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Research on the impact of environmental regulation on high-quality economic development

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Abstract

This study investigates how environmental regulation (envir) affects high-quality economic development using panel data from 278 Chinese prefecture-level cities over 2005–2023. Unlike prior work, this paper quantitatively compares three mediating pathways, green technological innovation (GTI), industrial structure rationalization (ISR), and industrial structure upgrading (ISU), within a unified mediation framework. The results show that envir's impact operates almost entirely through indirect channels. GTI acts as a crucial mediator, transmitting 91.7% of the total effect, making it the strongest and most policy-responsive pathway. ISR functions at 61.3% transmission, while ISU operates at only 18.9% transmission. Regional heterogeneity corresponds to the marginal regulatory effectiveness gradient. The positive effect is strongest in the western region, insignificant in the central region, and negative (though not significant) in the eastern region. Policy implications are that environmental policies should prioritize green innovation incentives, complemented by structural rationalization, while adopting region-specific stringency levels to avoid diminishing returns.

Keywords: Environmental regulation; High-quality economic development; Green technological innovation; Rationalization of industrial structure

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1. Introduction

1.1. Research background

China has shifted from rapid growth to high-quality economic development (EDHI). Historically, the policy focus was on gross domestic product (GDP) growth, fixed investment, and industrial expansion. Today, pollution, resource constraints, and innovation bottlenecks are compelling an economic transformation. Recent findings show that ecological security and economic resilience are closely intertwined.[1] Environmental regulations (envirs) are the key driver, propelling cities from "pollution zones" to "green growth poles." However, the mechanisms through which environmental policies achieve effectiveness remain underexplored.

The Porter hypothesis states that envir drives innovation, for example, enterprises increase green research and development (R & D), leading to more patents and higher

efficiency.[2] Some studies emphasize that industrial transformation is more direct: environmental protection reduces heavy industry and boosts the service sector, yielding quicker results.

Despite extensive research, a critical gap remains: the existing literature rarely compares the relative importance of different transmission pathways within a unified empirical framework. Most studies examine only one mediator in isolation, such as green technological innovation (GTI), industrial structure rationalization (ISR), or industrial structure upgrading (ISU). Consequently, policymakers lack a clear ranking of which mechanism contributes most to the transformation of envir into high-quality development.

1.2. Research objectives

This study answers the following research questions: (i) Do GTI, ISR, and ISU act as significant mediating pathways through which envir affects EDHI? (ii) What is the magnitude of the mediating effect of each pathway, and how do they rank in terms of their contribution to EDHI? Which mechanism is the most deserving of policy priority? (iii) How do these mediating effects vary across China's eastern, central, and western regions?

1.3. Research innovation

This study directly addresses that gap by making two core innovations. First, it quantitatively compares the transmission intensity of all three pathways (GTI, ISR and ISU) using the same dataset and methodology. Second, it employs a novel, policy-oriented measure of green innovation, the number of green patent applications per 10,000 residents, which is more precise and globally standardized than traditional R&D or total patent counts.

2. Literature review

A substantial body of empirical research has examined the relationship between envir and economic performance. The Porter hypothesis posits that well-designed environmental standards can trigger innovation offsets that partially or fully compensate for compliance costs, thereby enhancing competitiveness.[2] Consistent with this view, many studies report a positive direct effect of envir on economic quality.[3,4] However, the empirical evidence is far from unanimous. Several studies find null or even negative effects, particularly when regulations are poorly designed or enforced.[5] Why do such contradictions emerge? Three reasons stand out. First, most studies aggregate regulations into a single index, ignoring the fact that different policy instruments (command-and-control versus market-based) have heterogeneous effects. Second, the time horizon matters: innovation offsets typically take several years to materialize, whereas compliance costs appear immediately. Third, prior research often fails to distinguish between direct and indirect effects, specifically, whether envir influences economic outcomes through mediating mechanisms such as green innovation or structural adjustment.

Accordingly, the following hypotheses are proposed in this paper:

(i) Hypothesis 1: Envir has a significant positive direct effect on EDHI.

Industrial structure is widely regarded as a key driver of high-quality development.[6] The shifts in the composition of the economy improve resource allocation efficiency, reduce pollution intensity, and raise productivity.[7–9] Two distinct dimensions of structural change are often distinguished: ISR and ISU (which refers to the increasing share of high-value-added, knowledge-intensive sectors).

Theoretically, envir can accelerate both processes. By raising the cost of polluting activities, envir forces the exit of inefficient, high-emission firms (which improves ISR) and incentivizes reallocation of resources towards cleaner, more technologically advanced industries (which promotes ISU).

Yet empirical evidence on these mediating roles is strikingly inconsistent. Some studies find that ISU fully mediates the effect of envir on EDHI, suggesting that structural upgrading is the primary pathway.[7] Others report only partial or no mediation.[8,9] This paper identifies two sources for the divergence. First, many studies use crude measures of industrial structure,[10–12] such as the simple ratio of tertiary to secondary output,[13–16] which conflates quantity with quality. Second, few studies simultaneously test ISR and ISU within the same model.

This study addresses these gaps by testing both ISR and ISU in parallel, using refined indicators, and comparing their mediation magnitudes.

(ii) Hypothesis 2: Industrial structure mediates the relationship between Envir and EDHI. Specifically, ISR positively transmits the effect. ISU also positively mediates this relationship, albeit with a weaker effect than ISR.

Unlike structural adjustment, which often requires long-term reallocation of capital and labor, green innovation can produce more immediate and direct efficiency gains. Moreover, innovation is less likely to suffer from the "hollowing out" problem that sometimes accompanies rapid industrial upgrading (e.g., premature deindustrialization).

For these reasons, the Porter hypothesis is most directly operationalized through the innovation channel.

But, some studies find that GTI only partially mediates the envir–EDHI relationship, leaving room for direct effects or other mechanisms.[17] Others report that GTI plays a full mediating role, implying that without green innovation, envir would have no net economic benefit.[18,19] What explains these discrepancies? Measurement matters critically. Studies using R & D expenditure or total patents, which include non-environmental innovations, tend to find weaker or partial mediation because these measures are noisy. By contrast, studies using green patents (i.e., patents explicitly classified as environmentally friendly) yield stronger and more consistent evidence of mediation.

(iii) Hypothesis 3: GTI positively mediates the effect of envir on EDHI.

This hypothesis is grounded in the Porter hypothesis, which posits that well-designed environmental regulations can stimulate innovation. Specifically, stringent environmental policies increase compliance costs for polluting firms, forcing them to invest in GTI to offset these costs. These innovations, in turn, improve resource efficiency and reduce environmental degradation, thereby driving EDHI. Thus, GTI acts as a critical positive transmission channel. So, we put forward the following hypotheses: GTI mediates the relationship between Envir and EDHI. Specifically, GTI positively transmits the effect.

Figure 1 presents the theoretical framework underlying the three hypotheses. The diagram illustrates the direct positive effect of envir on EDHI, as well as the three mediating pathways: GTI, ISR, and ISU. The dashed arrows indicate indirect effects, while the solid arrow represents the direct effect.

3. Research design

3.1. Model construction

To examine the mediating roles of ISU, ISR and GTI in the process by which envir influence EDHI, this paper adopts the classic three-step mediation test framework.

(i) Step 1: Estimate the total effect of envir on EDHI:

In **Equation 1**, denotes the EDHI index for *i* city during *t* year, signifies the extent of envir for the i city at t year, the vector represents the ith control variable in period *t*, represents an individual fixed effect, means time effect; is the random error.

(ii) Step 2: Estimate the impact of envir on the three mediating variables:

(iii) Step 3: Incorporate envir and mediating variables simultaneously to test the direct and indirect effects:

The calculation method for indirect effects is:

Combined with **Equation 1**, the specific validation idea is as follows: first of all, regress the envir with the EDHI, and when the regression coefficient is significant, continue to construct the regression equation between the envir and , as well as the regression equation between the envir and the on the EDHI, and lastly, through the importance of regression coefficient values of **Equations 1–3** to determine whether the level of is a mediating variable. This approach aligns with standard conventions in applied econometrics for confirmatory policy evaluation.[20,21]

3.2. Measurement and explanation of variables

3.2.1. Dependent variable: High-quality economic development

Based on the concept of sustainable development, this paper constructs an EDHI index. It covers five key areas, including innovation, coordination, sustainability, openness, and sharing,[22,23] as detailed in Table 1.

To ensure objectivity and minimize subjective intervention, the index was calculated using the entropy weight method. This index is constructed in three steps: (i) unify the indicator direction and eliminate the dimensional differences; (ii) determine the indicator weights based on information entropy; (iii) weight and sum the standardized indicators to obtain the EDHI index.

The reliability test results indicate that the Cronbach's alpha coefficient is 0.839, well above 0.70. This indicates that the indicator system has a high degree of internal consistency and is suitable for further synthesis into a comprehensive index.

To verify the validity of the EDHI index system, an exploratory factor analysis was conducted in this study. A total of four core factors were extracted, with a cumulative variance explanation rate of 62.22%. The factor loadings for each item range from 0.30 to 0.86, and most exceed the 0.50 standard for validation. Thus, the indicator system has acceptable structural validity for empirical analysis.

3.2.2. Core explanatory variable: Environmental regulation intensity

This paper constructs the envir index using local government work reports and text analysis.[17–19] The selection and validation process is detailed as follows.

(i) Keyword selection: Drawing from policy discourse analysis and established literature, this paper selected

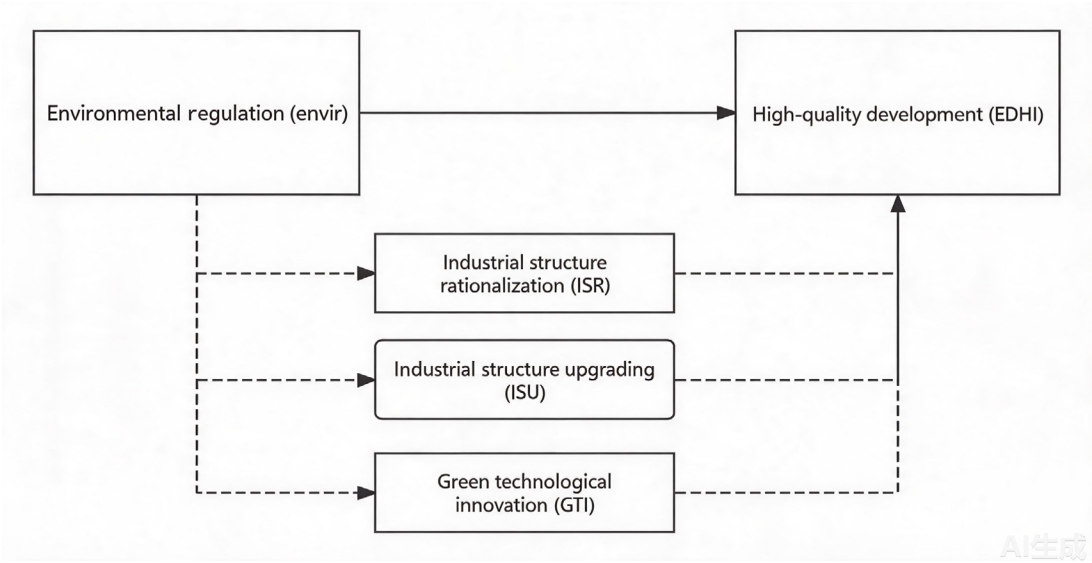

Figure 1. Theoretical framework

Table 1. Indicator system for high-quality economic development

Category	Sub-indicator	Calculation
Innovative development	Science and education investment	Research and development expenditure/FiscalExp
		EduExp/FiscalExp
	Patent level	Number of patents granted
Coordinated development	Finance development	Deposit balance/loan balance
	People's livelihood	Per capita income
Open development	Industrial structure	Tertiary (%)
	Foreign direct investment	Foreign investment
	Foreign-invested enterprise	Number of foreign-invested enterprises
Green development	Three wastes emission	Industrial wastewater discharge/industrial output
		Industrial sulfur dioxide emission/industrial output
		Industrial smoke (dust) emission/industrial output
	Waste treatment	Industrial solid waste utilization rate
		Centralized wastewater treatment rate
		Harmless treatment rate of municipal solid waste
Shared development	Welfare	Number of physicians per 10,000 population
		Average wage of employed workers
		Urban greening rate
	Consumption	Retail sales per capita/gross domestic product
	Government pressure	FiscalExp/revenue

15 environment-related keywords spanning four core governance dimensions: pollution control such as sulfur dioxide, carbon dioxide, PM10, PM2.5, emissions reduction, discharge of pollutants; sewage; energy management such as energy consumption, chemical oxygen demand; green transition such as air, ecological, green, low-carbon; and regulatory focus such as environmental protection and envir. This multi-dimensional set ensures comprehensive capture of governmental environmental commitments.

(ii) Data processing: This paper constructs the envir index using document frequency analysis implemented in Python. This process follows a clear algorithm. Firstly, preprocessing: the local government work reports were cleaned by removing punctuation and formatting. Secondly, the frequencies of the 15 target keywords determined in this article were extracted and standardized. Finally, the original keyword counts in each report were divided by the total document length to eliminate deviations caused by report size.

(iii) Index construction: The final envir index is the unweighted sum of the 15 normalized frequencies.

(iv) After verification, the envir index constructed in this paper shows a significant positive correlation with the per capita environmental protection expenditure ($p = 0.039 < 0.05$), and has passed the objective data convergence validity test.

3.2.3. Mediating variables

To examine the mechanisms through which the core explanatory variables influence the outcome variable, this study introduces three mediating variables: ISR, ISU, and GTI.

(i) Industrial structure rationalization

This paper follows Gan Chunhui's approach, using the Theil index to measure it.[24,25] This index uses the proportion of each industry's added value as the weight and compares the logarithmic differences between each industry's labor productivity and the overall average. The smaller the Theil index, the more balanced the industrial structure tends to be and the higher the efficiency of resource allocation; conversely, a higher Theil index indicates poor coordination among industries and structural imbalance.

(ii) Industrial structure upgrading

Industrial structure upgrading reflects the trend of the industrial system evolving towards high-technology, high-value-added directions. In this paper, the ratio of tertiary-industry value added to secondary-industry value added is used as a key indicator for understanding shifts in ISU. The higher it is, the more it indicates that the economy is shifting from a manufacturing-dominated structure to a service-dominated one. This suggests that the share of knowledge- and technology-intensive industries is steadily increasing.

(iii) Green technology innovation

We adopt the natural logarithm of green patent filings per 10,000 residents as an indicator of GTI capacity. The data is sourced from CNRDS and the National Intellectual Property Administration.[3,10] This indicator has been standardized by population and can effectively reflect the output capacity of green innovation in each region.

3.2.4. Control variables

To mitigate potential omitted-variable bias and isolate the net effects of the core explanatory variables, this study includes a set of control variables capturing demographic, economic, institutional, and human capital characteristics at the city level.

(i) Population size: This paper measures the population size of a city by the natural logarithm of the registered residents. Controlling for population size helps alleviate estimation bias arising from differences in urban agglomeration, market size, or environmental protection investment. Generally, large cities have stricter envir, but at the same time, they also face higher pollution pressure.

(ii) Financial development level: This study measures the level of financial development by calculating the annual ratio of the total deposits and loans held by financial institutions to the regional GDP. This reflects the concentration and allocation efficiency of local financial resources.[26] Better finance helps firms access green credit, boosting green innovation and ISU.

(iii) Level of openness: Measured as the actual foreign investment's share of GDP, this captures the city's integration into global value chains and absorption of technology spillovers.

(iv) Urbanization level: Measured as the share of non-agricultural population in total population, it drives service-sector growth—and thus industrial upgrading—while straining resources and the environment.[27]

(v) Degree of fiscal decentralization: Measured as local government revenue-to-expenditure ratio, this reflects fiscal capacity, driving proactive environmental governance and green industry support.[28]

(vi) Education expenditure level: Measured as local education spending's share of the general public budget, this signals stronger technology absorption,[29,30]

transformation, and industrial upgrading potential.

(vii) Human capital level: This indicator measures the share of tertiary-educated individuals in the population, reflecting workforce knowledge reserves and innovation potential.[31,32] The higher the density of human capital, the more conducive it is to promoting GTI.

3.3. Data sources and descriptive statistics

This paper constructs a panel dataset using 278 cities in China from 2005 to 2023 as the research subjects. All variables are derived from authoritative, publicly available statistical sources, mainly including the "China Urban Statistical Yearbook" and the "China Environmental Statistical Yearbook." To preserve the authentic regional distribution of high-quality development, EDHI was not winsorized or trimmed. The observed minimum of EDHI reflects genuine baseline conditions in less-developed prefecture-level cities where green, coordinated, and inclusive capacity was historically minimal. This paper explicitly excludes the four central municipalities in the robustness test, where the core conclusion remains unchanged.

As shown in Table 2, the mean of EDHI is 0.077 with a standard deviation of 0.057, indicating that there are significant differences among cities in envir, and the overall situation is still in the exploratory stage. The mean of envir is 0.959, with a standard deviation of 0.420, indicating significant differences in envir intensity among local governments.

Furthermore, the mean of population size (rk) is 5.869, indicating a relatively large average size of cities; the mean of financial development (fin) is 2.408, with a fluctuation range from 0.560 to 21.301, suggesting a highly uneven financial allocation among regions; the means human capital (hum) is 0.019 with standard deviation exceeding 0.024, indicating a highly dispersed distribution of related inputs among the two prefecture-level cities; the mean of urbanization level (ubr) is 0.381, with a slightly lower median, indicating that most cities are still in the middle stage of urbanization; the means of local government fiscal autonomy (govsper) and education investment (edu) are 0.456 and 0.180 respectively, with relatively small standard

Table 2. Summary statistics

VarName	Observation	Mean	Standard deviation	Minimum	Maximum	Median
EDHI	5,282	0.077	0.057	0.020	0.689	0.063
envir	5,282	0.959	0.420	0.000	11.000	0.904
rk	5,282	5.869	0.705	2.846	8.136	5.922
fin	5,282	2.408	1.251	0.560	21.301	2.060
fdi	5,282	0.003	0.003	0.000	0.029	0.002
ubr	5,282	0.381	0.206	0.015	1.000	0.328
govsper	5,282	0.456	0.224	0.054	1.541	0.422
edu	5,282	0.180	0.044	0.015	0.792	0.178
hum	5,282	0.019	0.024	0.0001	0.185	0.010

Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

deviations, suggesting a relatively stable distribution among regions.

As shown in Figure 2, EDHI rose overall, but high-value areas grew faster, widening regional disparities. The eastern coastal regions have always been leading, being the first to complete the transformation, with outstanding capabilities in innovation and coordination. The central regions have been steadily improving; the western regions are generally at a lower level, but there are signs of improvement in places like Chengdu and Chongqing.

The key changes occurred during the periods 2005–2010 and 2015–2023: the high-value area rose from 0.343 to 0.516 in the former period, and the highest value jumped to 0.688 in the latter. These changes are closely related to the promotion of policies such as regional coordination and innovation-driven development.

Overall, EDHI has been steadily improving, but the pattern of "high in the east and low in the west" persists. The rise of the central region and partial breakthroughs in the west signal positive signs of regional balance.

As shown in Figure 3, envir have been continuously tightened, expanding from the eastern region to the central and western regions, but the gap between the east and the west still exists. The intensity of national regulations has increased rapidly, with the highest value doubling, reflecting the country's shift from emphasizing growth to prioritizing environmental protection.[31-34] The eastern region remains the strongest, combining stringent environmental oversight with early industrial transformation; the central region has since narrowed the gap, advancing environmental protection and industrial upgrading; the western region is generally weaker, although some areas have shown slight improvement. The following text will empirically examine how envir affect EDHI and how these effects vary across regions.

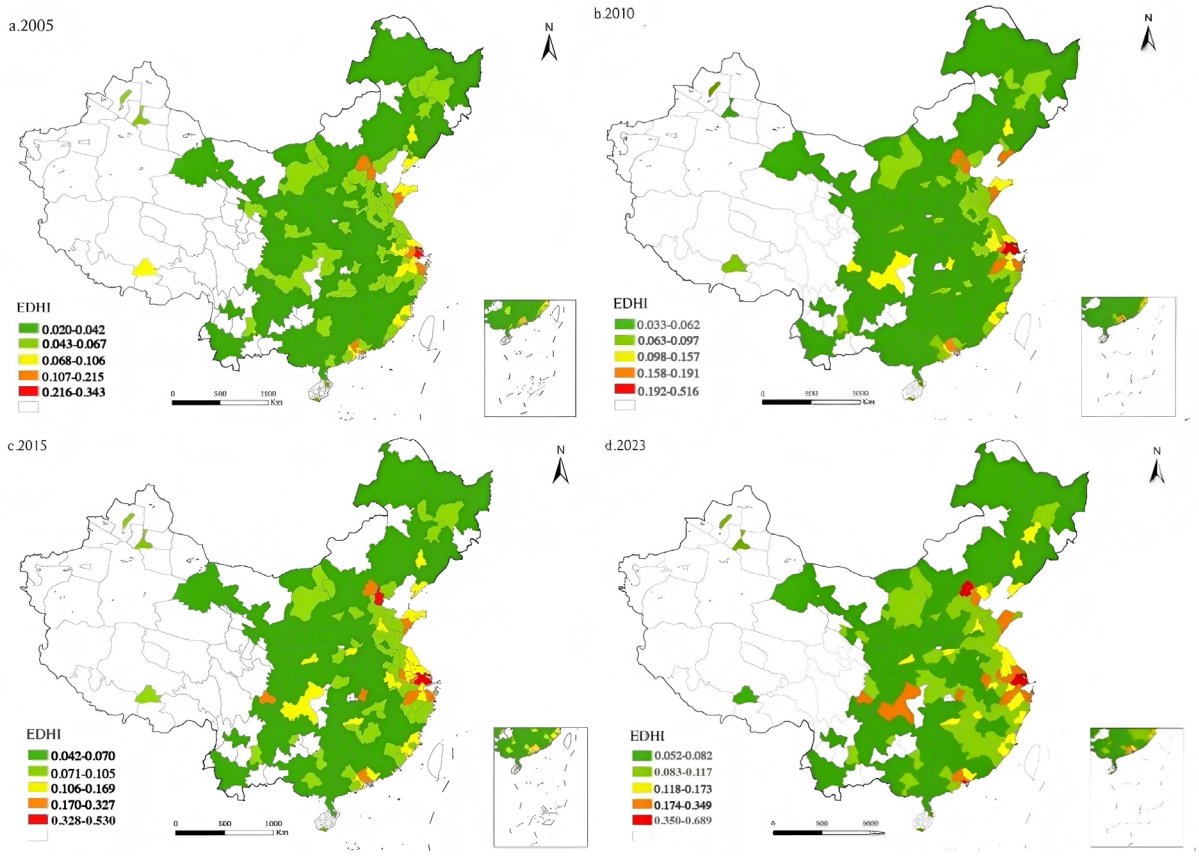

Figure 2. Spatial distribution map of high-quality economic development (EDHI)

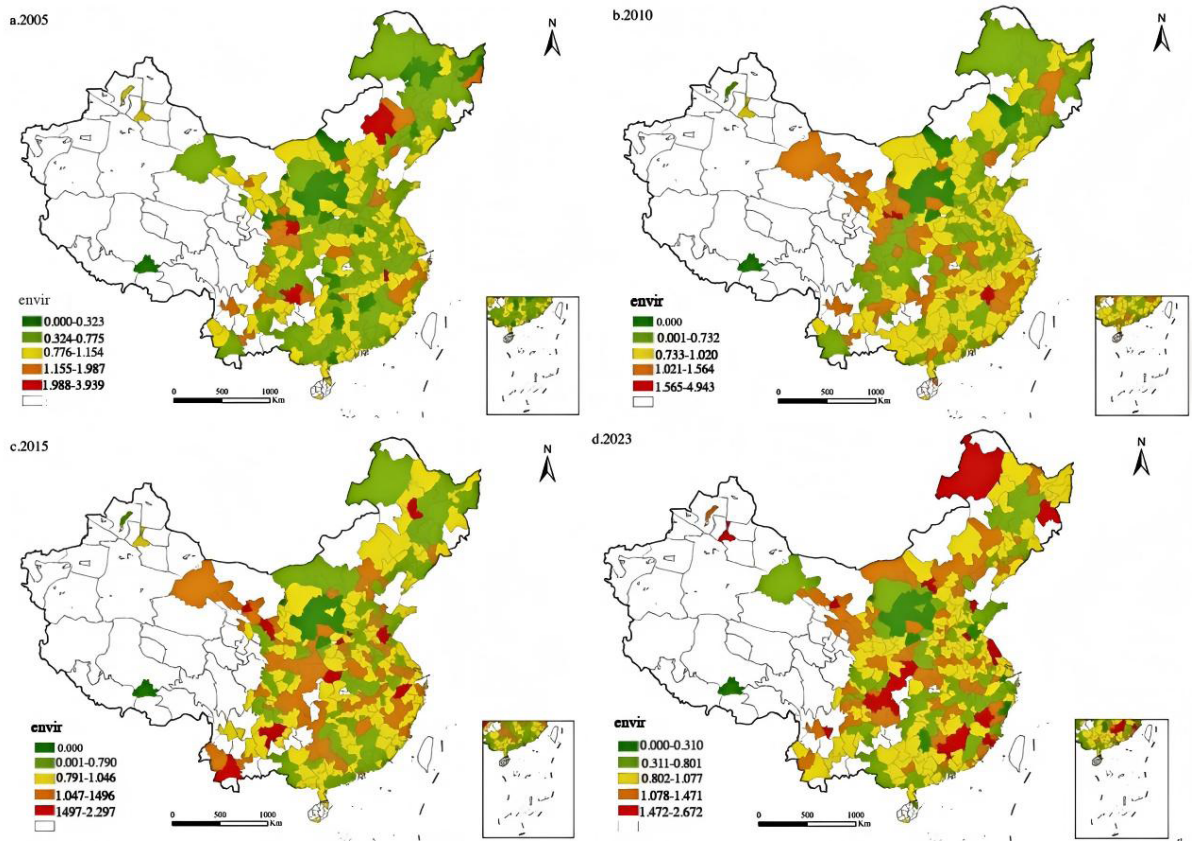

Figure 3. Spatial distribution map of environmental regulation (envir)

4. Empirical test

4.1. Results of the benchmark regression

As shown in Table 3, Model 1 indicates that for every one-unit increase in envir, the average EDHI index rises by 0.003, which is significant at the 1% level. This implies that even without considering other factors, envir itself is able to effectively promote EDHI.

After introducing control variables, the coefficient on envir in Model 2 remains significantly positive, indicating that its promoting effect still holds under more complex conditions.

In terms of control variables, population size, financial development, FDI, urbanization, and human capital all have a significant positive impact on EDHI, consistent with economic theory. Fiscal decentralization has a significant negative impact. This might be because when local governments rely less on central transfers, they tend to prioritize high-tax-yield sectors over long-term, low-margin green innovation. Simultaneously, self-funded budgets face binding constraints on financing cross-jurisdictional environmental governance and green public goods. This fiscal independence, without effective vertical coordination, systematically suppresses high-quality development.

4.2. Robustness test

4.2.1. Replacement of core explanatory variables

Table 4 tests robustness by replacing the envir measure. Model 1 replaces it with the natural logarithm of envir intensity to reduce the impact of outliers and potential non-linearities on estimation outcomes. In all specifications, the coefficient of envir (or its alternative) remains significantly positive at the 1% level.

Furthermore, when envir is replaced by per capita environmental protection expenditure, the coefficient remains strongly positive and significant at the 1% level. It confirms that the core conclusion is not sensitive to indicator construction methods.

Table 3. Results of the benchmark regression

Variables	(1)	(2)
	EDHI	EDHI
envir	0.003***	0.001**
	(2.98)	(2.21)
rk	–	0.065***
	–	(15.90)
fin	–	0.002***
	–	(4.76)
fdi	–	0.000***
	–	(3.83)
ubr	–	0.010**
	–	(2.46)
govsper	–	-0.005
	–	(−1.42)
edu	–	0.051***
	–	(4.18)
hum	–	0.000**
	–	(2.51)
Constant	0.073***	−0.315***
	(75.68)	(−12.71)
Observations	5,282	5,282
R-squared	0.003	0.465
Number of id	278	278
Year FE	Yes	Yes
Code FE	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

Table 4. Robustness test 1

Variables	(1)	(2)	(3)
	EDHI	EDHI	EDHI
envir	0.001**	–	–
	(2.21)	–	–
envir_log	–	0.005***	–
	–	(2.87)	–
PCEPE	–	–	0.008***
	–	–	(3.44)
rk	0.065***	0.065***	0.134***
	(15.90)	(15.77)	(37.91)
fin	0.002***	0.002***	0.006***
	(4.76)	(4.78)	(15.76)
fdi	0.000***	0.000***	0.438***
	(3.83)	(3.84)	(3.05)
ubr	0.010**	0.010**	0.058***
	(2.46)	(2.41)	(14.88)
govsper	−0.005	−0.005	−0.011***
	(−1.42)	(−1.39)	(−2.96)
edu	0.051***	0.051***	0.002
	(4.18)	(4.15)	(0.20)
hum	0.000**	0.000**	0.713***
	(2.51)	(2.54)	(19.07)
Constant	−0.315***	−0.311***	−0.769***
	(−12.71)	(−12.47)	(−36.32)
Observations	5,282	5,282	5,282
Number of id	278	278	278
R-squared	0.465	0.466	0.466
Year FE	Yes	Yes	Yes
Code FE	Yes	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; PCEPE: Per capita environmental protection expenditure; rk: Population size; ubr: Urbanization level.

Table 5. Robustness test 2

Variables	(1)	(2)
	EDHI	EDHI
envir	0.001**	0.001*
	(2.21)	(1.73)
rk	0.065***	0.071***
	(15.90)	(20.60)
fin	0.002***	0.001***
	(4.76)	(3.31)
fdi	0.000***	0.000*
	(3.83)	(1.80)
ubr	0.010**	0.017***
	(2.46)	(4.65)
govsper	−0.005	0.001
	(−1.42)	(0.37)
edu	0.051***	0.108***
	(4.18)	(11.32)
hum	0.000**	0.000***
	(2.51)	(5.58)
The level of market development	–	0.018***
	–	(4.77)
Constant	−0.315***	−0.379***
	(−12.71)	(−18.47)
Observations	5,282	5,282
R-squared	0.465	0.600
Number of id	278	278
Year FE	Yes	Yes
Code FE	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

This indicates that the core conclusion that envir can promote EDHI is not affected by the measurement method of the variable and has strong robustness.

4.2.2. Excluding systemic changes of other factors

To address omitted variable bias from unobserved institutional factors, Table 5 introduces the level of market development as an additional control. The market mechanism is an important institutional foundation for efficient resource allocation and the vitality of innovation, and has a fundamental impact on EDHI. After its introduction, the coefficient of envir slightly weakens but remains significant, indicating that its positive impact is robust. Moreover, after controlling for the core institutional variable of marketization quality, the results more closely reflect the true causal relationship.

4.2.3. Elimination of special cities

Table 6 re-runs the regression after excluding the four central municipalities (Beijing, Shanghai, Tianjin, and Chongqing). The results show that the coefficient of envir remains positive and significant, which indicates the stability of the model. The conclusion holds even after excluding the four centrally administered municipalities, confirming the core finding's broad generalizability—not driven by sample-specific features.

4.2.4. Elimination of special years

The sample period covers the 2008 financial crisis, 2015 supply-side reform, and 2020–2022 pandemic, which may introduce transient volatility. To assess temporal robustness, this paper sequentially excludes these periods and re-estimates the baseline model. As reported in Table 7, the coefficient of envir remains positive and statistically significant across all restricted samples, confirming that the core findings are not driven by short-term disruptions.

4.2.5. Sensitivity to EDHI index scale

Given the compressed distribution of the EDHI index and the concern that extremely high-development observations could bias estimates, this paper conducted a formal sensitivity test by truncating the EDHI distribution at the 10th percentile. As reported in Table 8, the coefficient on envir remains positive and significant. These findings validate that the core conclusions remain robust to alternative extreme-value treatments.

4.3. Heterogeneity test

Table 9 further examines the heterogeneous impacts of envir across eastern, central, and western regions. The results show a clear gradient: the positive effect is strongest and statistically significant in the western region,

Table 6. Robustness test 3

Variables	(1)	(2)
	EDHI	EDHI
envir	0.001**	0.001***
	(2.21)	(2.88)
rk	0.065***	0.066***
	(15.90)	(19.83)
fin	0.002***	0.001***
	(4.76)	(4.46)
fdi	0.000***	0.000***
	(3.83)	(4.06)
ubr	0.010**	0.008**
	(2.46)	(2.42)
govsper	−0.005	−0.006**
	(−1.42)	(−1.99)
edu	0.051***	0.043***
	(4.18)	(4.27)
hum	0.000**	−0.000
	(2.51)	(−1.44)
Constant	−0.315***	−0.325***
	(−12.71)	(−16.07)
Observations	5,282	5,282
Number of id	278	278
R-squared	0.465	0.547
Year FE	Yes	Yes
Code FE	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

statistically insignificant in the central region, and negative (though not statistically significant) in the eastern region.

This pattern corresponds to the marginal regulatory effectiveness gradient, rather than to a strict mathematical inflection point. But it requires structural unpacking to resolve an apparent inconsistency: while both western and central regions began from relatively low regulatory baselines, only the western region exhibits a significant positive response.

The key differentiator lies in the structural policy environment of transfer-receiving hubs. In the western region, economic development remains heavily resource-based with limited legacy industrial lock-in. Envir here acts as a clean efficiency signal that reliably forces the exit of backward capacity while incentivizing green reallocation, yielding strong and significant EDHI gains.

In contrast, the central region has become the primary destination for industrial relocation from the east. This creates a policy trade-off: local governments face dual mandates to maintain employment and output for incoming enterprises while enforcing stringent environmental standards. In practice, regulatory stringency often conflicts with short-term growth targets, leading to selective enforcement, fragmented coordination, and under-provision of green governance capacity. Consequently, the net marginal effect of envir is structurally diluted, rendering the coefficient statistically insignificant even though the underlying directional impact remains positive.

The eastern region reflects the opposite boundary condition: decades of regulatory tightening have already eliminated most high-pollution capacity, and further intensification may impose compliance costs that temporarily outweigh innovation offsets, consistent with diminishing returns.

Overall, the promoting effect of envir on EDHI is strongest in the west, weakest in the east, and diluted in the center. Policies should be regionally differentiated.

4.4. Endogeneity test

To address exogenous issues, this paper employs the IV method. This paper uses the air circulation coefficient and the density of urban rivers as instrumental variables. The former is obtained by multiplying the annual average wind speed by the boundary layer height, reflecting the regional atmospheric diffusion capacity. It is derived from EDHI and only affects the policy intensity by changing the difficulty of pollutant dilution. The latter is the total length of rivers within the administrative area, and only indirectly affects envir through influencing the inertia of water environment governance and the historical industrial layout.

Table 7. Robustness test 4

Variables	(1)	(2)	(3)	(4)	(5)
	Exclude 2008	Exclude 2015	Exclude 2020	Exclude 2021	Exclude 2022
	EDHI	EDHI	EDHI	EDHI	EDHI
envir	0.002***	0.002***	0.002***	0.002***	0.002***
	(2.74)	(2.65)	(2.74)	(2.76)	(3.44)
rk	0.135***	0.136***	0.136***	0.132***	0.133***
	(36.87)	(35.87)	(34.66)	(33.21)	(32.53)
fin	0.006***	0.006***	0.006***	0.006***	0.005***
	(14.75)	(14.59)	(14.34)	(13.74)	(12.21)
fdi	0.497***	0.485***	0.430***	0.480***	0.555***
	(3.33)	(3.13)	(2.71)	(3.05)	(3.57)
ubr	0.060***	0.059***	0.060***	0.062***	0.068***
	(14.83)	(14.16)	(13.91)	(14.02)	(14.69)
govsper	−0.011***	−0.011***	−0.007*	−0.007	−0.002
	(−2.85)	(−2.74)	(−1.73)	(−1.59)	(−0.52)
edu	0.004	0.003	0.004	0.002	−0.001
	(0.36)	(0.26)	(0.34)	(0.17)	(−0.07)
hum	0.735***	0.736***	0.732***	0.706***	0.719***
	(18.93)	(18.30)	(17.71)	(16.96)	(16.52)
Constant	−0.769***	−0.774***	−0.777***	−0.754***	−0.760***
	(−35.32)	(−34.37)	(−33.33)	(−31.89)	(−31.38)
Observations	5,004	4,984	5,001	4,997	5,004
R-squared	0.462	0.467	0.464	0.461	0.452
Number of id	278	278	278	278	278
Year FE	Yes	Yes	Yes	Yes	Yes
Code FE	Yes	Yes	Yes	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.
Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

Table 8. Robustness test 5

Variables	(1)
	EDHI
envir	0.001*
	(1.78)
rk	0.134***
	(37.37)
fin	0.007***
	(16.11)
fdi	0.000
	(0.55)
ubr	0.065***
	(16.56)
govsper	−0.012***
	(−3.12)
edu	0.029***
	(2.81)
hum	0.000***
	(16.46)
Constant	−0.771***
	(−36.37)
Observations	4597
Number of id	278
R-squared	0.455
Year FE	Yes
Code FE	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

Table 9. Heterogeneity test

Variables	East	Center	West
	EDHI	EDHI	EDHI
envir	−0.004	0.000	0.003***
	(−0.65)	(0.79)	(3.01)
rk	0.108***	0.032***	0.085***
	(13.57)	(8.13)	(14.40)
fin	0.004***	0.001**	0.001**
	(3.91)	(2.33)	(2.20)
fdi	0.000***	−0.000	0.000**
	(2.90)	(−0.11)	(2.56)
ubr	−0.007	0.018***	0.019***
	(−1.11)	(3.54)	(2.99)
govsper	−0.007	0.003	0.014***
	(−0.90)	(0.71)	(2.87)
edu	0.154***	0.121***	0.053***
	(6.41)	(10.67)	(5.07)
hum	0.000***	0.000***	0.000*
	(5.55)	(3.12)	(1.78)
Constant	−0.582***	−0.171***	−0.460***
	(−12.10)	(−7.22)	(−13.40)
Observations	1,900	1,786	1,596
R-squared	0.581	0.726	0.692
Number of id	100	94	84
Year FE	Yes	Yes	Yes
Code FE	Yes	Yes	Yes
Inter-group difference test		$p = 0.0105$	

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

As shown in Table 10, the coefficient of envir remains positive and significant, further supporting the core conclusion.

Furthermore, the *F*-value of the weak instrument test is 248.2, far exceeding the critical value of 10, which means that the strength of the IV is sufficient. The *p*-value of the over-identification test is 0.102, and the exogeneity hypothesis is not rejected, suggesting that the IVs are not related to the error term, and the model specification is reasonable.

In summary, the IV method effectively mitigates endogeneity, improves the accuracy of policy effect estimates, and enhances the persuasiveness of the empirical results.

4.5. Verification mechanism

4.5.1. Innovation level

Table 11 presents the results of the stepwise regression. Model 2 shows that the GTI coefficient is 0.108, which is significant at the 1% level. This confirms that envir can significantly promote GTI. In Model 3, the coefficient is significantly 0.009, while the coefficient of envir drops to 0.000 and is not significant. This indicates that GTI plays a crucial mediating role between envir and EDHI.

Given the sensitivity of traditional regression methods to non-normal distributions in tests of mediating effects, this paper further employs the bootstrap method to conduct a robustness test of the mediating effect.

As shown in Table 12, the bootstrap results based on 5,000 samples indicate that the indirect effect coefficient is 0.001015, with a *p*-value of 0.008, which is significant at the 1% statistical level. Its 95% confidence interval is (0.000267, 0.001763), and the interval does not include 0, indicating that the indirect effect is statistically significant.

In conclusion, GTI is the key path for envir to drive EDHI. It transmits approximately 91.72% of the total effect, confirming it as the core economic transmission channel.

Policies should focus on creating an institutional environment conducive to the development of green technologies, stimulating enterprises' intrinsic drive for innovation, and achieving the coordinated advancement of environmental governance and economic upgrading.

4.5.2. Industrial structure rationalization

As shown in Table 13, Model 1 indicates that envir has a significant positive direct effect on EDHI, which is consistent with the benchmark conclusion. Model 2 shows that envir can effectively promote the rationalization of the

Table 10. Endogeneity test

Variables	EDHI
envir	0.014***
	(2.60)
rk	0.027***
	(24.14)
fin	0.010***
	(14.11)
fdi	1.508***
	(5.16)
ubr	0.054***
	(13.47)
govsper	0.119***
	(28.97)
edu	−0.161***
	(−7.98)
hum	−0.227***
	(−5.97)
Constant	−0.159***
	(−17.29)
Weak IV test	$F = 248.200$
Overidentification test	$p = 0.102$
Observations	4,160
R-squared	0.491
Year FE	Yes
Code FE	Yes

Notes: *z*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; rk: Population size; ubr: Urbanization level.

Table 11. GTI

Variables	(1)	(2)	(3)
	EDHI	GTI	EDHI
envir	0.001**	0.137***	0.000
	(2.21)	(12.75)	(0.89)
GTI	–	–	0.008***
	–	–	(5.23)
rk	0.065***	1.138***	0.068***
	(15.90)	(11.08)	(19.63)
fin	0.002***	0.055***	0.001***
	(4.76)	(4.49)	(3.52)
fdi	0.000***	0.000***	0.000*
	(3.83)	(3.05)	(1.73)
ubr	0.010**	0.033	0.017***
	(2.46)	(0.31)	(4.85)
govsper	−0.005	0.432***	0.001
	(−1.42)	(4.28)	(0.22)
edu	0.051***	0.244	0.104***
	(4.18)	(0.86)	(10.93)
hum	0.000**	0.000***	−0.000***
	(2.51)	(5.70)	(−6.02)
Constant	−0.315***	−4.487***	−0.375***
	(−12.71)	(−7.34)	(−18.20)
Observations	5,282	5,207	5,207
R-squared	0.465	0.886	0.600
Number of id	278	278	278
Year FE	Yes	Yes	Yes
Code FE	Yes	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; GTI: Green technological innovation; hum: Human capital; rk: Population size; ubr: Urbanization level.

Table 12. GTI-bootstrap mediation effect test results

Indirect effect	
Bootstrap SE	0.0003818
LLCI	0.0002666
ULCI	0.0017634

Abbreviations: GTI: Green technological innovation; LLCI: Lower-level confidence interval; SE: Standard error; ULCI: Upper-level confidence interval.

industrial structure by eliminating backward production capacity, optimizing organizational methods, and facilitating resource reallocation, thereby enhancing the coordination efficiency among industries. In Model 3, after simultaneously including both, the direct effect of envir is no longer significant, while the coefficient on ISR increases significantly to 0.082 and is highly significant.

Further calculation shows that the indirect effect of envir transmitted through ISR is 0.000747. Accounts for roughly 61.3% of the total effect, aligning with its identified role as a mediating pathway.

Considering that the mediating effect is the product of the path coefficients. Its distribution is often non-normal. To further verify the reliability of the conclusion, the bootstrap method was used for testing. The results are shown in Table 14. It is indicated that the indirect effect coefficient of the mediating effect is 0.000738, and the 95% confidence interval is (0.0003, 0.0011), which does not include 0. This indicates that the mediating path is significant.

From an economic perspective, envir does not directly enhance EDHI but rather indirectly releases growth potential by optimizing resource allocation, strengthening industrial synergy, and factor matching.

4.5.3. Industrial structure upgrading

To clarify the role of ISU, this paper adopts a combined testing strategy of stepwise regression and the bootstrap method. The stepwise regression results in Table 15 show that, in Model 2, the coefficient for envir is 0.019, which is significant at the 5% level, indicating that envir effectively promotes ISU. In model 3, the ISU coefficient is 0.012 and is highly significant at the 1% level. However, the coefficient

Table 13. ISR

Variables	(1)	(2)	(3)
	EDHI	ISR	EDHI
envir	0.001**	0.009***	0.000
	(2.21)	(2.93)	(0.85)
ISR	–	–	0.082***
	–	–	(18.31)
rk	0.065***	−0.002	0.071***
	(15.90)	(−0.23)	(20.64)
fin	0.002***	0.002*	−0.002***
	(4.76)	(1.90)	(−3.87)
fdi	0.000***	0.000	0.000
	(3.83)	(0.96)	(1.49)
ubr	0.010**	0.033***	0.017***
	(2.46)	(3.10)	(4.82)
govsper	−0.005	0.086***	0.001
	(−1.42)	(8.43)	(0.43)
edu	0.051***	0.179***	0.103***
	(4.18)	(6.29)	(10.85)
hum	0.000**	0.000	0.000***
	(2.51)	(0.12)	(5.60)
Constant	−0.315***	2.106***	−0.394***
	(−12.71)	(34.22)	(−17.28)
Observations	5,282	5,253	5,253
R-squared	0.465	0.733	0.598
Number of id	278	278	278
Year FE	Yes	Yes	Yes
Code FE	Yes	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; ISR: Industrial structure rationalization; rk: Population size; ubr: Urbanization level.

Table 14. ISR-bootstrap mediation effect test results

Indirect effect	
Bootstrap SE	0.000213
LLCI	0.000308
ULCI	0.001141

Abbreviations: ISR: Industrial structure rationalization; LLCI: Lower-level confidence interval; SE: Standard error; ULCI: Upper-level confidence interval.

Table 15. ISU

Variables	(1)	(2)	(3)
	EDHI	ISU	EDHI
envir	0.001**	0.019**	0.001
	(2.21)	(2.43)	(0.78)
ISU	–	–	0.012***
	–	–	(13.89)
rk	0.065***	0.180***	0.072***
	(15.90)	(3.22)	(21.10)
fin	0.002***	0.140***	−0.003***
	(4.76)	(20.89)	(-5.94)
fdi	0.000***	0.000***	0.000
	(3.83)	(4.93)	(0.96)
ubr	0.010**	0.284***	0.015***
	(2.46)	(4.92)	(4.33)
govsper	−0.005	−0.258***	0.004
	(−1.42)	(−4.71)	(1.06)
edu	0.051***	0.973***	0.098***
	(4.18)	(6.33)	(10.29)
hum	0.000**	0.000***	0.000***
	(2.51)	(3.86)	(5.20)
Constant	−0.315***	1.550***	−0.397***
	(−12.71)	(4.66)	(−19.38)
Observations	5,282	5,262	5,262
R-squared	0.465	0.457	0.478
Number of id	278	278	278
Year FE	Yes	Yes	Yes
Code FE	Yes	Yes	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; hum: Human capital; ISU: Industrial structure upgrading; rk: Population size; ubr: Urbanization level.

of envir drops to 0.001 and its statistical significance disappears. The indirect effect is calculated as 0.000228. It accounts for roughly 18.94% of the total effect, aligning with its identified role as a mediating pathway.

However, the mediating effect is essentially the product of the path coefficients, and its sampling distribution is typically non-normal and skewed. The traditional stepwise regression method is insufficient for testing these.

The results of the bootstrap test based on 5,000 repeated samples are shown in Table 16. Its 95% confidence interval is (0.000137, 0.005471), which does not include 0. This indicates that the mediating path is significant.

As shown in Table 17, when all the mediating variables are included in the unified model, GTI presents the smallest standard error, the largest *t*-statistic, and a significant positive coefficient, confirming that it is the core channel through which envir drives EDHI. ISR still maintains statistical significance. However, ISU loses significance, indicating that its apparent effect in the single model has been largely absorbed or replaced by the stronger paths of GTI and ISR. At the same time, the direct effect of envir on EDHI becomes insignificant, suggesting that the influence of envir on EDHI is mediated by the mechanisms above, with GTI playing the most critical role. These findings further strengthen the empirical robustness of our original transmission path ranking (GTI > ISR > ISU), confirming that GTI's advantage persists in multi-channel direct competition.

Table 16. ISU-bootstrap mediation effect test results

Indirect effect	
Bootstrap SE	0.0001431
LLCI	0.0000137
ULCI	0.0005471

Abbreviations: ISU: Industrial structure upgrading; LLCI: Lower-level confidence interval; SE: Standard error; ULCI: Upper-level confidence interval.

Table 17. Competitive path analysis

Variables	**(1)**
	EHDI
ISU	0.005
	(0.97)
ISR	0.009***
	(9.13)
GTI	0.009***
	(27.51)
envir	0.000
	(0.08)
rk	0.081***
	(22.75)
fin	−0.000
	(−0.13)
fdi	0.644***
	(4.97)
ubr	0.029***
	(8.11)
govsper	−0.003
	(−0.78)
edu	0.085***
	(9.21)
hum	0.000
	(0.87)
Constant	−0.485***
	(−21.41)
Observations	5,282
Number of id	278
R-squared	0.569
Year FE	Yes
Code FE	Yes

Notes: *t*-statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Abbreviations: EDHI: High-quality economic development; edu: Education investment; envir: Environmental regulation; fdi: Foreign direct investment; FE: Fixed effect; fin: Financial development; govsper: Local government fiscal autonomy; GTI: Green technological innovation; hum: Human capital; ISR: Industrial structure rationalization; ISU: Industrial structure upgrading; rk: Population size; ubr: Urbanization level.

5. Conclusion

5.1. Conclusion and recommendations

This study employs panel data from 278 prefecture-level cities in China over the period 2005–2023 to examine how envir affects EDHI. with three transmission channels: GTI, ISU, and ISR.

Empirical results show that envir exerts a statistically significant positive effect on EDHI, yet the underlying transmission mechanisms differ across institutional levels. GTI has the strongest effect, indicating it is the core driving force; ISR yields the second-largest total effect on EDHI. It enables systemic coordination through two complementary channels: efficient resource reallocation and the retirement of obsolete production capacity; ISU exhibits the weakest total effect on EDHI, which means that the current expansion of the service sector has yet to translate into meaningful responsiveness to envir. The three transmission pathways are ranked by effect magnitude as follows: GTI > ISR > ISU. This offers empirically grounded priorities for targeted policy intervention. Regional heterogeneity is statistically significant: the effect of envir on EDHI is strongest in the western region, and insignificant in the central and eastern regions, consistent with the regulatory heterogeneity gradient. All results pass multiple robustness tests and endogeneity checks.

Building on these findings, we propose the following five evidence-informed policy recommendations:

(i) First, prioritize green innovation incentives. Given that GTI is the dominant transmission channel, environmental policies should shift from uniform command approaches towards market-based instruments that directly reward green patenting and R & D. This includes tax incentives, subsidized green credit, and transparent innovation benchmarks.

(ii) Second, complement innovation policies with industrial rationalization measures. Because ISR operates as a mediator, policies should facilitate the orderly exit of obsolete, polluting capacity, and improve resource reallocation across sectors. Coordination mechanisms, such as regional functional zoning and performance evaluations that include structural efficiency indicators, can enhance the effectiveness of envir.

(iii) Third, adopt a long-term perspective on industrial upgrading. The mediating role of ISU implies that simply expanding the service sector is insufficient. Policies should focus on capability-building (e.g., human capital, digital infrastructure) to ensure that upgrading translates into genuine responsiveness to environmental pressures, rather than premature deindustrialization.

(iv) Fourth, implement regional differentiated strategies. In the western region, promote green innovation and structural optimization; in the central region, guide environment-friendly foreign investment and prevent industrial hollowing out; in the eastern region, focus on institutional innovation and quality supervision, and develop green intelligence and high-end services.

(v) Fifth, establish a national-level policy transmission monitoring platform. Built jointly by relevant departments, it would dynamically track indicators such as green patents, the Theil index, the proportion of the three industries, and talent matching, and optimize regional policies in real time to avoid one-size-fits-all approaches and policy fatigue, achieving precise policy implementation and long-term governance.

5.2. Limitations and future research

While this study provides a comprehensive framework for comparing the transmission pathways of envir on high-quality economic development, several limitations warrant cautious interpretation and future extension.

First, the composition of local government work reports varies across regions and political cycles. Differences in administrative writing conventions, rhetorical style, and leadership transitions may introduce measurement noise that reflects institutional communication patterns rather than genuine shifts in regulatory stringency. And more importantly, textual frequency captures declared policy intent rather than de facto implementation. A recognized gap exists between the emphasis placed on environmental governance in official documents and the rigor of on-the-ground enforcement, which could potentially lead to an overstatement of policy intensity in certain jurisdictions. To address these limitations in future research, scholars could integrate text-based indices with direct enforcement metrics, such as ecological inspection records, environmental violation fines, or satellite-observed pollution concentrations, thereby offering a more granular assessment of the policy intent-implementation continuum.

Second, the regional heterogeneity analysis reveals a theoretically puzzling divergence: the central region, as the primary hub for inter-regional industrial transfer, exhibits an insignificant regulatory effect despite its low initial environmental baseline. This paper argues that this reflects structural policy friction in transfer-dependent economies, where growth mandates frequently constrain environmental enforcement. However, formally testing the interaction between transfer intensity and regulatory

stringency is beyond the scope of this panel, primarily because cross-regional capital flows are endogenous and there is no clean identification strategy to isolate the marginal dampening channel. Future research should employ spatial econometric models, multi-period difference-in-differences designs (e.g., leveraging national central-city policies or relocation directives), or firm-level regulatory enforcement data to directly quantify the transfer-regulation nexus.

Third, the text-based envir index captures declared policy attention, which may diverge from *de facto* implementation. Integrating regulatory intensity with satellite-observed pollution or inspection records would strengthen the measurement of actual policy stringency. Fifth, while the three mediating pathways are estimated in parallel to avoid multicollinearity confounding, their potential complementarity or substitution effects warrant system-level dynamic analysis. These extensions will help refine the policy calibration of environmental governance across China's heterogeneous regional landscapes.

Fourth, mediator endogeneity remains a recognized boundary in observational policy evaluation. While our IV strategy addresses reverse causality for envir, the mediating channels (GTI, ISR, ISU) may be subject to feedback effects or concurrent unobserved shocks. Finding valid instruments that satisfy the exclusion restriction for these structurally embedded variables is methodologically prohibitive in the current data environment. We acknowledge this limitation and recommend that future studies leverage exogenous policy shocks, spatial lag instruments, or structural equation modeling with multiple indicators to more rigorously isolate pathway-specific causality.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

*Conceptualization:*Jia Wang
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Methodology: Bo Ai
Writing–original draft: Hangdi Zhao
Writing–review & editing: Jia Wang

Availability of data

All variables are derived from authoritative and publicly available statistical sources, mainly including the "China Urban Statistical Yearbook" and the "China Environmental Statistical Yearbook."

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