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Impact of Heterogeneous Environmental Regulation on Manufacturing Sector Green Transformation and Sustainability

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This study aims to investigate the effect of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin by using the SBM-GML. Spatial econometrics and threshold regression models were utilized to examine the effect of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin and the regulatory function of green technology innovation. The results demonstrated that the green total factor productivity (GTFP) of the manufacturing sector in the Yellow River Basin increased with fluctuations from 2010 to 2019. The analysis revealed a U-shaped relationship between command-and-control type environmental regulation and the green transformation. It also signifies that market-incentive type environmental regulation had a negligible effect on the green transformation. The relationship between public-participation type environmental regulation and the green transformation of the manufacturing sector in the Yellow River Basin was "U"-shaped but inverted. Innovations in green technology are a significant variable that influences the heterogeneous environmental regulations that affect the green transformation.

Keywords: Yellow River Basin, heterogeneous environmental regulation, green transformation, threshold regression, sustainability, sustainable environment

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INTRODUCTION

As the foundation of material and the primary industrial sector of the nation's economy, the manufacturing sector generates enormous wealth and several negative environmental externalities. The ninth meeting of the China Central Financial and Economic Commission emphasized: "The key industries should implement the pollution reduction and carbon reduction actions, and the industrial sectors should promote green manufacturing." Meanwhile, the *Outline of Yellow River Basin Ecological Protection and High-quality Development* stated: "Through scientific and technological innovation, it was able to achieve old-and-novel development drivers' transformation; while promoting the high-quality development of manufacturing sector in the Yellow River Basin and the transformation of resource-based industries. The aim is to establish a modern industrial system with featured-advantages." The green transformation is also known as the technological uplift by considering the transformation from low-level labor products to technologically valuable products. The transition from high consumption and high emissions to low consumption and low pollution is a green-cycle development process (Poon, 2004; Kemp and Never, 2017; Shehzad et al., 2020). Consequently, the green transformation has become a vital goal and development paradigm for the manufacturing sector to achieve high quality and sustainability (Naseem et al., 2021; Wang et al., 2021). Currently, the Yellow River Basin's manufacturing sector has formed on a large scale due to the region's abundant resources.

Despite this, the Yellow River Basin is still dominated by "three-high" industries due to constraints imposed by location conditions, economic policies, and other factors. Inadequate endogenous power retards the transformation rate and upgrading of the traditional industries in the Yellow River Basin. Additionally, the energy and chemical industries cause irreversible harm to the Yellow River Basin ecosystem (Sarfraz et al., 2020; Jin et al., 2021). Therefore, the green transformation of the manufacturing sector in the Yellow River Basin is necessary to overcome resource and environmental constraints. It is also an efficient means of achieving environmental protection and high-quality development.

However, it is difficult to offset the negative environmental externalities by relying solely on market incentives, so an effective external-driving mechanism is also required. Environmental regulation can impose an external cost burden on businesses, constraining them from engaging in reasonable resource development, reducing environmental pollution and emissions, and compelling them to transition to green development (Zhang et al., 2020; Chen and Liu, 2022). Therefore, it is crucial to analyze the current state of the green transformation of the manufacturing sector in the Yellow River Basin. It will help investigate the non-linear effect of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin. Meanwhile, it can optimize the industrial structure, consider sustainable development an option, and achieve the coordinated promotion of ecological protection and high-quality development in the Yellow River Basin.

This article contributes to prior work in various aspects. First, this paper discusses the mechanism of heterogeneous environmental regulation affecting the green transformation of the manufacturing sector and the path of green technology innovation to play a regulatory role in greater depth than previous research. Second, when using SBM-GML to measure the green transformation level of the Yellow River Basin, water resources and carbon dioxide-related indicators are included in the calculation of the GTFP index to account for the Yellow River Basin's limited water resources and fragile ecological environment. Third, this article explores the non-linear relationship between the linear impact of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin and their non-linear relationship. Finally, apart from examining the regulatory role of green technology innovation, this article calculates the impact of heterogeneous environmental regulations on the green transformation of the manufacturing sector in the Yellow River Basin under varying green technology innovation thresholds.

The remaining structure of this article is as follows. The literature review is available in **Section 2**. In **Section 3**, theoretical research and study methodology are reported. **Section 4** analyzes the effect of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin. Finally, **Section 5** summarizes the non-linear effects of heterogeneous environmental regulation on the green transformation of manufacturing in the Yellow River Basin and makes policy recommendations based on the research findings.

LITERATURE REVIEW

Environmental regulation's effect on green development has been studied for many years, but no unified conclusion has been reached. The Porter Hypothesis (PH) holds that reasonable environmental regulations could stimulate enterprise innovation activities while triggering compensation effects of innovation that will help offset or even surpass the cost of environmental regulation. Reasonable environmental regulation can positively affect the long-term development of enterprises by increasing the level of green technology innovation (Matsuhashi and Takase, 2015; Dechezlepretrea and Sato, 2017). Yoo and Heshmati (2019) demonstrated that the negative effects of regulation anticipated in polluting industries are offset if a firm is also included in the green sector, producing environment-related products. Some academics are also of the opinion that environmental regulations will increase the cost of businesses and the barrier to entry, thereby diminishing the competitive advantage of businesses. Yana et al. (2015) stated that environmental regulation would inhibit the growth of global total factor productivity in the short term. Albrizios et al. (2014) noted that environmental regulation inhibits businesses with relatively low productivity. According to Efthymia and Anastasios (2013), environmental regulations increase enterprises' production and operating costs, thereby impeding the economic growth of the manufacturing sector. Lee and Lee (2022) supported the notion that environmental protection expenditures negatively correlate with total factor productivity, including a lag variable for environmental research and development. Environmental regulation and green development, according to some scholars, have a non-linear relationship. Li and Tao (2012) analyzed the relationship between GTFP and environmental regulation of various industries in the manufacturing sector. Yin (2012) discovered a U-shaped correlation between the intensity of environmental regulations and the GTFP of the manufacturing sector. In various sectors, the two are dissimilar. Cai and Zhou (2017) asserted that the effect of market-incentive type environmental regulation on GTFP would exhibit a "promote first and then inhibit" pattern. The voluntary-agreement type environmental regulation will initially inhibit and then promote the growth of GTFP, whereas the command-and-control type environmental regulation has no significant effect on GTFP.

In recent years, some academics have also analyzed the impact mechanism of environmental regulation on industry or manufacturing. In addition to direct effects, intermediate variables such as technological innovation (Zhang et al., 2020), foreign direct investment (Li et al., 2022), industrial structure (Lei et al., 2020), and pricing mechanism (Grimaud and Rouge, 2005) indirectly affect the impact of environmental regulation on the manufacturing sector in green transformation. As a crucial starting point for green development, green technology innovation has had significant effects on environmental regulation, thereby influencing the green transformation of the manufacturing sector (Cheng et al., 2020). Zhang (2020) discussed the role of green technology innovation in the transformation and upgrading of the manufacturing sector. The intensity of environmental regulation affects green technology innovation in promoting the progress of transformation and upgrading of the manufacturing sector. Yuan and Chen (2019) applied the Generalized Method of Moments (GMM) to study the relationship between environmental regulation, green technology innovation, and manufacturing transformation and upgrading. They determined that high-intensity environmental regulation can help increase green technology innovation, while a non-linear relationship exists between green technology innovation and the manufacturing sector's transformation and upgrading. Lei et al. (2020) believed that, with more attention being paid to the environment, enterprises at the forefront of implementing green technology innovation have the advantage of seizing the market share, thus producing a linkage effect. Yin et al. (2022) analyzed the effect of environmental regulation on GTFP in the Yangtze River Basin. They discovered that green technology innovation as an intermediary variable has heterogeneous properties.

A review of the relevant literature reveals no consensus regarding the effect of environmental regulations on the greening of manufacturing. The transformation of the manufacturing sector in the Yellow River Basin is the subject of relatively few studies. Consequently, based on Yellow River Basin characteristics, this article measures the green transformation level of the Yellow River Basin's manufacturing sector. Based on the heterogeneity of environmental regulation, green technology innovation is introduced as a moderator variable to investigate the non-linear impact of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin and its threshold effect to support the ecological protection and high-quality development of the Yellow River Basin.

THEORETICAL RESEARCH AND METHOD

According to studies, multiple forms of environmental regulation are more conducive to promoting the long-term development of businesses than a single mandatory environmental regulation. This is the case when the expected marginal revenue is relatively flat. This article draws on the relevant research of predecessors (Bao and Guo, 2022), classifying environmental regulation into three types: 1) command-and-control, 2) market incentive, and 3) public participation. Then, it analyzes the impact mechanism of different types of environmental regulation on the green transformation of the manufacturing sector.

Command-and-Control Type Environmental Regulation and Green Transformation of the Manufacturing Sector

Environmental regulation of the command-and-control type refers to the government's enforcement of environmental laws, rules, and regulations to curb and correct enterprise environmental pollution. The green transformation of the manufacturing sector will be influenced by its "crowding-out effect" and market competition mechanism. In contrast, in the early stages of policy implementation, the cost of environmental governance for businesses skyrockets. When enterprises have limited resources, they will likely invest less in other areas. While the multiplier effect further reduces corporate profits and consumes resources related to green development, the cost of implementing policies is higher than the penalty cost of not implementing policies, so companies will tend to maintain the status quo to maximize their profits.

From a microscopic perspective, technological innovation generates greater returns for businesses alongside the advancement of environmental policies, which can significantly mitigate or even offset the environmental cost caused by policy implementation. From a macroscopic perspective, under the principle of survival of the fittest, unqualified businesses are eliminated and replaced by those that are more clean-efficient, thereby promoting the green development of the entire industry.

Market-Incentive Type Environmental Regulation and Green Transformation of the Manufacturing Sector

The core of market-incentive environmental regulation is market competition and the price mechanism. Taxes, subsidies, and credits based on market signals regulate business-related pollution. Their flexible mechanism for adjusting prices can effectively stimulate market participant enthusiasm for environmental governance. For instance, market-incentive type environmental regulation influences the transformation of the manufacturing sector by modifying energy prices. The greater the energy consumption of manufacturing companies, the greater the significance of the energy price adjustment mechanism. Currently, businesses can reduce costs by enhancing their technological innovation, while market-incentive type environmental regulation can increase the emission costs of environmentally irresponsible businesses through emission trading policies. Free trade enables the market to achieve the optimal allocation of environmental resources, thereby compensating for the initial costs incurred by environmentally conscious businesses.

Public-Participation Type Environmental Regulation and Green Transformation of the Manufacturing Sector

Public-participation type environmental regulation refers to promoting pollution prevention and control knowledge to increase public awareness of environmental protection, which invisibly exerts pressure on the government and manufacturing enterprises to implement environmental protection measures *via* the "constraint effect." In addition, when the production activities of the manufacturing sector lead to pollution and negatively impact the public's health, the public may seek their legal rights through direct or indirect means, such as the right to supervise litigation or the use of the media. Moreover, with the proliferation of the Internet, information sharing and dissemination has increased, the "diffusion effect" has been amplified, and the channels for public participation in environmental governance have become more diverse, transparent, and flexible. This regulation is closely related to the public's awareness of environmental protection, but in practice, the public lacks a holistic perspective and is more concerned with their economic interests. Therefore, excessive public participation will not benefit the green transformation of the manufacturing sector over the long term.

The Regulatory Mechanism of Green Technology Innovation

The primary manifestations of the regulatory effect of green technology innovation on heterogeneous environmental regulation and manufacturing transformation are as follows. 1) The early implementation of command-and-control type environmental regulations will increase the production costs of businesses, which will consume the original resource allocated for green innovation. With the expansion of market competition, many businesses have embraced the development of green technologies. To initiate the transformation and upgrading of the entire industry, stricter command-and-control type environmental regulations are necessary at this time. 2) For market-incentive type environmental regulations, technological innovation subsidies and pollution taxes can reduce the decrease in production efficiency and loss of social welfare caused by mandatory environmental regulation implementation, which also promotes innovation in green technology to a greater extent. However, innovation cannot exist without the backing of funds and policies. Therefore, industry-wide innovation in green technology will result in increased market-incentive type environmental regulations. The interaction between the two will hasten the greening of the manufacturing sector. 3) The level of green technology innovation significantly impacts the relationship between public-participation type environmental regulation and the green transformation of the manufacturing sector from two different perspectives. First, under public oversight and pressure from public opinion, advanced manufacturing enterprises will consider the public's interests before production. They will take the lead in internalizing pollution costs *via* innovations in green technology. In contrast, the "competitive mechanism" influences the green transformation of other businesses to satisfy the public's demand for a green lifestyle. Second, as the level of green technology continues to advance, the concept of green consumption in society has been enhanced, generating novel demands for green technology innovation and driving the transformation and upgrading of the manufacturing sector.

Research Design

Model Construction

i) SBM Directional Distance Function

This article employs a non-radial and slack-based directional distance function—the Slacks-Based Measure (SBM), proposed by Fare, Grosskoph, and Weber—to address the issue that the traditional DEA model will overestimate the research object when considering excessive input or inadequate output. By introducing slack variables, it is possible to reduce the impact of input-output slack. Each municipality is designated as a unit of decision-making, and the SBM directional distance function is as follows:

$$\overrightarrow{S_v^t}\left(x^{tj'}, yg^{tj'}, yb^{tj'}, g^x, g^{yg}, g^{yb}\right) = \max_{s_n^x, s_m^{yg}, s_p^{yb}} \frac{\frac{1}{N}\sum_{n=1}^{N}\frac{S_n^x}{g_n^x} + \frac{1}{M+P}\left(\sum_{m=1}^{M}\frac{S_m^{yg}}{g_m^{yg}} + \sum_{p=1}^{P}\frac{S_p^{yb}}{g_p^{yb}}\right)}{2} \quad (1)$$

$$\text{s.t.}\begin{cases} \sum_{j=1}^{J}\lambda_j^t x_{jn}^t + S_n^x = x_{jn}^t, \forall n; \\ \sum_{j=1}^{J}\lambda_j^t yg_{jm}^t - S_m^{yg} = yg_{jm}^t, \forall m; \\ \sum_{j=1}^{J}\lambda_j^t yb_{jp}^t + S_p^{yb} = yb_{jp}^t, \forall p; \\ \sum_{j=1}^{J}\lambda_j^t = 1, \lambda_j^t \geq 0, \forall j; \\ S_n^x \geq 0, \forall n; \\ S_m^{yg} \geq 0, \forall m; \\ S_p^{yb} \geq 0, \forall p \end{cases} \quad (2)$$

where $\overrightarrow{S_v^t}$ represents the directional distance function of variable returns to scale (VRS), while $(x^{tj'}, yg^{tj'}, yb^{tj'})$, (g^x, g^{yg}, g^{yb}), and (S^x, S^{yg}, S^{yb}) denote the input-output vectors, direction vectors, and slack vectors of city j, respectively.

ii) Global Malmquist–Luenberger (GML) Productivity Index

The GML index features transmissibility and cyclic accumulation, making it superior to the ML index. This article also employs the GML productivity index to evaluate the changes in GTFP. The construction of the GML productivity index is as follows:

$$GML_t^{t+1} = \frac{1 + \underset{D_0^G}{\longrightarrow}(x^t, y^t, b^t; y^t, -b^t)}{1 + \underset{D_0^G}{\longrightarrow}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})} = GEC_t^{t+1} \times GTC_t^{t+1} \quad (3)$$

where t and t+1 represent the current period and the next consecutive period, respectively, while the GML productivity index is the ratio of t and t+1 periods of GTFP. If the GML productivity index is greater than 1, the GTFP is on the rise; otherwise, it means that the GTFP has decreased or maintained the status quo. GTC is the technological development from t to t+1, and GEC denotes the technical efficiency change from t to t+1. When GTC and GEC are greater than (or less than) 0, they signify technologically developed forward (or backward) and technological efficiency enhanced (or declined).

iii) Spatial Econometrics Model

To investigate the impact of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin and the regulatory role of green technology innovation, this article develops the following models as a starting point:

$$lnGTFP_{it} = \alpha_0 + \beta_1 lng_{it} + \beta_2 lnm_{it} + \beta_3 lns_{it} + \beta_4 lnr_{it} + \beta_5 lnX_{it} + \varepsilon_{it} \tag{4}$$

To determine the non-linear impact of command-and-control type and public-participation type environmental regulations on the green transformation of the manufacturing sector in the Yellow River Basin, this article introduces the square terms $(g_{it})^2$ and $(s_{it})^2$ to represent two types of environmental regulation, constructing the following model:

$$lnGTFP_{it} = \alpha_0 + \beta_1 lng_{it} + \beta_2 lnm_{it} + \beta_3 lns_{it} + \beta_4 lnr_{it} + \beta_5 lnX_{it} + ln(g_{it})^2 + ln(s_{it})^2 + \varepsilon_{it} \tag{5}$$

This article examines the green transformation of neighboring regions using the lag period method to determine the effect of the green transformation of the manufacturing sector in neighboring regions on the local green transformation of the manufacturing sector. The resulting dynamic spatial lag model is as follows:

$$lnGTFP_{it} = \alpha_0 + \rho_0\left(W_{ij} lnGTFP_{it} - 1\right) + \beta_1 lng_{it} + \beta_2 lnm_{it} + \beta_3 lns_{it} + \beta_4 lnr_{it} + \beta_5 lnX_{it} + \beta_6 ln(g_{it})^2 + \beta_7 ln(s_{it})^2 + \varepsilon_{it} \tag{6}$$

Based on the above models, this article introduces green technology innovation into three distinct types of environmental regulations to determine its regulatory effect. The following are the models:

$$lnGTFP_{it} = \alpha_0 + \rho_0\left(W_{ij} lnGTFP_{it} - 1\right) + \beta_1 lng_{it} + \beta_2 lnm_{it} + \beta_3 lns_{it} + \beta_4 lnr_{it} + \beta_5 lnX_{it} + \beta_6 ln(g_{it})^2 + \beta_7 ln(s_{it})^2 + \rho_1 (lnr_{it} \times lng_{it}) + \rho_2 (lnr_{it} \times lnm_{it}) + \rho_3 (lnr_{it} \times lns_{it}) + \varepsilon_{it} \tag{7}$$

where i and t represent the city and year, respectively, α_0 is the cross-sectional effect, β_1-β_7、 ρ_0-ρ_3 are the regression coefficients, $GTFP$ is the green transformation level of the manufacturing sector, g is the command-and-control type environmental regulation, m is the market-incentive type environmental regulation, s is the public-participation type environmental regulation, r is the level of green technological innovation, X is the control variable, $lnr_{it} \times lng_{it}$, $lnr_{it} \times lnm_{it}$, $lnr_{it} \times lns_{it}$ denote the intersection of green technological innovation and the three types of environmental regulations, respectively, and ε_{it} is the random error term.

iv) Determination of Spatial Weight Matrix

This article selects the spatial geographic matrix as the spatial weight matrix, W_{ij}:

$$W_{ij} = \frac{1}{d_{ij}} \tag{8}$$

where d_{ij} represents the straight-line distance from city i to city j.

v) Threshold Regression Model

Since different environmental regulations have a non-linear effect on the green transformation of the manufacturing sector, the threshold variable for testing in this study is the level of green technology innovation. In addition, there may be multiple thresholds to consider when evaluating the impact of green technology innovation on environmental regulation, which influences the green transformation of the manufacturing sector. Consequently, this study establishes the following threshold models: single, double, and triple.

$$GTFP_{i,t} = \alpha_0 + \beta_1 ER_{i,t} \cdot I\left(q_i \le r_1'\right) + \beta_2 ER_{i,t} \cdot I\left(q_i \ge r_1'\right) + \varphi Control_{i,t} + \varepsilon_{i,t} \tag{9}$$

$$GTFP_{i,t} = \alpha_0 + \beta_1 ER_{i,t} \cdot I\left(q_i \le r_1'\right) + \beta_2 ER_{i,t} \cdot I\left(r_1' \le q_i \le r_2'\right) + \beta_3 ER_{i,t} \cdot I\left(q_i \ge r_2'\right) + \varphi Control_{i,t} + \varepsilon_{i,t} \tag{10}$$

$$GTFP_{i,t} = \alpha_0 + \beta_1 ER_{i,t} \cdot I\left(q_i \le r_1'\right) + \beta_2 ER_{i,t} \cdot I\left(r_1' \le q_i \le r_2'\right) + \beta_3 ER_{i,t} \cdot I\left(r_2' \le q_i \le r_3'\right) + \beta_4 ER_{i,t} \cdot I\left(q_i \ge r_3'\right) + \varphi Control_{i,t} + \varepsilon_{i,t} \tag{11}$$

In **Eqs 9–11**, I is the threshold function, $ER_{i,t}$ represents the three types of environmental regulations, q_i is the threshold variable or the level of green technology innovation, r_1' is the specific threshold value, and $Control_{i,t}$ is the control variable.

Index Selection and Data Sources

i) Index Selection

This article integrates with the development trend of "Water resources are the biggest rigid constraint of the Yellow River Basin" (Yan et al., 2020) and "Dual Carbon" objectives (Liu and Qu, 2019). It exhaustively examines the scientific rigor, representativeness, and accessibility of each index. Thus, as input variables, capital resources, human resources, energy resources, and water resources are chosen. Calculated on the Yellow River Basin manufacturing sector's green transformation level (GTFP), industrial output value and profit are desirable output variables. At the same time, wastewater, waste gas, and dust are undesirable output variables. The particular indexes are chosen according to **Table 1**.

Table 2 displays the variable definitions of the spatial econometrics model and the panel threshold regression model. The manufacturing sector's level of green transformation is the explanatory variable. The three different environmental regulations are likewise the explanatory variables, while green technology innovation acts as the moderator variable and the threshold

TABLE 1 | Yellow River Basin Manufacturing sector Green Transformation Level (GTFP) Input-Output Index.

Green total factor productivity (GTFP)	Variable		Index
	Input	Capital Resource	Fixed Asset Inventory Level
		Human Resource	Society Employment Level
		Energy Resource	Total Annual Industrial Electricity Consumption
		Water Resources	Total Annual Water Supply
	Desired Output	Output Value	Industrial Value Added
		Profit	Total Profit of Industrial Enterprises
	Undesired Output	Wastewater	Total Industrial Wastewater Discharge
		Waste Gas	Total Carbon Dioxide Emissions
			Industrial Sulfur Dioxide Emissions
		Smoke and Dust	Industrial Soot(dust) Discharged

TABLE 2 | Variable definitions of the spatial econometrics model and the panel threshold regression model.

Variable		Index
Explanatory Var.	Green Total Factor Productivity (GTFP)	Represented by the Green Total Factor Productivity (GTFP) measured by the SBM-GML index method
Core Explanatory Var.	Command-and-Control Type (g)	Number of Environmental Administrative Penalties
	Market-Incentive Type (m)	Comprehensive Energy Prices
	Public-Participation Type (s)	Baidu Search Index (environment, pollution)
Moderator/ Threshold Var.	Green Technology Innovation (t)	Granted Amount of R&D Green Patents per 10,000 yuan
Control Var.	Economic Scale (e)	Gross Domestic Product per capita
	Foreign Investment (f)	Foreign Direct Investment
	Transportation Convenience (d)	Road Mileage per square kilometer
	Industrial Structure (l)	The proportion of the output value of the tertiary industry to the total regional GDP
	Urbanization Rate (c)	The proportion of the urban population to the total population of the region

variable. In terms of heterogeneous environmental regulation, since command-and-control type environmental regulations emphasize government means to prevent businesses from damaging the environment, the number of environmental administrative penalties is chosen to represent command-and-control type environmental regulations (Shah et al., 2019; Xie et al., 2021). This article argues that there are regional differences in the consumption structure and price of energy consumption (Ma et al., 2008; Wang and Qi, 2016). The all-inclusive energy prices are chosen to reflect market-incentive type environmental regulations. Public environmental demand is a positive incentive for businesses to reduce pollution and emissions, and it also enhances the efficacy of government oversight. Utilizing new media (such as search engines) for information exchange is crucial for the public to participate in environmental governance. This article uses the Baidu search engineer with "environment" and "pollution" as the search terms (Lv and Wu, 2021; Li and Wu, 2022) to illustrate public-participation type environmental regulation. This article selects the number of granted R&D green patents per 10,000 yuan as the innovation index for green technology (Mohsin et al., 2022; Sarfraz et al., 2022; Yi et al., 2022). The control variables selected for this study are as follows: for economic scale, represented by Gross Domestic Product, GDP per capita; the higher the GDP per capita, the greater the green development of manufacturing in the region. Foreign investment, represented by foreign direct investment or FDI as the integration of capital, technology, and knowledge, has a profound effect on the green transformation of the manufacturing sector. Transportation convenience is represented by the distance to the nearest major port. It is widely believed that the improvement and rationalization of the industrial structure will aid in the transformation and growth of the manufacturing sector. Generally, the advance and rationalization of the industrial structure will help the manufacturing sector's transformation and development. Finally, the urbanization rate is the proportion of the region's total population that resides in urban areas. Thus, the urbanization rate is represented by the proportion of the urban population to the region's total population.

ii) Research Area and Data Source

Referencing related research (Guo et al., 2022), this article examines the impact of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin using 57 prefecture-level cities as research samples. The area of study is depicted in **Figure 1**. The data comes from the "China City Statistical Yearbook," the "Price Yearbook of China," the "China Energy Statistical Yearbook," and the "Statistical Yearbook" of each province and city, as well as statistical bulletins, water resources bulletins, the China Stock Market and Accounting Research Database (CSMAR), the EPS Data Platform, and other sources.

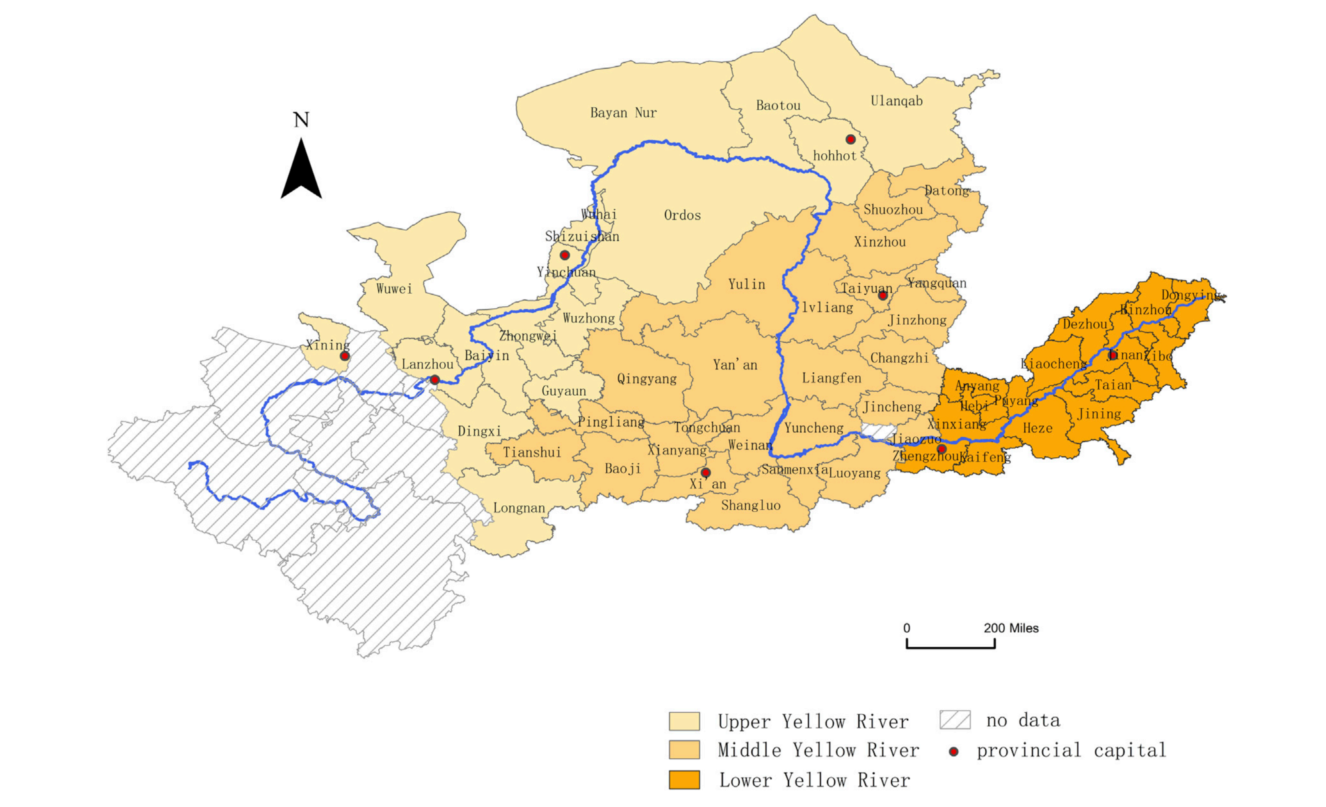

FIGURE 1 | Map of the research area.

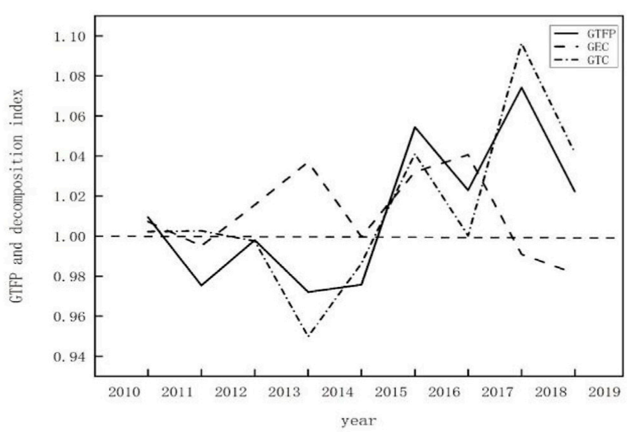

FIGURE 2 | GTFP and its decomposition item index.

EMPIRICAL ANALYSIS

Yellow River Basin Manufacturing Sector Green Transformation Level (GTFP) Calculation

This article uses Stata 16 to measure the manufacturing sector's gross total factor productivity (GTFP) trend in the Yellow River Basin and its decomposition items, as shown in **Figure 2**. From 2010 to 2019, the manufacturing sector's transformation level in the Yellow River Basin increased amid fluctuations and with sufficient driving force, but the driving force sources were unbalanced. From 2010 to 2019, the manufacturing sector's transformation level in the Yellow River Basin increased from 1.009 to 1.022. In particular, between 2010 and 2015, GTFP in the Yellow River Basin was in a period of decline or slow increase. From 2015 to 2016, GTFP in the Yellow River Basin increased rapidly, and from 2015 to 2019, GTFP remained consistently greater than 1. From 2010 to 2015, the trend of changes in GEC is consistent with GTFP, whereas the trend of changes in GTC is consistent with GTFP from 2015 to 2019. China's Yellow River Basin has always been a vital energy production and supply source. Under the dual effects of national policies and development needs around 2010, to narrow the economic gap with the eastern coastal areas, increase the development and utilization of resources, and introduce foreign capital, thereby expanding the scope of international trade. In tandem with the rapid growth of the economy, severe ecological and environmental problems have arisen, impeding the green transformation of the manufacturing sector.

Consequently, the "13th Five-Year Plan" development requirements emphasized quality-and-efficiency enhancements and optimization and transformation. A series of incentive measures were implemented at various national and local

TABLE 3 | The GTFP of the Yellow River Basin and its sources analysis in 2010–2019.

Duration	Upper reaches			Middle reaches			Lower reaches		
	GTFP	GEC	GTC	GTFP	GEC	GTC	GTFP	GEC	GTC
2010–2011	1.139	1.126	1.041	1.054	1.002	1.071	1.027	1.033	1.057
2011–2012	0.930	0.938	1.035	0.992	1.042	0.972	1.100	0.982	1.016
2012–2013	0.987	1.038	0.999	1.002	1.001	1.000	1.044	1.015	1.199
2013–2014	0.977	1.031	0.938	0.964	1.038	0.942	0.980	1.005	0.977
2014–2015	0.991	1.012	0.947	0.951	0.967	1.000	0.999	0.992	1.008
2015–2016	1.002	0.947	1.090	1.041	1.038	1.018	1.037	1.015	1.023
2016–2017	1.042	1.003	1.028	1.040	1.060	0.991	0.972	0.988	0.984
2017–2018	1.028	0.978	1.078	1.121	0.998	1.133	1.049	0.993	1.056
2018–2019	1.008	0.920	1.146	0.999	0.991	1.021	1.091	0.959	1.096
Average Value	1.012	0.999	1.034	1.018	1.015	1.017	1.033	0.998	1.046

levels to encourage enterprise innovation, laying the groundwork for accelerating the transformation of the manufacturing sector. From 2010 to 2015, the GEC index was greater than 1 and increased at the same rate as the GTFP trend. This demonstrates that before 2015, the green transformation of manufacturing in the Yellow River Basin was primarily driven by technical efficiency gains. After 2015, the GTC index exhibited significant volatility. It had a significant impact on GTFP, indicating that the implementation of various innovation-related policies and incentive measures has led to the green transformation of the manufacturing sector in the Yellow River Basin due to technological development. It is still necessary to strengthen the intensity of scientific and technological innovation, thereby driving the adjustment of industrial structure and improving the level of green transformation in the manufacturing sector.

Table 3 depicts the green transformation of the manufacturing sector in the upper, middle, and lower Yellow River Basin and its driving index. The transformation level of the manufacturing sector in the Yellow River Basin decreases from the lower to the upper reaches, as shown in **Table 3**. The manufacturing sector in the Yellow River Basin's lower reaches has shown the greatest improvement in green transformation, with an average annual growth rate of 3.3%. The decomposed technological development index has increased by 4.6%, while the technical efficiency index has decreased by 0.2%; the average annual growth rate of the manufacturing sector's green transformation level in the middle Yellow River Basin is 1.8%, and the technical efficiency index has increased by 1.5%. Comparatively, the technological development index has grown by 1.7%. Among 56 cities, Xi'an's manufacturing sector has the highest level of green transformation, signifying the city's solid foundation for technological innovation. The Yellow River Basin's upper reaches have the lowest level of green transformation in the manufacturing sector. The average annual growth rate of the GTFP index is 1.2%, and technological development has increased by 3.4%, but the average annual growth rate of the technical efficiency index is −0.1%. In conclusion, in the process of green transformation of the manufacturing sector in the Yellow River Basin, we must maximize the driving and leading role of technological progress, enhance the internal management capabilities of enterprises, enhance technical efficiency, and promote the coordinated development of inputs and outputs.

Spatial Econometric Regression Results

Spatial Correlation Test

In this article, the spatial correlation of the green transformation of the manufacturing sector in the Yellow River Basin is examined using Moran's I index. **Table 4** reveals that, with the exception of 2013, the Moran index is significantly positive in all other years, indicating a spatial correlation between the green transformation of the manufacturing sector in the Yellow River Basin.

Basin-Wide Regression Results

Initially, the Augmented Dickey–Fuller (ADF) unit root test and Variance Inflation Factor (VIF) test were conducted. There was no multicollinearity, and all variables passed the stationarity test. Consequently, it was possible to conduct the regression analysis. In the Ordinary Least Squares (OLS) Regression and LM tests, the LM spatial lag is significantly greater than the LM spatial error. The R-LM spatial lag passed the 1% significance test, while the R-LM spatial error failed. The Spatial Lag Model (SLM) was therefore chosen for this article. **Table 5** displays the results of the Hausman test, which is used to select the time and space double fixed model for regression analysis.

The spatial spillover coefficient of GTFP is significantly positive at the 5% significance level, as shown in **Table 5**. This indicates that the green transformation of the manufacturing sector in the Yellow River Basin has a positive spatial correlation. It also suggests that the green transformation of the manufacturing sector in neighboring regions can provide new impetus for local development and drive the transformation of the manufacturing sector to a green development model.

From the perspective of command-and-control type environmental regulations, the linear coefficient is negative at the 10% significance level. In contrast, the quadratic coefficient is positive at the 5% significance level, indicating a "U"-shaped relationship between command-and-control type environmental regulations and the green transformation of manufacturing in the Yellow River Basin. Additionally, the intersection coefficient of command-and-control type environmental regulations and the

TABLE 4 | Spatial correlation.

Year	GTFP	Command-and control type	Market-incentive type	Public-participation type
2010	0.016***	0.095***	0.136***	0.157**
2011	0.008**	0.016*	0.119**	0.147***
2012	0.005**	0.016**	0.107***	0.145*
2013	−0.032	0.015*	0.086	0.148**
2014	0.029**	0.131***	0.111***	0.140**
2015	0.010*	0.183***	0.094*	0.174***
2016	0.001*	0.146***	0.083*	0.195**
2017	0.011*	0.211***	0.085***	0.195**
2018	0.040***	0.184***	0.048**	0.190*
2019	0.019**	0.220***	0.082***	0.167**

, **, * indicate significant at the 10%, 5%, and 1% levels respectively.*

TABLE 5 | Basin-wide regression results.

Variable	Model 1	Model 2	Model 3	Model 4
lng	−0.008**	−0.005*	−0.020*	−0.021**
(lng)^2		0.003**	0.000**	0.000*
lnm	0.005	0.003*	0.036	−0.035
lns	0.002*	0.001*	0.002**	0.001*
(lns)^2		−0.011**	−0.005*	−0.005*
lnt	0.014*	0.022*	0.021**	0.022**
Lnt×lng				0.011*
Lnt×lnm				0.005***
Lnt×lns				0.002*
lne	0.030**	0.033	0.035*	0.037*
lnfdi	−0.004	−0.003*	−0.021**	−0.023**
lnd	0.019*	0.021	0.021*	0.024**
lnl	0.009***	0.002**	0.005*	0.005**
lnc	0.000*	0.001**	0.001	0.000*
ρ			0.104*	0.108**
R^2	0.311	0.002	0.005	0.009
σ^2	0.010	0.163	0.103	0.078
N	570	570	570	570

, **, * indicate significant at the 10%, 5%, and 1% levels respectively.*

level of green technology innovation is positive at the 5% significance level, indicating that green technology innovation positively affects command-and-control type environmental regulations. From the standpoint of market-incentive type environmental regulations, not all regression coefficients passed the significance test, indicating that their role was not fully demonstrated throughout the process of green transformation of manufacturing in the Yellow River Basin. The Yellow River Basin has not yet established a complete green trading market with both supply and demand terminals and a comprehensive concept of green production and consumption (Liu et al., 2022). The current market mechanism is inadequate to support the green transformation of the manufacturing sector. The intersection coefficient of market-incentive type environmental regulation and green technology innovation is significantly positive, indicating that green technology innovation and market-incentive type environmental regulation can have a positive effect on the green transformation of the manufacturing sector in the Yellow River Basin; the linear coefficient of public-participation type environmental regulation is significantly positive, and the quadratic coefficient of market-incentive type environmental regulation is significantly negative. Thus, an inverted "U"-shaped relationship exists between the public-participation type environmental regulation and the green transformation of the manufacturing sector in the Yellow River Basin. Meanwhile, its interaction with green technology innovation is significantly positive, signifying that the coordinated development will aid the green transformation of the Yellow River Basin manufacturing sector.

In terms of control variables, the coefficient of the economic development index is significantly positive, indicating that a developed economy can provide a strong guarantee for the transformation of the manufacturing sector. Significantly negative is the foreign investment index. The "Pollution Paradise" hypothesis asserts that developed regions will transfer environmentally unfriendly industries to developing regions *via* investment, which will impede the region's green development due to demonstration and competition effects. The Yellow River Basin has a moderate degree of overall development. When used as a location to receive foreign investment, it will accelerate the development and consumption of natural resources, thereby slowing the rate of green transformation. The coefficient of transportation infrastructure is significantly positive, as comprehensive transportation facilities can facilitate the movement of green resources and factors between regions. The coefficient of the industrial structure is significantly positive, indicating that the advanced and rational development of the industrial structure promotes the green transformation of the manufacturing sector. The rate of urbanization has a positive coefficient. The inevitable consequence of industrialization is urbanization. Continuous urbanization growth will positively affect the manufacturing sector's green transformation process.

Estimation Results and Analysis of Threshold Regression Model

Threshold Effect Test

This article aims to determine whether the level of green technology innovation at different stages will contribute to the

TABLE 6 | Threshold effect result of heterogeneous environmental regulation in the Yellow River Basin.

Type of environmental regulation	Threshold type	RSS	MSE	F value	*p*-value	Critical value		
						10%	5%	1%
Command-and-Control Type	Single	11.418	0.020	6.105**	0.040	4.732	5.840	9.618
	Double	11.311	0.020	7.314**	0.047	5.260	7.139	11.114
	Triple	11.300	0.020	0.561	0.837	4.084	5.452	10.726
Market-Incentive Type	Single	11.236	0.020	15.580**	0.043	13.480	15.00	22.123
	Double	11.318	0.020	11.062*	0.0415	10.481	12.75	23.561
	Triple	11.372	0.020	2.483	0.815	12.267	17.87	24.819
Public-Participation Type	Single	11.133	0.011	21.857**	0.035	10.390	16.47	26.863
	Double	11.014	0.020	6.010	0.245	8.340	11.01	14.541

, **, * indicate significant at the 10%, 5%, and 1% levels respectively.*

TABLE 7 | Threshold effect estimation results of Yellow River Basin government regulation in 2010–2019.

Variable	Command-and control type	Market-incentive type	Public-participation type
Economic Scale	0.000*	–0.036*	0.002*
Foreign Investment	0.000*	0.018	0.023**
Infrastructure	–0.049*	–0.070**	0.012*
Industrial structure	0.062	0.046**	0.017**
Urbanization Rate	0.002*	0.015*	0.008**
$q_i \le r'_1$	–0.002*	0.043	0.000**
$r'_1 \le q_i \le r'_2$	0.001***	0.082**	0.001*
$r'_2 \le q_i \le r'_3$	0.006*	0.040*	
Constant Estimate Value	1.018**	1.15***	0.831**

, **, * indicate significant at the 10%, 5%, and 1% levels respectively.*

heterogeneous environmental regulation affecting the Yellow River and the green transformation of the manufacturing sector, thereby producing a threshold effect. This article refers to Hansen's (1999) threshold effect model design. Green technology innovation serves as a criterion variable for further analysis. We determine the threshold value and the number of thresholds before proceeding. Then, we analyze the triple, double, and single thresholds in succession and test their significance using the bootstrapping technique for 300 times. **Table 6** demonstrates that the command-and-control type of environmental regulation has double thresholds. At the 5% significance level, both the single and double thresholds are significant. The two thresholds are $r'_1 = 0.300$ and $r'_2 = 0.707$; the double thresholds of the market-incentive type environmental regulation are significant at 5 and 10% levels, respectively, with a double threshold value of $r'_1 = 0.381$ and $r'_2 = 0.511$. The single threshold of public-participation type environmental regulation is significant at the 5% level, with a single threshold value of $r'_1 = 0.022$.

Analysis of Threshold Regression Results

The threshold model of heterogeneous environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin is regressed based on the above test results. **Table 7** displays the results.

From the perspective of command-and-control type environmental regulation, when the green technology innovation level is below 0.300, the regulatory effect is significantly negative; when it is between 0.3001 and 0.707, it is significantly positive; and after crossing the double threshold, the effect is significantly enhanced. When the level of innovation in green technology is low, command-and-control type environmental regulation imposes strict restrictions on high-pollution, high-energy consumption, and high-emission businesses through coercive or restrictive government action. Specifically for enterprises that prioritize profit maximization and environmental protection, short-term increases in operating costs and industry barriers will have a negative effect on their green transformation. Long-term, enterprises will gradually transform into clean, energy-saving, and emission-reduction enterprises by enhancing their green technology innovation level and repositioning their development strategies, thereby promoting the overall green transformation and development of the Yellow River Basin's manufacturing sector.

From the perspective of market-incentive type environmental regulation, when the level of green technology innovation is below 0.381, its effect on the green transformation of manufacturing in the Yellow River Basin is negligible. When the level of innovation in green technology is between 0.381 and 0.511, the coefficient is significantly positive and remains so after crossing the double threshold. This demonstrates that when the level of green technology innovation is low, as a result of the absence of relevant supporting conditions and the low level of green innovation, it will inevitably result in a lack of green products on the supply side, rendering market competition and the price mechanism of green products ineffective in

TABLE 8 | Results of robustness test.

Variable	M1	M2
lng	−0.056*	−0.043**
(lng)^2	0.019*	0.013*
lnm	−0.037	0.041*
lns	0.000*	0.005**
(lns)^2	−0.003	−0.074**
lnt	0.000***	0.002**
Lnt×lng	0.053*	0.036*
Lnt×lnm	0.012***	0.043**
Lnt×lns	0.041*	0.001
lne	0.005*	0.053**
lnfdi	−0.013**	−0.006*
lnd	0.052**	0.083**
lnl	0.006*	0.004***
lnc	0.002**	0.011**
ρ	0.185*	0.148*
R^2	0.342	0.009
σ^2	0.206	0.37
N	570	570

driving policy effectiveness. With the continuous advancement of green technology innovation, the green market trading mechanism in the Yellow River Basin has been gradually enhanced, fostering the manufacturing sector's green transformation.

When the level of green technology innovation is less than 0.022, public participation in environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin is significantly positive from the perspective of public-participation type environmental regulation. When the rate of green technology innovation exceeds 0.022, its impact is significantly enhanced. This indicates that public-participation type environmental regulation can catalyze the transformation of manufacturing in the Yellow River Basin. It is because green products will subtly shape the public's pursuit of a green lifestyle and the concept of green consumption in the Yellow River Basin. Through public opinion, propaganda, and other channels, the public will convey its demands for the green transformation of the manufacturing sector. Thus, invisible environmental pressure on governments and businesses promotes the green transformation of the manufacturing sector.

Robustness Test

To ensure the validity of the research's conclusions, **Table 8** displays the results of a robustness test conducted by substituting the relevant variables and the spatial weight matrix. M1 is the regression result obtained by substituting the 0–1 matrix for the geographic distance matrix; based on the research findings of Li et al. (2020) and Zhang et al. (2021), the "three simultaneous" environmental protection investment is used to measure the command-and-control type environmental regulation, while the investment in pollution control is used to measure the market-incentive type environmental regulation, as shown by M2. The robustness test results are consistent with the results of the preceding tests, demonstrating the non-linear relationship between heterogeneous environmental regulation and the green transformation of the manufacturing sector in the Yellow River Basin, as well as the central role of green technology innovation in the process of environmental regulation.

CONCLUSION

This article measures the green transformation level of the manufacturing sector in the Yellow River Basin using the SBM-GML model. The study analyzes the impact mechanism and effect of three diverse environmental regulations on the green transformation of the manufacturing sector in the Yellow River Basin. From 2010 to 2019, the green transformation of the manufacturing sector in the Yellow River Basin rose amid fluctuations, with rapid development momentum, but the sources of driving forces were unbalanced. The trend of changes in GEC from 2010 to 2015 is compatible with GTFP, and the trend of changes of GTC from 2015 to 2019 is compatible with GTFP. From the perspective of the different reaches of the Yellow River Basin, the level of manufacturing transformation decreases from the lower to upper reaches. The analysis reveals that there is a "U"-shaped relationship between command-and-control type environmental regulation and the green transformation of the manufacturing sector in the Yellow River Basin. Due to the lack of a mature green trading market, the impact of public-participation type environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin is negligible. Meanwhile, the impact of market-incentive type environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin indicates an inverted "U"-shaped relationship, signifying that an excessive public intervention can hinder transformation. Innovations in green technology have played a crucial role in regulating the process of environmental regulation in relation to the green transformation of the manufacturing sector in the Yellow River Basin. When innovation in green technology is used as the threshold variable, the impact of command-and-control type environmental regulation on the green transformation of the manufacturing sector will change from negative to positive. The impact of market-incentive type environmental regulation on the green transformation of the manufacturing sector in the Yellow River Basin will shift from negligible to positive. Public-participation type environmental regulation will have a continuous and substantial positive impact on the green transformation of the manufacturing sector.

Recommendations

Based on the above findings, this article makes the following recommendations for the green transformation of the manufacturing sector in the Yellow River Basin.

1) Enhance green technology innovation and green technology transformation effectiveness. The article discovered that technological innovation could directly drive the green transformation of the manufacturing sector in the Yellow River Basin and play a significant role in regulating the effect of environmental regulations on the green transformation of

manufacturing. Therefore, we should maximize the leadership role of innovation and accelerate green scientific and technological innovation accomplishments. It is necessary not only to improve the innovation-driven institutional guarantee, formulate a long-term and effective talent development mechanism, promote the cross-regional flow of innovation resources, and effectively enhance the innovation capabilities of different regions but also to improve the innovation-driven system of the three main bodies "government, industry, and enterprise," deepen industry-university-research cooperation and knowledge sharing among Yellow River Basin members, optimize the market-oriented mode of Yellow River Basin science and technology incubators, and enhance the mechanism for the transformation and transfer of relevant green technological achievements.

2) Standardize the green economy assessment system and establish an intelligent monitoring platform. Long-term, command-and-control type environmental regulations will positively impact the green transformation of the Yellow River Basin's manufacturing sector. A comprehensive investigation should be conducted into the environmental activities and operating conditions of manufacturing enterprises in the Yellow River Basin, and a reasonable and standardized assessment system should be developed, along with dynamic adjustments. Additionally, the government should intensify environmental regulation enforcement, improve the efficiency of environmental regulation enforcement, fully promote the construction of a smart platform for ecological and environmental supervision in the Yellow River Basin, and explore a new path of "Internet + environmental protection," and realize data sharing and real-time monitoring of water, gas, and matter pollution throughout the entire basin.
3) Cultivate the public's understanding of green development and expand the market for green products. Environmental regulations based on market incentives and public participation have a significant impact on transforming the manufacturing sector in the Yellow River Basin. However, policy measures have not yielded the expected results due to the lack of a mature green consumer market. To this end, it is necessary to educate the public on environmental protection in a forward-looking manner, increase national awareness of green conservation, form a new trend of civilized environmental protection, smooth and accelerate the flow of green product sales channels, increase the value of ecological products, and strive to develop a mature and comprehensive green consumer market.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors contributed equally in this study.

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