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Abstract: This study finds that environmental protection inspections (EPI) significantly improve the green total factor productivity (GTFP) of China's A-share heavy polluters, primarily through modest gains in green innovation and compliance behaviour. Using panel data spanning from 2011 to 2019, this study employs the super-slacks-based measure (SBM) model and the Malmquist–Luenberger (ML) index to quantify GTFP, and applies a difference-in-differences (DID) approach to examine the dynamic relationship between EPI and GTFP. The empirical results indicate that EPI exerts a statistically significant and positive effect on GTFP among heavily polluting enterprises, with green technological innovation identified as a key mediating mechanism. Furthermore, regional heterogeneity analysis reveals that the positive impacts of EPI are primarily concentrated in China's eastern and central regions, underscoring the influence of regional economic development levels on the effectiveness of environmental governance.

Keywords: EPI; environmental protection inspections; GTFP; green total factor productivity; heavy polluters; green technological innovation; environmental governance; sustainable economic development.

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1 Introduction

China's economic trajectory since the reform and opening-up era has been marked by rapid and sustained growth, with an average annual GDP increase of 8.1% from 1979 to 2022, reaching 121.02 trillion yuan by 2022 (National Bureau of Statistics). However, this growth has long relied on a resource-intensive and environmentally unsustainable model. In response, the Chinese government has increasingly emphasised the importance of ecological preservation and green development, fostering the parallel pursuit of environmental and economic goals (Ren and Ji, 2021). Key initiatives include the construction of an ecological civilisation framework and the establishment of an Environmental Protection Index system to guide sustainable governance.

Since the 11th Five-Year Plan, environmental performance has been incorporated into official evaluation systems, reinforcing its role in shaping industrial upgrading and economic decision-making (Yu and Wang, 2021; Wu et al., 2020). Despite the progress, decentralisation has led to enforcement asymmetries, with some local governments tolerating non-compliant polluting behaviours. To address these issues, the Central Committee of the Communist Party of China launched a centralised environmental protection inspections (EPI) program in 2016. This initiative empowered independent inspection teams to oversee provincial compliance, mitigate regional protectionism, and enhance the effectiveness of environmental regulation. While existing literature has explored EPI's deterrent and compliance effects, its broader impact on green total factor productivity (GTFP) – a key measure of environmentally adjusted economic performance – remains underexplored. This study aims to fill that gap by evaluating the causal influence of EPI on the GTFP of China's heavy polluters. At the current stage of development, it is imperative to reconcile environmental preservation with economic growth, positioning heavily polluting enterprises as critical actors in the implementation of environmental protection policies (Cai et al., 2020; Zhong et al., 2022). These enterprises are expected to assume significant responsibility in environmental governance as China advances toward high-quality and sustainable economic development.

Research objectives and questions:

Objective 1: To investigate the impact of environmental regulation on economic growth and regional economic disparities in China.

Research Question: In what ways does environmental regulation affect economic growth and the spatial distribution of regional economic disparities across China?

Objective 2: To examine the role of heavily polluting listed enterprises in enforcing environmental protection policies.

Research Question: What contributions do heavily polluting listed enterprises make to regional economic development, and how do they respond to environmental regulatory interventions?

Objective 3: To assess the effectiveness of the EPI system and central inspection teams in mitigating regional protectionism and strengthening the implementation of environmental regulation.

Research Question: How effective are the EPI system and central inspection teams in curbing regional protectionism and enhancing the enforcement of environmental regulations?

By addressing these objectives and research questions, this study seeks to offer comprehensive insights into the evolving relationship between environmental regulation and economic development in China, thereby providing empirical support and strategic guidance for more effective policy design and implementation.

This study investigates the impact of EPI policy on the GTFP of heavily polluting listed enterprises in China, combining theoretical analysis with empirical evaluation. As a key indicator of high-quality economic development, GTFP captures the environmental costs of economic activities, extending beyond traditional productivity metrics. By focusing on listed enterprises, this research empirically assesses the effectiveness of EPI policy in promoting ecological performance, offering theoretical and practical insights for the sustainable transformation of enterprises amid growing environmental pressures.

2   Literature review

Environmental regulation (ER) has long served as a foundational lens for examining the relationship between environmental governance and economic development. However, scholarly views on its economic impact remain divided. The neoclassical school argues that ER increases production costs, thereby imposing financial burdens that inhibit enterprise growth – an effect known as the cost crowding-out effect (Barbera and McConnell, 1990). In contrast, Porter's hypothesis suggests that under appropriate ER intensity, firms may reduce costs by improving efficiency and investing in innovation – referred to as the innovation compensation effect (Porter and van der Linde, 1995). Reasonable regulatory pressure may thus stimulate R&D investment, enabling enterprises to meet future standards while enhancing competitiveness.

Although the framework by Barbera and McConnell (1990) remains influential, it is based on dated assumptions that may not fully capture the complexity of modern industrial dynamics. Porter and van der Linde (1995) offer a compelling counterpoint, but the presumed direct causality between ER and innovation still requires robust empirical validation. The relative strength of these opposing effects determines firm behaviour: when the innovation compensation effect outweighs regulatory costs, firms are likely to upgrade technologically; otherwise, they may cut production or relocate high-pollution operations.

As a stringent and centrally administered form of ER, EPI has proven effective in curbing the relocation of polluting industries. Zhang et al. (2020) employed comprehensive panel data analysis, enhancing the credibility of their conclusions.

However, the study's regional scope limits its generalisability. Notably, this study focuses on listed enterprises, which typically possess greater resilience. Despite the financial constraints imposed by EPI, such enterprises often adopt long-term green development strategies. These strategies may, in turn, positively influence GTFP, suggesting that EPI could act as a catalyst for sustainable transformation.

Based on the above theoretical framework, this study proposes the following hypothesis:

H1: EPI has a positive effect on the GTFP of heavy polluters.

At the macro level, existing research consistently highlights that well-designed ER implemented by governments can positively influence economic development. Strict enforcement of environmental standards serves as a strategic mechanism, guiding firms toward the adoption of environmentally friendly technologies and promoting innovation (Shao et al., 2020). Ahmad et al. (2023) provide empirical support through multi-layer regression analysis; however, the limited geographic scope of their study constrains the generalisability of their findings.

At the micro level, ER can stimulate firms – especially small and medium-sized enterprises – to identify opportunities for profit maximisation through technological innovation. By combining market-based mechanisms with rational regulatory frameworks, the government can guide enterprises toward environmental compliance while maintaining economic viability. The implementation of the EPI compels firms to intensify pollution control efforts, thereby increasing operating costs. Compliance with EPI mandates often requires investment in pollution abatement technologies or payment of sewage treatment fees, which can reduce returns. For many firms, particularly those with constrained capital resources, such expenditures crowd out investment in core production activities (Ing and Nicolaï, 2020; Zhang, 2021). While both studies provide valuable insights, their reliance on self-reported data introduces potential concerns regarding objectivity and measurement accuracy. Smaller enterprises, in particular, bear disproportionate burdens due to limited financial flexibility, exacerbating their operational challenges under EPI.

Unlike other forms of ER, EPI entails centralised oversight and post-inspection reevaluation by provincial authorities, compelling enterprises to formulate long-term strategic responses. This often involves increased investment in R&D to upgrade pollution control equipment and develop advanced environmental protection technologies. In recent years, the tightening of industrial regulatory standards has further amplified policy incentives, driving firms to enhance their technological capabilities and improve production processes to meet emission targets (Du and Li, 2020; Zhu et al., 2019; Sun et al., 2021). Li et al. (2023) employed advanced econometric methods to validate their findings, though future research could be strengthened through cross-validation with external datasets to improve robustness. Government subsidies targeting clean technologies and high energy-efficiency enterprises have also played a role in reducing costs and improving competitiveness. Additionally, the rise of environmental awareness among consumers has enhanced the reputation and market performance of eco-friendly firms.

Technological advancement thus exerts a dual effect: it not only facilitates pollution reduction and tax incentives but also enhances production efficiency and competitiveness (Xie et al., 2019; Safitri et al., 2020). Su et al. (2024) offer compelling empirical evidence in support of these dynamics; however, their analysis primarily captures short-term

effects, leaving long-term impacts underexplored. In this study, the focus is placed on listed enterprises, which are typically characterised by sound financial standing and strategic foresight. As such, despite the regulatory pressures imposed by EPI, these firms demonstrate strong capacity and motivation to pursue green innovation, ultimately contributing to improvements in GTFP.

The formulation of Hypotheses H1 and H2 is grounded in the Porter Hypothesis and institutional theory. Specifically, EPI imposes regulatory pressure that compels firms to reallocate resources toward compliance and adaptation. This regulatory stress catalyses internal reconfiguration, including increased investment in R&D and adoption of green technologies. Under EPI's centrally imposed and high-authority framework, firms – especially in regions with developed innovation infrastructure – are incentivised not merely to comply but to innovate for long-term competitiveness. Consequently, EPI not only curbs environmental externalities but also initiates an innovation-driven productivity shift, thereby enhancing GTFP. This logic forms the foundation of the following hypothesis:

H2: EPI will stimulate GTFP for heavy polluters by fostering green innovation.

Compared with prior works such as Zhang et al. (2020) and Cai et al. (2020), this study extends the analytical frontier by integrating the Super-SBM model with the Malmquist-Luenberger index to obtain a dynamic, enterprise-level evaluation of GTFP, while simultaneously leveraging the policy discontinuity captured by the difference-in-differences (DID) model. This dual-model design not only strengthens causal inference but also enables a finer-grained exploration of policy impact across space and time. Moreover, the paper innovatively situates EPI within the context of green innovation mechanisms and regional heterogeneity, offering a comprehensive framework to unpack the spatial variance in environmental regulation effectiveness – a dimension often overlooked in previous city- or province-level studies. Thus, the originality of this research lies in its methodological fusion and its focus on dynamic enterprise behaviour under regulatory shock.

3   Methodology

This study employs the DID approach to rigorously assess the impact of EPI as an exogenous policy shock. As a widely recognised empirical strategy in economic research (Bergemann et al., 2009), DID has undergone substantial refinement over the past two decades and has become a primary tool for evaluating policy effects in the Chinese context. The selection of DID in this study offers several methodological advantages. It provides a clear and tractable framework for estimating causal effects, effectively controlling for time-invariant unobserved heterogeneity between treated and control groups. Moreover, the simplicity and interpretability of the DID model are well aligned with the objective of this paper – namely, to evaluate the influence of EPI on the GTFP of heavily polluting enterprises.

3.1   DID model

In this study, the DID approach is employed to estimate the causal effect of EPI policy implementation on GTFP among heavily polluting enterprises. The core of the DID

model involves interacting a time dummy variable – representing the period after EPI enforcement – with a treatment dummy variable that identifies enterprises located in provinces targeted by EPI teams and belonging to the heavy-pollution sector. This interaction term isolates the average treatment effect, allowing for an effective identification of policy impact.

DID offers several methodological advantages. First, it provides improved control over endogeneity concerns compared to alternative econometric approaches by differencing out time-invariant unobserved heterogeneity. Second, the use of micro-level panel data enables the incorporation of both entity-fixed effects and time-fixed effects, controlling for unobserved firm-level characteristics and common temporal shocks, thereby enhancing the accuracy and internal validity of the estimates.

To implement the DID strategy, treatment and control groups must be clearly defined. The treatment group consists of heavily polluting enterprises in provinces subjected to EPI interventions, while the control group includes comparable enterprises in regions not yet covered by EPI. The baseline DID model includes the outcome variable (GTFP), the treatment indicator, a post-policy indicator, their interaction term, control variables, and fixed effects for entities and time periods.

A critical assumption underpinning the DID methodology is the parallel trends assumption, which posits that, in the absence of treatment, the treated and control groups would have followed similar trends in the outcome variable. Ensuring the validity of this assumption is essential for causal interpretation. To reinforce robustness, additional sensitivity analyses are conducted, including the incorporation of alternative model specifications, control variables, and robustness checks.

By systematically applying this framework, the study provides rigorous empirical evidence on the dynamic relationship between EPI and GTFP, offering insights into the broader economic and environmental implications of policy-driven environmental regulation.

Based on the above analysis, this paper constructs the DID model, as shown in equation (1):

$$GTFP_{it} = \beta_0 + \beta_1 Year_t \times Treat_i + \beta_2 X_{it} + \delta_i + \delta_t + \delta_c + \varepsilon_{it} \tag{1}$$

where i denotes the firm, t denotes the year, and c denotes the province. The explanatory variable $GTFP_{it}$ represents the GTFP of firm i in year t, while $Year_t \times Treat_i$ is a dummy variable for the cross-multiplier of the EPI shock and whether it is a heavy polluting enterprise, which is the core explanatory variable of this paper, and β_1 represents the causal impact effect of the EPI policy on the GTFP of heavy-polluting enterprises. δ_i, δ_t and δ_c denote firm, year, and province fixed effects, respectively. X_{itc} is the control variable ensemble, including firm-level control variables and province-level control variables.

One concern regarding the validity of the DID design is the potential endogeneity in the assignment of EPI across provinces. Although the central government ostensibly deployed inspection teams in a staggered and systematic manner, it is conceivable that the timing of inspections may correlate with unobserved regional or firm-level characteristics – such as political salience, environmental urgency, or industrial lobbying – that also influence GTFP. To mitigate this concern, we exploit the quasi-randomness of EPI rollout, where inspection rounds were centrally determined rather than locally requested, minimising selection bias. Furthermore, our empirical strategy incorporates

firm, year, and province fixed effects, which effectively absorb time-invariant unobserved heterogeneity and common shocks. We also conduct robustness checks using placebo tests and region-year trends, which confirm the absence of systematic pre-treatment divergences between treatment and control groups.

3.2   Slacks-based measure model

Most existing studies measure GTFP at the city or regional level, often overlooking firm-level heterogeneity. To address this gap, this paper innovatively combines the undesirable-output slacks-based measure (SBM) model with the super-efficiency data envelopment analysis (DEA) framework to evaluate GTFP at the enterprise level. This integrated model captures the influence of input resources, desirable outputs, and undesirable outputs (e.g., emissions), thereby providing a more holistic assessment of an enterprise's green development status.

The inclusion of the super-efficiency extension allows for the differentiation of decision-making units (DMUs) that would otherwise share an efficiency score of 1 in conventional DEA models, thereby improving the model's discriminative capability.

The specific steps for GTFP measurement using the SBM-super-efficiency model are as follows:

Firstly, it is assumed that the production system has n decision-making units (DMUs). In the measurements of this paper, a single firm acts as a production DMU $\left(DMU_j, j = 1, 2, \ldots, n \right)$. Each DMU is characterised by three sets of variables: inputs x, desired outputs y, and undesired outputs z. Specifically, each DMU utilises m input factors $x \in \mathbb{R}^m$, produces q desirable outputs $y \in \mathbb{R}^q$, and generates p undesirable outputs $z \in \mathbb{R}^p$.

The formal specification of the model is presented in equations (2) and (3):

$$\rho = \frac{1 + 1/m \sum_{i=1}^{m} s_i^- / x_{ik}}{1 - \frac{1}{q+p} \left(\sum_{r=1}^{q} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{p} \frac{s_t^{z^-}}{z_{rk}} \right)} \tag{2}$$

$$s.t. \begin{cases} \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1, j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \geq y_{rk} \\ \sum_{j=1, j\neq k}^{n} b_{tj}\lambda_j - s_t^{z^-} \leq z_{tk} \\ \lambda \geq 0, s_i^- \geq 0, s_r^+ \geq 0, s_t^{z^-} \geq 0 \end{cases} \tag{3}$$

where $i \in [1, m], r \in [1, q], t \in [1, p], j \in [1, n]$, $s_i^-, s_r^+, s_t^{z^-}$ denote the relaxation vectors representing the non-radial input factors, desired outputs, and non-desired outputs, respectively, and λ is the weight vector of the input factors. The directional distance function obtained by linear programming solution can be expressed by equation (4):

$$\vec{D}_0^t \left(x^t, y^t, z^t; y^t, -z^t \right) \tag{4}$$

The estimation outcomes derived from the SBM model signify the proximity of a decision-making unit's production technology to the frontier of similar product types within a specified timeframe. However, the measured GTFP remains static, diverging from the dynamic nature of enterprises' production processes, where technology continuously evolves amid ongoing production.

This paper draws from (Oh and Heshmati, 2010) and introduces the dynamic ML index as follows:

$$ML_t^{t+1} = \left[\frac{1 + \vec{D}_0^t(x^t, y^t, z^t; y^t, -z^t)}{1 + \vec{D}_0^t(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})} \times \frac{1 + \vec{D}_0^{t+1}(x^t, y^t, z^t; y^t, -z^t)}{1 + \vec{D}_0^{t+1}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})} \right]^{1/2} \quad (5)$$

Where the ML index can be further decomposed into changes in Efficiency Change Index (EC) and Technological Change Index (TC) and with $ML_t^{t+1} = TC_t^{t+1} \times EC_t^{t+1}$, EC and TC are calculated as follows:

$$EC_t^{t+1} = \frac{1 + \vec{D}_0^t(x^t, y^t, z^t; y^t, -z^t)}{1 + D^{t+1}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})} \quad (6)$$

$$TC_t^{t+1} = \left[\frac{1 + \vec{D}_0^t(x^t, y^t, z^t; y^t, -z^t)}{1 + \vec{D}_0^{t+1}(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})} \times \frac{1 + \vec{D}_0^t(x^{t+1}, y^{t+1}, z^{t+1})}{1 + \vec{D}_0^t(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})} \right]^{1/2} \quad (7)$$

where $\vec{D}_0^t$ and $\vec{D}_0^{t+1}$ denote the directional distance functions of a DMU in periods t and $t+1$, respectively, as measured using the SBM model with reference to the production frontier technology. These functions capture the distance of a DMU from the efficient production frontier while considering both desirable and undesirable outputs. TC reflects the rate of technological progress and quantifies the shift of the production possibility frontier between two periods. A value of $TC > 1$ indicates outward movement of the frontier in the direction of increased desirable output, implying technological improvement. EC captures changes in a DMU's relative efficiency over time, representing the degree of convergence or divergence of the DMU from the frontier. In essence, EC measures whether a DMU moves closer to or further from the production frontier, holding the frontier itself constant.

3.3   Description of indicators

To evaluate enterprise-level GTFP, this study incorporates input factors, desirable outputs, and undesirable outputs:

Inputs: Net fixed assets represent capital input, and the number of employees denotes labour input, following established literature.

Desirable output: Primary business income is used to capture expected output. All monetary values are deflated using the city-level consumer price index (CPI), with 2011 as the base year, to eliminate the effect of inflation.

Undesirable Outputs: Emissions of industrial wastewater, waste gas, and soot are selected as key indicators of environmental pollution, reflecting the enterprise's non-desired outputs.

The core explanatory variables in this paper are dummy variables, i.e., the cross-multipliers of whether or not they have suffered an EPI shock and whether or not they are heavy polluters ($Post_t \times Treat_i$), where $Post_t$ indicates the year of the impact of the EPI. If the enterprise suffered the EPI in that year, then take the value of 1; otherwise, take the value of 0; $Treat_i$ is a group dummy variable, i.e., the enterprises in the sample are located in the heavy pollution industry and take the value of 1; otherwise, it takes the value of 0.

To ensure robust estimation, this study includes a comprehensive set of firm-level and region-level control variables, each selected based on its theoretical relevance to GTFP. Firm size (*size*) reflects economies of scale, diversification capacity, and access to financing, all of which can enhance a firm's ability to invest in environmental technologies. Firm age (*age*) captures the accumulation of managerial experience and technological capabilities that support operational efficiency and regulatory adaptability. Leverage ratio (*LEV*) represents financial constraints; higher debt levels may limit firms' willingness or ability to undertake environmentally oriented investments. Fixed asset ratio (*FR*) indicates the degree of capital intensity and potential long-term commitment to asset upgrading, which can facilitate cleaner production processes. Institutional investor shareholding (*INST*) serves as a proxy for external governance pressure, as institutional investors often advocate for sustainable corporate practices. At the regional level, GDP per capita (*lngdp*) reflects the local economic development stage, while openness (*open*) captures exposure to global environmental standards and trade-driven regulatory pressures. Together, these variables help isolate the net effect of EPI on GTFP by accounting for firm heterogeneity and regional policy environments. The variables selected in this paper and their measurement methods are shown in Table 1.

Table 1   Variable definition

Variable type	Variable name	Symbol	Variable definition
Dependent variable	Green total factor productivity	*GTFP*	Calculated using the method described above
Core explanatory variable	Policy interaction term	*Post × Treat*	Interaction of group variable and policy time variable
Province control variables	Regional productivity level	*lngdp*	Natural logarithm of regional GDP
	Degree of opening to foreign investment	*open*	Natural logarithm of foreign direct investment
Enterprise control variables	Enterprise size	*size*	Natural logarithm of total assets
	Enterprise age	*age*	ln(current year – year of establishment + 1)
	Enterprise leverage ratio	*LEV*	Total liabilities at year-end/Total assets at year-end
	Fixed asset ratio	*FR*	End-of-period fixed assets/End-of-period total assets
	Institutional investor holding ratio	*INST*	Number of shares held by institutional investors/Total shares outstanding

The provincial-level data utilised in this study are sourced from the China Statistical Yearbook and the National Bureau of Statistics' official website in previous years. Concurrently, data regarding listed companies are retrieved from the Cathay Pacific CSMER database.

4 Empirical analysis

The primary objective is to determine whether the GTFP trajectories of treatment and control groups – namely, heavy and non-heavy polluters – exhibited parallel trends prior to the implementation of the EPI policy. To ensure the robustness of the DID estimation, a parallel trends test is conducted to confirm that the observed effects can be attributed to the EPI intervention rather than to confounding factors. The empirical analysis is structured around three components: a benchmark regression to estimate the baseline effect, a mechanism analysis to explore underlying transmission channels, and a heterogeneity analysis to identify differential impacts across subgroups.

4.1 Benchmark regression analysis

Although parallel trend tests are typically visualised using trend charts, such graphical approaches yield coarse and imprecise results when applied to provincial-level policy shocks, as in this study. These charts often fail to capture the statistical significance required to rigorously validate policy effects. To address this limitation, the tvdiff command is employed to formally test for parallel trends between the treatment and control groups before and after the implementation of the EPI policy. The empirical results report an individual trend F-value of 0.341 ($p > F = 0.676$) and a time trend F-value of 0.229 ($p > F = 0.703$), thereby confirming the absence of significant pre-treatment differences and supporting the validity of the DID estimation strategy.

The results of the benchmark regression are summarised in Table 2, which presents four specifications. Column (1) omits control variables and fixed effects; Column (2) includes control variables but excludes province fixed effects; Column (3) excludes control variables while incorporating year, firm, and province fixed effects; and Column (4) includes both control variables and all fixed effects. Across all specifications, the coefficient of the interaction term *Post × Treat* is consistently positive and statistically significant at the 1% level. This finding suggests that the EPI policy significantly enhances the GTFP of heavily polluting enterprises, thereby providing robust empirical support for Research Hypothesis 1 proposed in the theoretical framework of this study.

4.2 Mechanism analysis

This paper adopts the mediation effect model to verify the mechanism effect played by enterprise green technology innovation in the impact of EPI on GTFP of heavy-polluting enterprises. Equations (8) and (9) shows the mediation effect test mode.

$$GI_{it} = \beta_0 + \beta_1 Year_t \times Treat_i + \beta_2 X_{it} + \delta_i + \delta_t + \delta_c + \varepsilon_{it} \tag{8}$$

$$GTFP_{it} = \beta_0 + \beta_1 Year_t \times Treat_i + \beta_2 GI_{it} + \beta_3 X_{it} + \delta_i + \delta_t + \delta_c + \varepsilon_{it} \tag{9}$$

where GI_{it} denotes the level of green innovation of enterprises. This paper uses the number of green patent applications as a proxy for green innovation, and the regression results are reported in Table 3. The results confirm that the EPI significantly promotes green innovation activities among heavy polluters, thereby enhancing GTFP. These findings provide robust support for Hypothesis 2.

Table 2   Benchmark regression results of EPI on GTFP (DID estimation)

Variant	Model (1)	Model (2)	Model (3)	Model (4)
Post×Treat	0.212***	0.192***	0.074***	0.076***
	(0.038)	(0.041)	(0.005)	(0.003)
Size		0.023***		0.044***
		(0.0)		(0.0148)
age		0.064***		0.083***
		(0.010)		(0.106)
LEV		−0.096***		−0.087***
		(0.011)		(0.018)
FR		0.105		0.108
		(0.113)		(0.121)
INST		0.014		0.010
		(0.095)		(0.084)
lngdp		0.012***		0.020***
		(0.000)		(0.000)
open		0.007**		0.007**
		(0.003)		(0.003)
Year fixed	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES
Province fixed	NO	NO	YES	YES
Constant term	1.023***	0.851*	1.100***	0.864**
	(0.020)	(0.435)	(0.049)	(0.340)
Observed value	8046	8046	8046	8046
R^2	0.058	0.063	0.079	0.084

***, **, and * indicate that they have passed the significance test of 1%, 5%, and 10%. The value of *t* is in brackets. R2 represents the fit coefficient of the model.

Although the estimated coefficient of the mediation path via green innovation is statistically significant, its magnitude (0.006) is relatively small, suggesting a modest short-term effect. However, such a result may reflect the structural characteristics of green innovation itself – typically marked by long development cycles, high sunk costs, and delayed output realisation. The cumulative and compounding nature of green R&D implies that even marginal improvements today can translate into substantial GTFP gains over extended horizons. Moreover, the observed weak mediation may signal that

innovation is not the sole channel – compliance-based investment, process optimisation, or external stakeholder pressures may concurrently shape GTFP outcomes. These findings suggest the need for expanded mechanism testing, potentially incorporating dynamic panel models or lag-structured mediation analysis to better capture innovation's delayed productivity effects.

Table 3 Results of the mechanism test

Variant	Model (1)	Model (2)	Model (3)
Post×Treat	0.076***	0.006***	0.063
	(0.003)	(0.000)	(0.003)
	(0.038)	(0.041)	(0.005)
GI			0.036***
Control variable	YES	YES	YES
Year fixed	YES	YES	YES
Enterprise fixed	YES	YES	YES
Province fixed	YES	YES	YES
Constant term	0.464**	1.343***	0.557***
	(0.050)	(0.102)	(0.200)
Observed value	8046	8046	8046
R^2	0.084	0.331	0.360

While the number of green patent applications provides a direct and quantifiable proxy for green innovation, this measure may not fully capture the breadth of innovation activities within enterprises. Alternative or complementary indicators, such as firm-level green R&D expenditures, adoption rates of clean technologies, or collaborative innovation metrics, could yield a more nuanced representation.

4.3 Heterogeneity analysis

China's long-standing issue of unbalanced and insufficient regional development can be largely attributed to its historically stratified development strategy. This approach involved differentiated policy orientations across regions and was further exacerbated by substantial disparities in natural conditions – such as geographic location and resource endowments. Notably, the earlier onset of industrialisation in northern regions has led to relatively higher levels of environmental pollution. As a result, enterprises across different regions find themselves at varying stages in the transition toward a green economy.

Based on this context, the paper posits that the impact of the EPI on the GTFP of heavy-polluting enterprises is heterogeneous across provinces. To empirically examine this hypothesis, the sample is divided into three geographic regions: East, Central, and West. The model is then restructured to capture potential regional variations in the policy effect.

$$GTFP_{it} = \beta_0 + \beta_1 Year_t \times Treat_i \times zone_{it} + \beta_2 X_{it} + \delta_i + \delta_t + \delta_c + \varepsilon_{it} \qquad (10)$$

where $zone_{it}$ is a dummy variable for province region, which in this paper denotes eastern, central, and western provinces, respectively, and the variable zone is multiplied with $Post \times Treat$ to construct the interaction term and the regression results of the regional heterogeneity analyses based on the above model are shown in Table 4.

Table 4   Results of regional heterogeneity

Variant	Model (1) Eastern part	Model (2) Central region	Model (3) Western region
$Post \times Treat$	0.052***	0.035***	0.067
	(0.013)	(0.011)	(0.063)
Control variable	YES	YES	YES
Year fixed	YES	YES	YES
Enterprise fixed	YES	YES	YES
Province fixed	YES	YES	YES
Constant term	0.947***	0.663***	0.438***
	(0.105)	(0.133)	(0.107)
Observed value	4028	2746	1272
R^2	0.254	0.243	0.104

As shown in Table 4, the EPI policy exerts a significantly positive effect on the GTFP of heavy-polluting enterprises located in the eastern and central regions. These regions benefit from stronger innovation capacity, more developed infrastructure, and higher levels of economic development, all of which facilitate the effective implementation of environmental regulations and enhance firms' green productivity. In contrast, the western region – characterised by relatively weaker economic foundations, limited technological innovation capacity, and lower public awareness of environmental protection – exhibits no significant improvement in GTFP following the EPI. Moreover, the more severe pollution conditions and weaker enforcement incentives in this region limit the effectiveness of the policy in promoting green development.

In addition, this paper explores the heterogeneity of EPI effects across different ownership structures. Generally, state-owned enterprises are more responsive to national policy directives, including EPI mandates, and are more inclined to invest in improving environmental performance, which contributes to higher GTFP. In contrast, non-state-owned enterprise, driven primarily by profit maximisation, tend to face weaker pressure to fulfil environmental responsibilities. Table 5 presents the results of the ownership heterogeneity analysis. The findings indicate that the EPI has a significantly greater positive impact on the GTFP of SOEs compared to non-SOEs, thereby supporting the notion that ownership structure influences firms' environmental responses.

Table 5   Results of property rights heterogeneity

Variant	State-owned enterprises	Non-state-owned enterprises
	GTFP	GTFP
Post×Treat	0.037***	0.011***
	(0.010)	(0.001)
Year fixed	YES	YES
Enterprise fixed	YES	YES
Province fixed	YES	YES
Constant term	YES	YES
Constant term	2.334***	1.776*
	(0.398)	(0.108)
Observed value	4598	3448
R^2	0.198	0.301

5   Discussion

This study provides important empirical insights into the impact of EPI on GTFP across different regions in China, integrating primary data analysis with findings from existing literature. Through the application of benchmark regression, mechanism exploration, and heterogeneity analysis, the results reveal pronounced regional disparities. Specifically, enterprises in the eastern and central regions – characterised by advanced infrastructure and higher levels of economic development – exhibit substantial improvements in GTFP following the EPI. In contrast, firms in the western region face constraints such as geographic isolation, lower economic capacity, and weaker innovation ecosystems, which collectively hinder the policy's effectiveness.

Compared with prior studies, this research advances the understanding of environmental policy impacts in several respects. First, it clarifies the role of regional economic contexts in shaping the efficacy of regulatory interventions, illustrating that the success of policies like EPI is contingent upon localised conditions such as infrastructure quality and innovation capacity. Second, it uncovers notable differences in policy responsiveness based on ownership structure, with state-owned enterprises demonstrating stronger alignment with sustainability goals and more proactive adaptation to environmental mandates than their non-state-owned counterparts. These findings underscore the importance of tailoring environmental policy implementation to regional and institutional heterogeneity.

The practical implications for policymakers and corporate sustainability strategies are significant. While the continuation of EPI across regions is essential, its implementation must be refined to account for regional disparities in institutional capacity and responsiveness. In particular, adapting EPI for less responsive regions – such as western provinces – requires a shift from uniform enforcement to differentiated, incentive-compatible mechanisms. First, fiscal instruments such as green transformation subsidies, targeted tax credits, and pollution abatement co-financing schemes can alleviate financial burdens on firms undertaking environmental upgrades. Second, performance-based inspection incentives should be introduced for local governments, linking inspection

outcomes to regional fiscal transfers or administrative evaluations. Third, inspection teams should adopt tiered enforcement protocols – combining mandatory compliance audits with technical guidance and capacity-building initiatives – especially in regions with limited green technology infrastructure.

At the national level, EPI's scope should be expanded to integrate dynamic environmental performance metrics and data-driven early warning systems, enabling proactive rather than reactive inspections. Furthermore, region-specific green technology demonstration zones could serve as innovation incubators, leveraging existing capabilities in the East and Central regions to diffuse sustainable practices westward.

For corporate actors, particularly in pollution-intensive sectors, aligning investment strategies with emerging environmental regulatory standards is essential. Firms can mitigate regulatory risks and enhance GTFP by investing in clean production systems, strengthening environmental disclosures, and participating in industry–university–research consortia that accelerate green innovation. Understanding spatial differences in regulatory stringency also enables firms to tailor compliance strategies and optimise the deployment of environmental capital across geographic operations.

6   Conclusions

6.1   Theoretical implications

This study employs panel data from 2011 to 2019, utilising SBM model and the ML index to investigate the relationship between the EPI policy and GTFP among heavily polluting enterprises. It addresses a significant gap in the literature by empirically demonstrating that EPI exerts a substantial positive influence on GTFP, particularly through the channel of green technological innovation. The benchmark regression results provide robust evidence of this effect, underscoring the practical significance of environmental regulation in driving sustainable corporate transformation. Mechanism analysis further reveals that EPI incentivises green innovation, which in turn enhances GTFP – thereby establishing a theoretical foundation for understanding how environmental policies catalyse technological upgrading in environmentally intensive industries.

6.2   Managerial and policy implications

The findings of this study highlight the importance of sustained enforcement of EPI and increased institutional support for green innovation. To maximise policy effectiveness, it is imperative that environmental regulatory strategies account for regional heterogeneity in economic development, innovation capacity, and environmental awareness. Policymakers are encouraged to design differentiated regulatory frameworks that adapt to local conditions, while enterprises should proactively align their strategies with national sustainability goals. Enhanced coordination between governmental bodies and firms can facilitate more effective implementation of green transition initiatives and optimise policy outcomes across diverse regions.

6.3 Future research directions

Future research could extend the analysis by examining the long-term impact of EPI on GTFP and its broader implications for green economic transformation. In particular, further investigation is warranted into the micro-mechanisms through which EPI fosters innovation – such as R&D investment, inter-firm technology spillovers, and policy-driven knowledge transfer. Comparative studies across multiple regulatory regimes and industrial sectors would enhance the generalisability of the findings. Additionally, exploring the roles of stakeholder engagement, environmental governance, and corporate social responsibility in reinforcing the effectiveness of EPI would contribute to the development of more holistic and sustainable environmental policy frameworks.

Conflicts of interest

All authors declare that they have no conflicts of interest.

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