on industry Gross territorial gross factor product (GTFP) [5]; a company's own GTFP can also positively modify the impact of environmental judicial sanctions on pollution reduction [14]. Crucially, it was found that the level of regional green technological innovation serves as an important threshold variable in the impact of clean

technology innovation on industrial GTFP, and the moderating effects in the eastern, central and western regions were all in the opposite direction, revealing a complex situation where "synergy" and "crowding-out" coexisted [11]. Green finance and public interest [1], as well as intellectual property protection and financial development levels [3], have also been identified as components of the "ecosystem" for the effectiveness of regulatory policies. The scope and direction of the regulatory effect will change significantly under these conditional factors, and their moderating effects are frequently non-uniform in both space and time.

The new and extended research system will also explore transmission paths and circumstances. The addition of spatial econometrics has changed the general form of research for regional differences and no longer assumes that areas are independent of one another. A large number of studies have been conducted empirically, and it has generally been found that economic performance, innovation activities, and the effects of environmental policies are spatially dependent to some extent and have spillover effects. Therefore, the degree of intensity and the form of governance for environmental regulations in a specific area are not limited to that area. On the contrary, via various paths such as knowledge spillovers, technology diffusion, industrial linkages, and factor mobility, they can generate significant "learning effects" and positive (or negative) spatial spillovers in adjacent or even larger areas, thus forming an interconnected network among these areas [6, 15]. Although an industrial ecological system has been formed in the construction industry, research has also shown that environmental regulations and related institutional arrangements (such as decentralisation of the environment) exhibit significant spatial spillover effects and are therefore subject to cross-regional policy coordination [16]. The verification of this spatial interactivity indicates that any in-depth analysis of the policy's effectiveness should take into account the all-encompassing perspective of regional synergy and competition; thus, examining only one area will fail to provide a full picture of the policy's impact.

As a result of the above development in research methods and theoretical concepts, extensive studies have also been carried out on the green transition of particular industries. China's construction industry is a large consumer of energy and carbon emissions, so although research on the green total factor productivity of this sector has been relatively late, it has started to advance rapidly in recent years and achieved some impressive results. Scholars have not only applied frontier methods for measuring macro-level GTFP (such as the EBM-GML model) to this industry to systematically quantify its green productivity level and dynamic changes for the first time [16], but have also actively used causal inference strategies. For example, by using a difference-in-differences model, the net effect of a specific environmental policy, such as the "Action Plan for Comprehensive Air Pollution Control in Autumn and Winter in the Beijing-Tianjin-Hebei Region and Surrounding Areas," on the GTFP of the construction industry in the pilot area can be evaluated to see if such a policy has significantly improved the GTFP. These effects have shown a trend of increasing over time and are not uniform across different areas of the market [17]. This provides strong, quasi-natural experimental causal evidence for the "effective environmental regulation" thesis in the construction sector. Research on the reasons for changes in this particular industry has also started. Research has shown that the main motivation for the green technological innovation behaviour in this industry is direct government investment, and the effect of regulations may also have a non-linear pattern specific to this sector [18]. In sum, the above studies have moved away from large-scale data collection and started focusing on the effects of policies and the internal mechanisms of changes in the construction industry.

### 3 Measurement of Green Total Factor Productivity in the Construction Industry

With the reduction in resources and environmental constraints, efforts are now focused on promoting green total factor productivity (GTFP) to foster high-quality development of our economy. The traditional measure of Total Factor Productivity (TFP) fails to consider the constraints of environmental carrying capacity. Therefore, the productivity figures in high-pollution and high-energy-consumption models are artificially high and do not reflect real development quality. GTFP is also an undesirable output of the system for evaluating efficiency, carbon emissions. Thus, a high-value-added, low-ecological-cost model can be established.

#### (1) Super-SBM Model

Traditional DEA models cannot differentiate the efficiency of different effective decision-making units (DMUs) and fail to consider slack improvements for undesirable outputs, thus leading to an overestimation of DMU efficiency. Tone (2002) combined the concept of super-efficiency with the SBM model to put forward the Super-SBM model in light of the above. The above model is not a traditional DEA model and does not use slack variables. It can also be used to further distinguish among several good DMUs by setting the threshold for efficiency scores higher than 1, thus solving the ranking problem for equally effective units [19].

The model is as follows:

$$1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{io}}$$

$$1 - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{ro}^g} + \sum_{k=1}^{s_2} \frac{s_k^b}{y_{ko}^b} \right)$$

$$\begin{cases} x_{io} = \sum_{j=1}^n \lambda_j x_{ij} + s_i^- \\ y_{ro}^g = \sum_{j=1}^n \lambda_j y_{rj}^g - s_r^g \\ y_{ko}^b = \sum_{j=1}^n \lambda_j y_{kj}^b + s_k^b \\ \lambda_j \geq 0, s_i^- \geq 0, s_r^g \geq 0, s_k^b \geq 0 \end{cases}$$

where  $x$  denotes the input variables;  $y_r$  denotes the desirable outputs;  $y_k$  denotes the undesirable outputs;  $i$  represents the number of input variables, with its value ranging from 1 to  $m$ ;  $r$  represents the number of desirable outputs, with its value ranging from 1 to  $s_1$ ;  $k$  represents the number of undesirable outputs, with its value ranging from 1 to  $s_2$ ;  $s_i^-$  is the slack variable for inputs;  $x_{io}$  denotes the  $i$ -th input of the  $o$ -th decision-making unit;  $s_k^b$  denotes the slack variable for undesirable outputs;  $y_{ko}^b$  denotes the  $k$ -th undesirable output of the  $o$ -th decision-making unit.

#### (2) GML Index Model

Traditional productivity indices have a short-term perspective bias and are not easily comparable. Oh (2010) combined the Global Malmquist productivity concept and the directional distance function to put forward the GML index in response to the above. A global frontier and a dynamic decomposition mechanism have been constructed to ensure the long-term comparability and immunity to interference of the GML index, and its drivers can also be analysed separately [20].

#### (3) Measurement Results

Based on the calculation of the regionally decomposed GML index for the construction industry and its components, the average values of these were used to derive the trends of the construction industry's GML index and its decomposition items, as shown in Figure 2009-2012; all three indices reached a peak exceeding 1.1 and then fluctuated. It is likely that this is related to the "four trillion yuan" investment stimulus plan released in response to the global financial crisis at that time. Large-scale infrastructure investment temporarily improved capacity utilisation and scale effects. However, the efficiency improvement that resulted from the investment was not maintained; from 2013 to 2021, after an initial increase, the index fell and then remained at a high level of volatility or plateaued. It can be seen from the above that, after the effect of the stimulus policy has gradually faded, problems such as a lack of internal innovation impetus and rigid management systems in the construction industry have gradually become apparent. Although concepts such as "New Urbanisation" and "Intelligent Construction" were put forward during this time, the indices indicate that the significant, industry-wide efficiency changes these concepts aimed to promote had not yet fully occurred.

The above chart shows that the construction industry in China has not been advancing in efficiency over the past decade. It is clear that to achieve the goals of "true efficiency", technological innovation and management reform need to be carried out in the future.

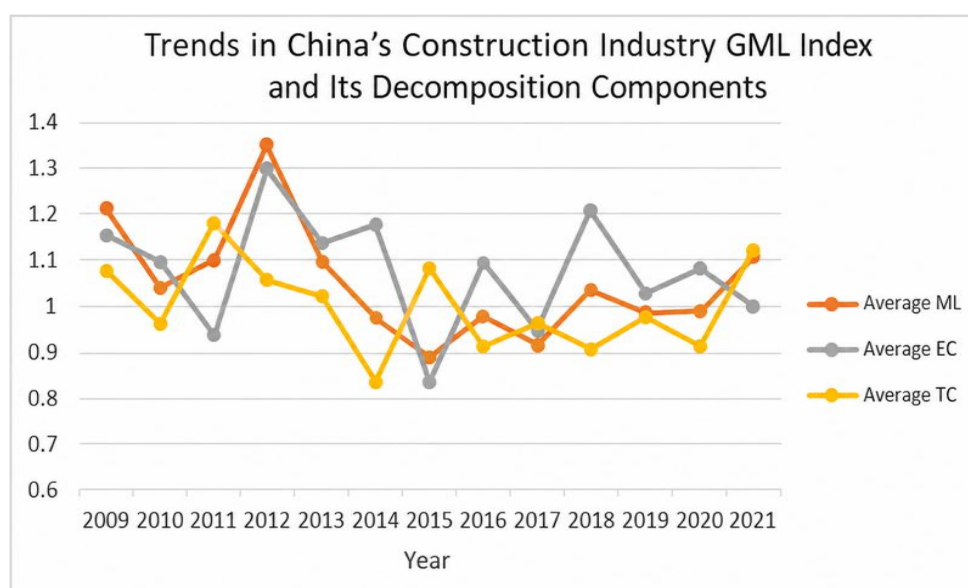


Figure 1: Trends in China's Construction Industry GML Index and Its Decomposition Components, 2009–2021

#### (4) Econometric Model Specification

Recently, many scholars have conducted rich theoretical and empirical research on the influence of environmental regulations on technological innovation and Green Total Factor Productivity (GTFP) in the construction industry. Research on the impact of environmental regulation on GTFP has moved from the general view of whether it "promotes" or "hinders" to an in-depth study of the circumstances under which both are true. Many studies at all levels have found that the relationship between the strength of environmental regulation and GTFP is not monotonic. For example, at the city level, environmental regulation has been shown to have a significant inverted U-shaped impact on green total factor productivity (GTFP); that is to say, it promotes GTFP up to an optimal intensity, and then may be detrimental [21]. A similar non-linear relationship has been observed in the construction industry; a particular

kind of environmental regulation (public participation-based) has also been found to have an inverted U-shaped curve for construction industry productivity, rising initially and then falling [22]. Collectively, these show that there is an "optimal range" for the policy effectiveness of environmental regulation, and the direction of the impact depends on whether the regulatory intensity is within a reasonable scope. The research has found no intervening role for technology innovation in the connection between the two. Although numerous studies have identified green technological innovation as an important intermediary variable [23, 24], in depth, other researchers believe that the extent of technological innovation itself determines whether environmental regulation can effectively boost GTFP. According to the above empirical studies, technological innovation serves as a moderator in the path of the impact of environmental regulations on GTFP, and this role generally takes the form of positive synergy and facilitation [4, 25]. For example, a high capacity for technological innovation can increase the amplification effect of the "innovation compensation" effect of environmental regulation and thus enhance its positive impact on GTFP [26].

Based on the cross-industry literature review above, and considering the particular attributes of the construction industry such as high energy consumption and emissions, as well as policy sensitivity, this study applies the same logical system to the construction sector. It intends to verify the above basic relationships in this particular field through empirical studies and puts forward the following two specific hypotheses:

Hypothesis H1: The effect of environmental regulation on the Green Total Factor Productivity (GTFP) of the construction industry is non-linear. In short, it is positive in a certain range of strength and inhibitory outside this range.

Thus, Model I is set up as follows:

$$CGTFP = \alpha_0 + \alpha_1 \ln ER + \alpha_2 (\ln ER)^2 + \alpha_3 con + \varepsilon$$

where  $CGTFP$  represents the total factor productivity of the construction industry,  $ER$  denotes the intensity of environmental regulation,  $con$  denotes the control variables, and  $\varepsilon$  is the random error term.

Hypothesis H2: Technological innovation moderates the relationship between environmental regulation and the Green Total Factor Productivity of the construction industry, and this effect is positive (facilitating).

Therefore, Model II is as follows:

$$GTFP = \alpha_0 + \alpha_1 ER + \alpha_2 TI + \alpha_3 (ER \times TI) + \sum_{i=4}^k \alpha_i Con_{i-3} + \varepsilon$$

where:  $GTFP$  represents the Green Total Factor Productivity of the construction industry,  $ER$  denotes the intensity of environmental regulation,  $TI$  indicates the level of technological innovation,  $ER \times TI$  is the interaction term,  $Con_{i-3}$  refers to multiple control variables,  $\alpha_3$  is the moderating effect coefficient,  $\varepsilon$  stands for the random error term.

##### (5) Variable Selection and Data Description

**Dependent Variable:** Green Total Factor Productivity of the Construction Industry (CGTFP); measured by the super-efficiency SBM–GML index method. The GML value calculated is a chain index that shows the proportion of this year's CGTFP to that in the previous year. Therefore, the CGTFP values for all regions in 2008 are set to 1. The CGTFP value in 2009 is the product of the GML value for that year and the CGTFP value of the previous year, and so on.

**Primary Explanatory Variable:** Environmental Regulation (ER). In general, the more aware a regional government is of environmental problems, the more resources it will allocate

for pollution control by enterprises and in other areas, thus establishing stricter environmental standards for those enterprises in the region. Based on the previous studies, this paper will use the total investment in regional environmental pollution control as the measure of the severity of environmental pollution. A relatively large value of this index shows a stronger environmental regulation system in that area. Logarithmic transformation will be applied to the data for stationarity.

**Moderator: Technological Innovation (TI).** Earlier studies have explored the moderating effect of technological innovation on the relationship between environmental regulations and total factor productivity. Determine whether technological innovation has the dual function of mechanisms simultaneously. The technical equipment rate of the construction industry is selected to be used as this variable, and specifically refers to the ratio of the net value of machinery and equipment (in yuan) to the number of employees at the end of the reporting period.

**Control Variables: Economic Development Level (EDL), Foreign Direct Investment (FDI), Ownership Structure (SOE), and Per Capita Profit Rate of the Construction Industry (PP).**

**Level of economic development (EDL):** Provinces with a higher level of economic development generally have a better innovation environment and are more attractive to foreign investment; thus, they can promote the economic growth of regional construction enterprises. For the level of regional economic development in this paper, Hu Jianhui and Hao Conghui's method is used, and per capita Gross Domestic Product is selected as the indicator. Data from the China Statistical Yearbook are used.

**Foreign Direct Investment (FDI)** can increase the amount of foreign capital inflow, introduce new technologies and know-how, and promote the improvement of green total factor productivity in the construction industry. The proportion of foreign-direct investment in the regional construction industry to GDP.

**Ownership Structure (SOE):** There are different organizational models for state-owned and non-state-owned enterprises, and varying degrees of policy support from the government for them, which affect resource allocation efficiency and thus impact the enhancement of green total factor productivity in the construction industry. This is the proportion of the total output value of state-owned construction enterprises to the total output value of the construction industry.

**PP:** The per capita profit rate of the construction industry can indicate the relative health of the construction industry at present. A higher per capita profit will promote the transformation and upgrading of construction enterprises at a faster rate. It can promote the development of prefabricated buildings, smart construction sites and digital construction, and thus help to improve the total factor productivity of the construction industry.

## **4 Analysis**

### **(1) Descriptive Statistics**

To address heteroscedasticity, some variables were taken as their logarithms. The descriptive statistics of the above variables are shown in the table.

*Table 1: Variable Definitions and Descriptive Statistics*

Variables	Variable Description	Sample Size	Max	min	Std.	Average
CGTFP	Green Total Factor Productivity in the Construction Industry	420	16.648	0.221	1.790	1.545
ER	Environmental Regulation Intensity	420	7.256	2.462	0.885	5.262
EDL	Economic Development Level	420	187526	9697	29092.12	50232
FDI	Foreign Direct Investment	420	0.045	0	0.006	0.003
SOE	State-Owned Enterprise	420	0.161	0.003	0.027	0.045
PP	Per Capita Profit Rate	420	19.717	0.391	1.768	1.682
TI	Technological Innovation	420	141254	646.722	11509.7	13654.93

As shown in the table, the largest and smallest values of Green Total Factor Productivity (GTFP) in the construction industry are 16.648 and 0.221, respectively. The two values are relatively far apart, and therefore, the extent of change and modernisation in the regional construction industry varies considerably. The maximum value of Environmental Regulation (ER) is 7.256 and the minimum is 2.462; they are not close. It can also be seen that the degree of environmental damage in these areas is not uniform, and the strength of government environmental protection regulations also varies. A relatively large difference in the maximum and minimum values of Technological Innovation (TI) indicates that innovation intensity among regions in the construction sector is not uniform.

**(2) Empirical Results Benchmark Regression**

Using Stata 16.0, regress and analyze the impact of China's environmental regulations on the green total factor productivity efficiency value of its construction industry from 2008 to 2021, as shown in Table 3-2.

*Table 2: Baseline Regression Results of Environmental Regulation on Construction Industry GTFP*

	(1)	(2)	(3)	(4)
	CGTFP	CGTFP	CGTFP	CGTFP
ER	0.522*** (2.97)	0.599*** (3.35)	1.929** (2.18)	1.788** (2.00)
ER <sup>2</sup>			-0.138 (-1.62)	-0.116 (-1.35)
FDI		-48.29* (-2.57)		-47.36* (-2.52)
SOE		-13.07* (-2.36)		-12.67* (-2.29)
PP		0.0555 (0.72)		0.0502 (0.65)
EDL		-0.107 (-0.06)		0.314 (0.17)
Con	-1.337 (-1.63)	-0.865 (-1.03)	-4.772* (-2.10)	-3.822 (-1.63)
N	420	420	420	420
R <sup>2</sup>	0.140	0.169	0.146	0.174

According to the result (1), the coefficient of environmental regulation is positively correlated with the other variables at the 5% level and thus can be considered to support the green total factor productivity of the construction industry. Based on the above, a quadratic term of environmental regulation is added. Result (4) shows that the coefficient of the linear term in the model for environmental regulation is significantly positive at the 10% level, and the coefficient of the quadratic term is not significant; thus, the null hypothesis 1 cannot be rejected. The Effect of Environmental Regulations on Green Total Factor Productivity in the Construction Industry is Not Linear. Then, the quadratic term of the model is not included. Result (2) shows that the coefficient of the linear term for environmental regulation is significantly positive at the 1% level, and thus environmental regulation can be said to have positively increased the green total factor productivity of the construction industry.

*Table 3: Moderating Effect of Technological Innovation on the Relationship Between Environmental Regulation and Construction Industry GTFP*

	(1)	(2)
	CGTFP	CGTFP
ER	0.595 <sup>***</sup> (3.32)	0.958 <sup>***</sup> (4.32)
TI	-0.294 (-0.31)	23.51 <sup>**</sup> (2.68)
ER*TI		-4.586 <sup>**</sup> (-2.73)
SOE	-12.94 <sup>*</sup> (-2.33)	-12.70 <sup>*</sup> (-2.30)
FDI	-48.59 <sup>*</sup> (-2.58)	-39.06 <sup>*</sup> (-2.06)
PP	0.0609 (0.77)	0.118 (1.45)
EDL	-0.182 (-0.10)	-0.267 (-0.15)
Con	-0.830 (-0.98)	-2.918 <sup>*</sup> (-2.57)
N	420	420
R <sup>2</sup>	0.170	0.186

As shown in result (2) of Table 3-3, the interaction term of environmental regulation and technological innovation is significantly negative at the 5% level. This shows that technological innovation has a negative moderating effect on the impact of environmental regulations for improving green total factor productivity in the construction industry, and thus the null hypothesis 2 cannot be rejected.

#### **4.1 Robustness Test**

If one ignores the problem of endogeneity and only uses ordinary least squares (OLS) regression to study the "effect of environmental regulation on the construction industry's GTFP", the results will be unreliable; it may lead to an excessive overstatement of the promotional effect of environmental regulation on GTFP due to reverse causality (that is, high GTFP may cause stricter regulations). Therefore, it may incorrectly confirm the "Porter Hypothesis" (that good-designed, stringent environmental regulations can motivate innovation

and boost productivity) in the construction industry, but in fact, the positive impact may be significantly smaller.

Therefore, endogeneity tests will be performed. However, due to the lack of suitable instrumental variables, this paper uses alternative approaches: regression analysis with the stepwise inclusion of control variables and sequential lagging of the explanatory variables for analysis.

*Table 4: Robustness Test Results Based on Stepwise Regression and Lagged Environmental Regulation*

	(1)	(2)	(3)	(4)
	CGTFP	CGTFP	CGTFP	CGTFP
ER	0.522*** (2.97)	0.570*** (3.24)	0.599*** (3.35)	
L-ER				0.736** (3.92)
FDI		-49.70** (-2.64)	-48.29* (-2.57)	-16.38 (-0.60)
SOE			-13.07* (-2.36)	-11.22 (-1.95)
PP			0.0555 (0.72)	0.0409 (0.51)
EDL		-0.657 (-0.42)	-0.107 (-0.06)	-0.973 (-0.50)
Con	-1.337 (-1.63)	-1.216 (-1.46)	-0.865 (-1.03)	-1.399 (-1.55)
N	420	420	420	399
R <sup>2</sup>	0.140	0.156	0.169	0.167

As shown in Table 3-4, only column (1) is the first explanatory variable: environmental regulation. Based on the above estimates, it is determined that the coefficient of environmental regulation is positively correlated with the other 99% level. Subsequently, in column (2), we controlled for the level of economic development (e.g., GDP per capita) and industrial structure. The coefficient of environmental regulation was 0.570 and significantly larger than 1 at the 1% level. Finally, in column (3), after accounting for technological progress and the degree of opening up, the coefficient of environmental regulation was still 0.599 and significantly large at the 1% level.

The two above results are shown in this series. First, the sign, magnitude and significance of the environmental regulation coefficient were all relatively stable; thus, the promotional effect of environmental regulation on the green total factor productivity of the construction industry was determined to be very strong and not easily altered by other potential confounding factors. Second, the coefficient value increased slightly after adding the control variables. Therefore, it may be that some control variables (e.g., industrial structure) have a weak negative relationship with environmental regulation but are positively associated with green total factor productivity. Without the above items, the positive effect of environmental regulation would be relatively small. Based on the reasons mentioned above, the actual impact of environmental regulations has been more clearly observed and is now statistically reliable. Together, they show that our main results are relatively reliable.

Although the baseline regression shows that environmental regulations are positively correlated with green total factor productivity, it is not known whether the cause is other than the effect. That is to say, the areas with a higher GTFP may also have a greater capacity and willingness to enforce strict regulations, and thus result in estimation bias. To solve the

problem of endogeneity mentioned above, we use a lag regression method and re-estimate the model with the main independent variable, environmental regulation, lagged by one period.

The results are as follows: Column (4) of Table 3-4. The coefficient of environmental regulation in the lagged period is 0.736; it is larger than the 0.599 in the baseline model and significantly higher, at the 1% level ( $t=3.92$ ). The two following are its reasons.

First, it can solve the problem of reverse causality. Since the current green total factor productivity cannot influence past environmental regulation policies, it is hard to prove that 'environmental regulation leads to productivity growth'. Second, it can be seen that there is a lag in the effect of environmental regulation policies on productivity. An increase in the coefficient indicates that the positive effects of regulation need some time to be fully realised, and the long-term impact will be stronger than the short-term effect. In line with the economy's general theory, enterprises will take some time for green technology innovation and process changes, and the corresponding benefits will be realised in later years. Based on the above, it can be concluded that the initial regression model probably underestimated the actual promotion effect of environmental regulation on green total factor productivity in the construction industry.

## 4.2 Heterogeneity Test

The above global regression model shows the general relationship between environmental regulations and the green total factor productivity (GTFP) of the construction industry. However, this mean effect may not consider the heterogeneity in region-specific features, such as different levels of economic development, resource endowments and policy environments. To explore whether the impact of environmental regulation differs in different areas further and to test the hypothesis H4, the 30 provinces of China have been divided into the East, Central, Northeast and West. The division criteria are as follows: Eastern Area: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan. Central Region: Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan. Northeastern Region: Liaoning, Jilin and Heilongjiang. Western Region: Inner Mongolia Autonomous Region, Guangxi Zhuang Autonomous Region, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region. The purpose of the above is to study spatial variations systematically.

*Table 5: Regional Heterogeneity Test of Environmental Regulation Effects on Construction Industry GTFP*

	(1)	(2)	(3)	(4)
	East	Central	West	Northeast
ER	1.312 <sup>***</sup> (0.430)	0.895 <sup>**</sup> (0.357)	-0.048 (0.157)	0.297 (0.226)
EDL	-8.316 <sup>**</sup> (3.797)	-22.126 <sup>***</sup> (5.445)	18.421 <sup>***</sup> (2.899)	-33.638 <sup>***</sup> (8.650)
FDI	-75.619 <sup>**</sup> (34.912)	8.218 (44.431)	-45.607 <sup>**</sup> (22.236)	18.976 (20.125)
SOE	-47.584 <sup>***</sup> (15.797)	9.462 (12.772)	2.176 (3.958)	-5.875 (8.075)
PP	0.115 (0.116)	1.118 <sup>**</sup> (0.514)	0.481 <sup>**</sup> (0.186)	0.173 (0.199)
Con	2.648 (3.326)	1.885 (2.611)	-4.119 <sup>***</sup> (1.367)	8.481 <sup>***</sup> (2.750)
N	140	84	154	42
R <sup>2</sup>	0.385	0.401	0.393	0.746

As shown in Table 3-5, according to the regression results for the Eastern and Central regions, the coefficient of the linear term of environmental regulation is significantly positive at the 1% level. Therefore, environmental regulations will help boost the green total factor productivity of the construction industry in the areas above. According to the regression results for the Western and Northeastern Regions, the coefficient of the linear term in environmental regulation is also not statistically significant. Therefore, environmental regulation does not show a significant promotion or inhibition effect on the green total factor productivity of the construction industry in the Western and Northeastern regions.

The weight of the control variables is as follows: The coefficient for Economic Development Level (EDL) in the Western region is 18.421 and is positively and significantly correlated; in all other regions, it is negatively and significantly correlated. Therefore, it can be assumed that a larger economic expansion in the Western region will have a relatively greater impact on the development of green technology due to a lower initial level. The coefficient for Foreign Direct Investment (FDI) is considerably lower in the East and West, but not statistically significant for the Central and Northeast areas. The Eastern Area has a better economy and stricter environmental regulations, so it will attract Foreign Direct Investment that includes polluting enterprises moving to avoid high-environmental-standard areas, thus reducing the green total factor productivity of the construction industry. The Western Region has a high demand for economic development and may lower environmental standards to attract foreign investment, thus turning into a "pollution haven" that accepts polluting industries from the East or abroad and harms green productivity. Deepening reforms of the State-owned Enterprise (SOE) coefficient in the East will likely lead to stronger environmental regulations and thus more green transformation in the area, whereas reforms are lagging in other parts of the country. The coefficient of Policy Pressure (PP) shows that the implementation of policies in the Central and Western regions will rely more heavily on administrative measures, and market mechanisms are relatively mature in the Eastern region.

## 5 Conclusions and Recommendations

### 5.1 Conclusions

The panel data for the construction industry in 30 Chinese provinces from 2008 to 2021 will be used in this paper. Use the super-efficiency SBM-GML index method to measure the green total factor productivity (GTFP) of the construction sector. A two-way fixed-effects benchmark regression is employed to test the impact of environmental regulations on construction green, and at the same time, the role of technological innovation in this process will also be analyzed. Based on the above empirical results, the following conclusions have been drawn: First, there is a significant difference in GTFP levels among the construction industries in China. Second, a relatively high level of environmental regulations promotes green transformation and upgrading in the construction industry, and as shown by the GTFP index, a high level of regulation is associated with high GTFP values. Thirdly, technological innovation by itself will not promote the growth of GTFP and needs to be combined with adjustments to the environment to avoid inhibiting factors. The "innovation compensation effect" caused by environmental regulation is currently smaller than the "compliance cost effect", and this may be due to insufficient innovation efforts at the construction enterprise level.

### 5.2 Policy Recommendations

As the main recipients of environmental regulations are enterprises in the hands of the

government, policy suggestions will come from both sides of the government and enterprises.

## **6 Government Side**

### **6.1 Implement Regionally Differentiated and Targeted Support Policies to Bridge the GTFP Gap**

Given the considerable regional differences in construction GTFP, the areas should be divided into three groups: high-efficiency, medium-efficiency, and low-efficiency. For areas with low GTFP, specific fiscal transfer funds or subsidies will be allocated to promote the introduction and application of high-end green building technologies, equipment, management models, etc. Strengthen inter-regional cooperation by providing targeted technical support and talent training programmes under the leadership of high-efficiency areas. Based on the different levels of economic development and environmental carrying capacity in the various areas, the central government can introduce specific plans at the regional level for strengthening GTFPs in a phased manner.

### **6.2 Gradually Increase Environmental Regulation Standards and Enforcement to Strengthen the Impetus for Green Transition**

Systematically assess and improve the current environmental regulatory system for the construction sector (including emissions, energy consumption, waste treatment and use of green materials). Establish more ambitious yet feasible medium- and long-term mandatory standards for green/low-carbon buildings based on scientific assessment. Strengthen the enforcement of environmental laws and impose heavy fines for non-compliance to raise the cost of behaviour (e.g., increase pollution charges and limit market access for energy-inefficient buildings). Build a public disclosure platform for the company's environmental data (such as energy consumption and carbon emissions) to strengthen social accountability by expanding transparency. Strengthen policy tools in the construction phase to achieve "dual carbon" goals and introduce carbon emission quotas and carbon taxes to increase the role of market mechanisms for resource allocation.

### **6.3 Build a Strong Green Innovation Incentive and Support System to Improve the Innovation Compensation Effect**

Increase government investment in core green and low-carbon technologies and large-scale demonstration projects. Strengthen tax incentives, add more R&D expense super-deductions, provide accelerated depreciation for green technology equipment, and offer VAT refunds. Broaden the green financing channels for the construction industry by developing green finance, establishing national or local green transition funds, promoting preferential green credit from banks, and supporting eligible enterprises in issuing green bonds. Explore a "government-bank-guarantee" risk-sharing mechanism to lower the financing costs of green innovation by small and medium-sized enterprises.

## **7 Enterprise Viewpoint**

### **7.1 Proactive Benchmarking and Differentiation to Strengthen Core Competitiveness**

The company can choose to select an excellent benchmark enterprise at the regional or national level for GTFP voluntarily, carry out extensive research on its technical route, management model and supply chain strategy, identify deficiencies and areas for improvement. Given the particular circumstances of the regional market and the firm's own resources, it is necessary to find a competitive edge and a position in the green construction industry within this area (e.g., ultra-low-energy buildings, prefabricated buildings, green building materials, construction waste recycling, retrofitting of old buildings) and avoid head-to-head competition with other firms. The company will pay attention to the support policies of the local government for areas with low GTFP (such as special subsidies and demonstration project support) and actively participate in the construction of its green foundation.

### **7.2 Forward-Looking Compliance Layout for Transforming Pressure into Competitive Advantage**

Passive Response to Making Environmental Compliance and Green Development Strategic Investments. Resources should be reserved in advance to purchase or develop more energy-saving equipment and environmentally friendly construction machinery (such as electric engineering vehicles) and waste treatment facilities. Promote green construction technology, such as water- and material-saving technology and low-disturbance construction methods, strengthen on-site management and reduce pollution risk. Enterprises should highlight their abilities and track records in meeting high-environmental-standard demands (e.g., low-emission certifications, green building ratings) in the bidding documents and marketing to secure high-end projects and gain the approval of clients and governments.

### **7.3 Focus on Regulatory Orientation and Efficiency Improvement to Build a High-ROI Green Innovation System**

Allocate research and development funds to green and low-carbon technologies such as energy-saving, emission-reducing, material-efficient and digital/intelligent construction, and possibly establish special R&D funds for this purpose. The company will proactively apply for relevant government support policies for R&D funds and other tax deductions. Joint R&D platforms will be built in collaboration with key suppliers and subcontractors to share the risks and rewards of innovation more closely with the supply chain. The successful pilot technology should be promptly turned into a standardised process, prefabricated module or management system, and supported by detailed cost-benefit analysis manuals and training systems for scale replication, R&D cost dilution, and maximum impact of innovation compensation.

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Author Affiliations: School of Energy and Architectural Engineering, Harbin University of Commerce, Harbin 150028, China; National Center of Technology Innovation for Green and Low-Carbon Building, Beijing 100012, China

## About the Author

Prof. Xiaozhuang Yang is Dean of the School of Energy and Architectural Engineering at Harbin University of Commerce. His academic work covers provincial and municipal research projects, intellectual property development, and textbook/publication output. He has led or participated in multiple funded projects, holds invention and utility model patents, and has received awards for scientific and social science achievements. His publications include monographs, SCI/EI-indexed papers, and national planning textbooks.

Xin Wang is a master's student in Management Science and Engineering at the School of Management, Harbin University of Commerce, China. Her research interest is project management.

## References

- [1] YE Z, LIU Y, RONG Y. How environmental regulations affect green total factor productivity—evidence from chinese cities[J/OL]. *Sustainability*, 2024, 16(7): 3010. DOI:10.3390/su16073010.
- [2] CHENG Z, KONG S. The effect of environmental regulation on green total-factor productivity in China's industry[J/OL]. *Environmental Impact Assessment Review*, 2022, 94: 106757. DOI:10.1016/j.eiar.2022.106757.
- [3] LI J, HUANG D, WU X. The impact of China's carbon emission TradingPolicy on green total factor productivity— influence analysis based on super-EBMand multiple mediators[J/OL]. *Polish Journal of Environmental Studies*, 2022, 31(6): 5107-5123. DOI:10.15244/pjoes/151538.
- [4] MA Y, LIN T, XIAO Q. The relationship between environmental regulation, green-technology innovation and green total-factor productivity—evidence from 279 cities in China[J/OL]. *International Journal of Environmental Research and Public Health*, 2022, 19(23): 16290. DOI:10.3390/ijerph192316290.
- [5] WEI B, CHENXI L, SHANSHAN L. Environmental regulation, R&D subsidies, and industrial green total factor productivity[J/OL]. *Sustainable Futures*, 2024, 8: 100333. DOI:10.1016/j.sftr.2024.100333.
- [6] XIONG R, GAO D. Exploring the impact of heterogeneous environmental regulations on green innovation efficiency: evidence from China's yangtze river economic belt[J/OL]. *Systems*, 2023, 11(10): 516-536. DOI:10.3390/systems11100516.
- [7] DONG X, GUO K, XUE G, etc. Environmental regulation, resource misallocation, and total factor productivity: an empirical analysis based on 284 cities at the prefecture-level and above in China[J/OL]. *International Journal of Environmental Research and Public Health*, 2023, 20(1): 854-869. DOI:10.3390/ijerph20010854.

- [8] MA X, XU J. Impact of environmental regulation on high-quality economic development[J/OL]. *Frontiers in Environmental Science*, 2022, 10: 896892. DOI: 10.3389/fenvs.2022.896892.
- [9] ZHENG Y, ZHOU Z, ZHOU F. The non-linear effect of dual environmental regulation on urban green total factor productivity: evidence from 284 cities in China[J/OL]. *Sustainability*, 2024, 16(12): 4894. DOI:10.3390/su16124894.
- [10] CHEN M, SHI V, WEI X. Environmental regulations, R&D intensity, and enterprise profit rate: understanding firm performance in heavy pollution industries[J/OL]. *Frontiers in Environmental Science*, 2022, 10: 1077209. DOI:10.3389/fenvs.2022.1077209.
- [11] SUN H, ZHANG Z, LIU Z. Regional differences and threshold effect of clean technology innovation on industrial green total factor productivity[J/OL]. *Frontiers in Environmental Science*, 2022, 10: 985591. DOI:10.3389/fenvs.2022.985591.
- [12] XU W, JIANG C, JIA K, etc. Did the “double carbon” policy improve the green total factor productivity of iron and steel enterprises? a quasi-natural experiment based on carbon emission trading pilot[J/OL]. *Frontiers in Energy Research*, 2023, 11: 1307347. DOI:10.3389/fenrg.2023.1307347.
- [13] LI Y, LIU W. Spatial effects of environmental regulation on high-quality economic development: from the perspective of industrial upgrading[J/OL]. *Frontiers in Public Health*, 2023, 11: 1099887. DOI:10.3389/fpubh.2023.1099887.
- [14] ZHANG X, YOU M. Environmental justice, corporate green total factor productivity, and pollution control: a quasi-natural experiment based on the establishment of environmental courts[J/OL]. *International Review of Economics & Finance*, 2025, 100: 104126. DOI:10.1016/j.iref.2025.104126.
- [15] WANG X, CHAI Y, WU W, etc. The empirical analysis of environmental regulation’s spatial spillover effects on green technology innovation in China[J/OL]. *International Journal of Environmental Research and Public Health*, 2023, 20(2): 1069. DOI:10.3390/ijerph20021069.
- [16] YANG Z, FANG H. How Do Environmental Regulation and Decentralization Interactively Affect the Green Productivity of the Construction Industry? Evidence from China[J/OL]. *Sustainability*, 2024, 16(14): 6138. DOI:10.3390/su16146138.
- [17] ZHOU W, LIU C, ZHOU Y, etc. The influence of environmental policy on green total factor productivity in the chinese construction industry[J/OL]. *Buildings*, 2025, 15(15): 2688. DOI:10.3390/buildings15152688.
- [18] LI X, HUANG Y, LI J, etc. The mechanism of influencing green technology innovation behavior: evidence from chinese construction enterprises[J/OL]. *Buildings*, 2022, 12(2): 237-253. DOI:10.3390/buildings12020237.
- [19] TONE K. A slacks-based measure of super-efficiency in data envelopment analysis[J/OL]. *European Journal of Operational Research*, 2002, 143(1): 32-41. DOI:10.1016/S0377-2217(01)00324-1.

- [20] OH D hyun. A global malmquist-luenberger productivity index[J/OL]. *Journal of Productivity Analysis*, 2010, 34(3): 183-197. DOI:10.1007/s11123-010-0178-y.
- [21] LIU M, ZHU Y, ZHANG J. Can environmental regulation enhance green total factor productivity?—evidence from 107 cities in the Yangtze River economic belt[J/OL]. *Sustainability*, 2024, 16(12): 5243. DOI:10.3390/su16125243.
- [22] ZHANG J, PU S, PHILBIN S P, etc. Environmental regulation and green productivity of the construction industry in China[J/OL]. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 2021, 174(2): 58-68. DOI:10.1680/jensu.20.00013.
- [23] SHI Y, LU W, LIN L, etc. Does environmental regulation affect china’s agricultural green total factor productivity? Considering the role of technological innovation[J/OL]. *Agriculture*, 2025, 15(6): 649-673. DOI:10.3390/agriculture15060649.
- [24] MA Y, LIN T, XIAO Q. The relationship between environmental regulation, green-technology innovation and green total-factor productivity—evidence from 279 cities in China[J/OL]. *International Journal of Environmental Research and Public Health*, 2022, 19(23): 16290. DOI:10.3390/ijerph192316290.
- [25] ZHAO X, WANG J, FU X, etc. Technological innovation, EnvironmentalRegulation, and green total FactorProductivity in the logistics industry:dynamic spatial durbin model analysis[J/OL]. *Polish Journal of Environmental Studies*, 2024, 33(3): 3471-3488. DOI:10.15244/pjoes/175779.
- [26] HUANG L, PING Y. The impact of technological innovation on agricultural green total factor productivity: the mediating role of environmental regulation in China[J/OL]. *Sustainability*, 2024, 16(10): 4035. DOI:10.3390/su16104035.