

Article

Environmental Regulation and Green Technology Innovation Driving Industrial Structure Upgrading: From the Perspective of Heterogeneous Environmental Regulation

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Abstract

This study incorporates environmental regulation, green technological innovation, and industrial structure upgrading into a unified analytical framework. Collecting panel data from 71 core prefecture-level cities in the Chengdu–Chongqing, Middle Reaches of the Yangtze River and Yangtze River Delta urban agglomerations from 2011 to 2023, adopting fixed-effects, mediation, and moderation models to investigate how environmental regulation and green technological innovation affect industrial structure upgrading, through which mechanisms these effects occur, and how inclusive digital finance moderates these relationships. The findings reveal that command-and-control and guidance-based environmental regulations all exert positive effects on industrial structure upgrading. Green technological innovation serves as a mediating mechanism through which command-and-control environmental regulation promotes industrial structure upgrading. Inclusive digital finance acts as a boundary condition shaping the effect of environmental regulation on industrial structure upgrading. Further heterogeneity analysis reveals regional variation in how different types of environmental regulation affect industrial structure upgrading. This study proposes policy recommendations that urban agglomerations should attach greater importance to green innovation, enhance the breadth and depth of inclusive digital finance utilization, and establish appropriate local environmental regulatory support systems so as to promote industrial structure upgrading.

Keywords: environmental regulation; green technology innovation; industrial structure upgrading; mediation effect; regulating role; heterogeneity



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1. Introduction

China's 14th Five-Year Plan and Long-Range Objectives through 2035 emphasize advancing industrial base upgrading and industrial chain modernization. Achieving these goals requires comprehensive promotion of industrial structure upgrading to realize high-quality economic development. Furthermore, the rapid expansion of China's economy has brought about excessive resource consumption and severe environmental degradation [1], rendering the traditional extensive growth model unsustainable. Under these circumstances, promoting industrial transformation is seen as an important way of achieving greener development while sustaining high-quality economic growth.

During the upgrading process, government environmental regulation plays an important role in steering industrial adjustment. Rather than referring to a single policy tool, environmental regulation covers a range of legal and policy instruments through which governments

influence firms' environmental behavior and encourage the internalization of environmental externalities [2,3]. Existing studies show that such regulation can reshape industrial development through several channels, including changes in production decisions, technological innovation, and the reallocation of resources. Among these channels, green technological innovation plays an important role. By increasing regulatory pressure and creating incentives for cleaner production, environmental regulation may encourage firms to improve technologies, enhance productivity, and move toward higher-value and greener industrial activities [4,5]. Therefore, this study treats green technological innovation as the main mediating channel linking environmental regulation to industrial structure upgrading.

Effective environmental regulations may induce technological innovation, with the possibility of offsetting or even fully compensating for the compliance costs [6]. In this sense, a regulatory instrument does not simply impose compliance pressure on firms. Furthermore, it may also encourage firms to pursue technological innovation and strengthen their competitiveness when the regulatory design is appropriate. For example, government interventions aimed at high-pollution activities have been shown to promote green technological innovation [7].

Building on the demonstration above, technological innovation provides a useful lens for understanding how environmental regulation contributes to industrial structure upgrading. Previous research has shown that innovation is closely associated with industrial transformation [8]. However, under growing environmental constraints, conventional innovation alone may no longer be sufficient to align with the goals of quality-oriented economic growth. Green technology development is therefore especially relevant, as it places greater emphasis on resource efficiency, environmental protection, and sustainable production. By encouraging cleaner technologies and more efficient production methods, green technological innovation can help industries move toward higher-value and more environmentally sustainable forms of development [5].

Although a large body of research has discussed the links among environmental policy instruments, green technological development, and upgrading of the industrial system, the existing literature still leaves several issues unresolved. One limitation is that environmental regulation is often examined as a single, undifferentiated policy instrument. This treatment may obscure the fact that command-and-control policy and guidance-based tools operate through different policy logics and may therefore generate different effects on industrial structure upgrading.

Another issue concerns the role of green technological innovation. While it is commonly regarded as an important force behind industrial transformation, less is known about whether it actually explains the pathway through which different regulatory instruments promote structural upgrading. As a result, the internal mechanism connecting regulatory pressure with industrial transformation remains only partly clarified.

Moreover, previous studies have mainly treated inclusive digital finance as an independent variable and examined its direct effects on green innovation, industrial upgrading, or green development. However, limited attention has been paid to its role as a broader macroeconomic condition that may shape the effectiveness of environmental regulation. By reshaping market environments and firm capabilities, digital development may condition firms' responses to regulatory instruments, potentially leading to different moderating effects across distinct forms of environmental regulation.

The main contributions are threefold. First, it broadens the existing analytical perspective, which has largely been confined to examining pairwise relationships among the three variables, by revealing the transmission mechanisms and effects through which environmental regulation and green technological innovation drive structural improvement across industries. This offers practical insights for further understanding the intrinsic relationships among the three.

Second, it further examines regional variations in how regulatory tools influence industrial structure upgrading. This not only strengthens the reliability of the findings, but more importantly, it yields practical implications for governments in designing more targeted and coordinated policy frameworks that align environmental regulation and green technological innovation in the process of promoting industrial upgrading.

Third, this paper contributes to the literature by repositioning inclusive digital finance from a direct explanatory variable to a macro-level contextual factor. By introducing inclusive digital finance as a moderating variable, it provides a more conditional understanding of environmental regulation. The result reveals that the policy effect of environmental regulation does not depend only on regulatory intensity itself, but also on the broader financial and digital environment in which regulation is implemented. Environmental regulation is normally.

2. Literature Review and Hypotheses Development

Ecological modernization theory posits that economic development and environmental improvement can be mutually reinforcing rather than contradictory. It emphasizes that institutional environmental constraints can drive structural transformation by reshaping production systems toward cleaner and more efficient pathways [9]. In this framework, environmental regulation serves as an important institutional force that internalizes environmental externalities and induces firms and industries to adjust their production structures. Accordingly, stricter environmental regulation can accelerate the exit of pollution-intensive industries and promote the expansion of cleaner and more technology-intensive sectors, thereby contributing to industrial structure upgrading [10].

Environmental regulation is normally categorized by command-and-control, guidance-oriented, and public participation-oriented types based on how they operate [11]. From the perspective of policy implementation effects, command-and-control environmental regulation is characterized by the coercive nature of governmental administrative power; guidance-based environmental regulation is easily constrained by firms' profit-maximization objectives. Therefore, the effects of environmental regulation vary across regulatory forms in the process of green technology innovation-driven industrial upgrading.

A closer examination of the relationship between regulatory policy and industrial transformation suggests that environmental regulation can support structural upgrading over the long run [12].

First of all, strict environmental regulations directly and indirectly influence investment in high-carbon industries, thereby encouraging these sectors to relocate to areas with more relaxed regulations. This migration impacts the industrial upgrading of the regions these industries leave [13]. Secondly, stricter environmental tools raise the entry barriers for pollution-intensive firms, shrinking their scale while expanding that of cleaner industries, thereby driving regional industrial structure upgrading [14]. Finally, appropriate environmental regulation intensity can stimulate corporate innovation, as the potential for extraordinary returns from successful research and development may partially or fully offset the increased production costs due to strict regulations. This enhances production technology levels, improves production efficiency, optimizes internal corporate structures, and promotes industrial structure upgrading [15].

In general, command-and-control environmental regulation is characterized by mandatory and stringent constraints, while guidance-based regulation tends to rely on more flexible and market-oriented instruments. Thus, both types of regulation, though differing in their implementation mechanisms, may promote industrial structure upgrading. Thus, the following hypothesis is.

H1. *All types of environmental regulation promote industrial structure upgrading in the nodal cities of the three urban clusters.*

The Porter Hypothesis further extends the role of environmental regulation by emphasizing its innovation-inducing effect. It argues that well-designed regulatory policy does not merely impose compliance costs but can foster innovation by raising the relative cost of polluting activities and encouraging firms to shift toward cleaner production technologies [6]. Faced with regulatory pressure, firms are incentivized to improve production efficiency, adopt green technologies, and optimize resource allocation. These innovation responses may offset compliance costs and enhance long-term competitiveness [16,17].

There are several studies providing support for the Porter Hypothesis, arguing that ecological policy pressure may drive companies to engage in pursuing green technological innovation [18]. Under stricter regulatory pressure, firms often face higher compliance costs and greater penalties for pollution emissions. In response, they may adjust production processes, improve resource efficiency, and adopt cleaner technologies, which in turn creates incentives for innovation.

However, the Porter Hypothesis has also been questioned. Some scholars argue that environmental regulation may weaken firms' green innovation activities rather than promote them under certain conditions [19]. One reason is that stricter regulation raises compliance costs and pollution-related expenditures, leaving firms with fewer financial resources for innovation. These additional costs may also reduce profit margins and weaken firms' willingness to invest in long-term green technologies. Moreover, when regulatory pressure is not strong enough, firms may choose cheaper and more immediate responses such as end-of-pipe treatment, simply to satisfy regulatory requirements. Such responses help firms meet short-term compliance needs but do not necessarily lead to substantive technological innovation [20].

These mixed findings from the previous literature suggest that the impact of environmental regulation on green technological innovation may vary according to the type of regulatory instrument adopted.

Further evidence suggests that the effects of different regulatory instruments are non-linear. To be more specific, the impact of command-and-control regulation on green technological innovation follows an inverted U-shaped pattern, whereas public participation-oriented regulation demonstrates a U-shaped relationship. In addition, empirical studies indicate that, compared with other regulatory types, command-and-control environmental regulation tends to exert a relatively stronger overall effect on green technological innovation [21].

Although prior studies report mixed findings, this study follows the Porter Hypothesis and expects environmental regulation to promote green technology innovation, because appropriately designed or sufficiently binding regulation can change firms' cost-benefit calculations, increase the relative cost of pollution-intensive production, and encourage companies to apply greener technical solutions and refine production processes [22,23]. Therefore, environmental regulation provides the first link in the mediation chain by promoting green technology innovation.

In addition, according to innovation theory, technological innovation serves as a central force driving industrial structure upgrading. Several scholars affirm the beneficial effect of green technology innovation in promoting industrial upgrading [24–26]. A panel-data regression analysis from 35 industrial sectors in China from 2002 to 2019 demonstrates that green technological innovation effectively promotes cleaner industrial upgrading, although its effect is limited in low-value-added and relatively clean industries [5].

How eco-oriented innovation contributes to industrial transformation is realized through multiple channels, including productivity differentials, factor reallocation, and agglomeration economies. Green technology innovation creates differences in labor pro-

ductivity within the manufacturing sector, driving the reallocation of production factors. High-tech manufacturing industries attract more production factors, thereby promoting the upgrading of the manufacturing sector's industrial structure [27]. Urban clusters generate specialization economies, providing advantageous conditions for firms' technological innovation [28]. The clustering of enterprises within the same urban cluster can yield increasing returns, leading to a linkage effect in innovation behaviors among enterprises, improving the overall efficiency of the industrial chain [29].

Furthermore, there is an interactive relationship among income disparity, innovation level, and consumer demand. Under the condition of income equality, technological progress stimulates consumption growth [30], leading to changes in consumption demand and structure. This, in turn, causes the expansion or contraction of related industries, ultimately influencing industrial structure upgrading.

Building on the foregoing analysis, we propose the following hypothesis.

H2. *Green technology innovation mediates the relationship between environmental regulation and industrial structure upgrading in the nodal cities of the three urban clusters.*

Financial intermediation theory emphasizes that financial systems are important for reducing information asymmetry and facilitating the efficient allocation of capital from savers to productive investment opportunities [31].

Inclusive digital finance refers to the use of digital technologies to expand the coverage, accessibility, and efficiency of financial services, such as easing financing constraints and reducing information asymmetry. Building on this framework, inclusive digital finance can be understood as an evolution of the traditional financial intermediation system enabled by digital technologies. By leveraging big data analytics, cloud computing, and platform-based financial services, it improves the information processing capacity of financial intermediaries and reduces transaction and screening costs [32]. As a result, financial institutions are better able to evaluate firms' environmental performance and risk profiles, thereby enhancing the efficiency of capital allocation [33].

Within the framework of environmental regulation, the role of inclusive digital finance extends beyond merely providing additional financial resources. As a coin has two sides, its effects operate through a dual-channel mechanism that may either strengthen or weaken the transmission of environmental regulatory signals depending on the nature of the regulatory instrument.

On the one hand, inclusive digital finance strengthens firms' sensitivity to price-based policy instruments by improving information accessibility and capital allocation efficiency; digital finance helps firms better identify and obtain green financing opportunities, fiscal support, and tax-related incentives, while increasing financing constraints for pollution-intensive sectors [34,35]. On the other hand, when digital finance is highly developed, market-based information flows and financing constraints may already exert disciplinary effects on firms' environmental behavior. Under such conditions, the additional marginal role of administrative regulation may become weaker. Chen and Zhang [36] prove this possibility and find that the interaction between digital financial inclusion and environmental regulation can have a significant negative effect on industrial structure upgrading.

Considering different types of environmental regulation operate through different policy instruments and implementation mechanisms, it is reasonable to propose the hypothesis that:

H3. *Digital finance moderates the impact of environmental regulation on industrial structure upgrading, and this moderating effect may vary across different types of environmental regulation.*

The Heckscher–Ohlin theory suggests that differences in regional factor endowments lead to heterogeneous industrial structures and patterns of specialization across regions [37].

Proponents of locational determinism, such as Sachs, argue that geographical factors are crucial for economic development. Differences in economic performance among countries reflect variations in geographic location, climate, and ecological characteristics [38]. Regional disparities in terms of economic, technological, and human resources contribute to varying approaches to environmental protection. More developed regions are likely to implement stricter environmental regulation policies. At the regional level, the impact of environmental regulation on industrial structure transformation and upgrading shows significant regional variation [39].

Technology advancement is subject to the “path dependence effect”, and regions with dense populations, well-developed technology markets, and lighter fiscal burdens experience stronger impacts on industrial structure upgrading [40]. Green technology innovation positively influences the advancement and rationalization of industrial structures, with the strength of this effect differing across regions [41–43]. Within the framework of sustainable growth, technological progress in renewable energy has potential implications for industrial structure upgrading. Heterogeneity analysis shows that renewable energy technology innovation significantly promotes industrial structure upgrading in the eastern regions of China [44]. Therefore, we propose the following hypothesis.

H4. *The impact of environmental regulation on industrial structure upgrading exhibits regional heterogeneity.*

Figure 1 below shows the whole theoretical framework of this paper.

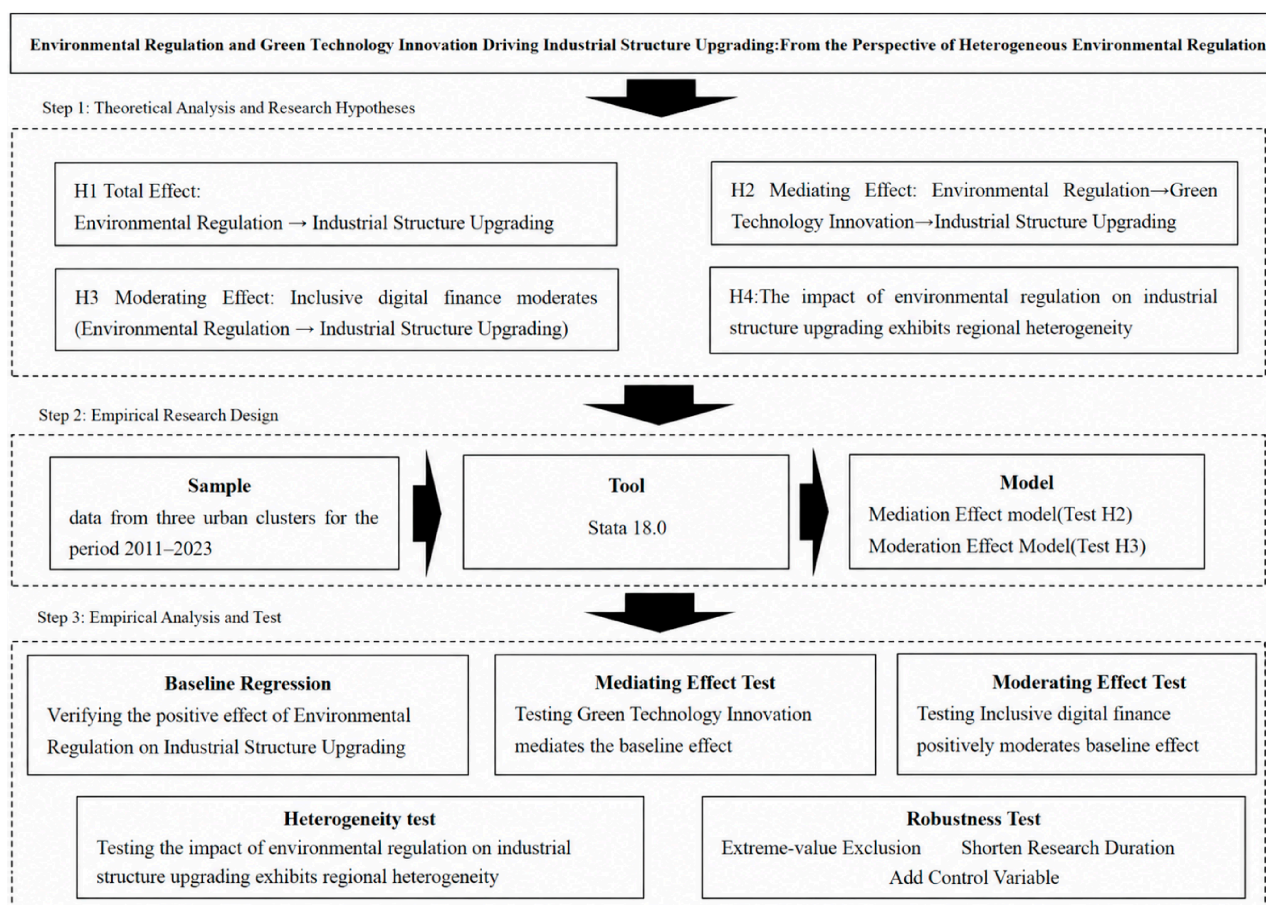


Figure 1. Theoretical framework.

3. Methodology

3.1. Baseline Model Construction

The following baseline research model (1) is constructed to test the baseline fixed-effects estimation of the impact of environmental regulation on industrial structure upgrading:

$$ISU_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_j Controls_{it} + \mu_i + \lambda_t + \mathcal{E}_{it} \quad (1)$$

To analyze whether green technology innovation provides a mediating effect between environmental regulation and industrial structure upgrading in the nodal cities of the three urban clusters, Equations (2) and (3) are constructed based on Equation (1) to test Hypothesis 2:

$$GTI_{it} = \varphi_0 + \varphi_1 ER_{it} + \varphi_j Controls_{it} + \mu_i + \lambda_t + \mathcal{E}_{it} \quad (2)$$

$$ISU_{it} = \varphi_0 + \varphi_1 ER_{it} + \varphi_2 GTI_{it} + \varphi_j Controls_{it} + \mu_i + \lambda_t + \mathcal{E}_{it} \quad (3)$$

Models (2) and (3) adopt a two-step mediation testing approach. Model (2) examines whether environmental regulation significantly promotes green technological innovation, while Model (3) tests the overall mediation effect by including green technological innovation in the baseline regression to assess whether it transmits the impact of environmental regulation on industrial structure upgrading.

To examine the moderating effect of inclusive digital finance on the relationship between environmental regulation and industrial structure upgrading in the node cities of the three urban agglomerations, Equation (4) is constructed to test Hypothesis 3:

$$ISU_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 DF_{it} + \beta_3 ER_{it} DF_{it} + \beta_j Controls_{it} + \mu_i + \lambda_t + \mathcal{E}_{it} \quad (4)$$

Equation (4) introduces an interaction term between environmental regulation and inclusive digital finance into the baseline fixed-effects model. This specification aims to identify whether inclusive digital finance strengthens or weakens the impact of environmental regulation on industrial structure upgrading.

Where:

ISU_{it} represents the industrial structure upgrading level of prefecture-level city i in year t .

ER_{it} represents the environmental regulation of city i in year t .

GTI_{it} represents the mediating variable, representing green technology innovation of city i in year t .

DF_{it} represents the digital finance of city i in year t .

$Controls_{it}$: Control variables, including factors such as economic development level, technological level, and population density for city i in year t .

μ_i : Fixed effects of city i (city-specific effects).

λ_t : Fixed effects for year t (time-specific effects).

$\mathcal{E}_{it}$: Random error term for city i in year t .

3.2. Variable Selection

3.2.1. Dependent Variable

Industrial Structure Upgrading

Industrial structure upgrading reflects the process of optimizing industries from low-value-added forms to high-value-added forms, marked by a transition toward a service-based economic structure. The industrial structure hierarchy coefficient is adopted to represent industrial structure upgrading, following Du [4] et al., the ratio of tertiary

industry value added to secondary industry value added is used as a proxy for industrial structure upgrading. The specific calculation formula is as follows:

$$ISU = y_{3,i,t}/y_{2,i,t} \quad (5)$$

where $y_{3,i,t}$ denotes value added in the tertiary industry in regional GDP in region i at time t , whereas $y_{2,i,t}$ is value added in the secondary industry in regional GDP in region i at time t . This index reflects the evolving proportional relationship in China's three-industry structure, whereby dominance gradually shifts from the primary and secondary industries to the tertiary industries.

Although it cannot fully capture upgrading within the secondary industry, such as the transition from traditional manufacturing to advanced or green manufacturing, it can be seen as a proper measurement because the secondary industry is more closely associated with resource consumption and environmental pressure, while the tertiary industry mainly reflects service-oriented and higher-value economic activities. Moreover, the growth of service-oriented industries indicates cleaner and greener production and can clearly describe the extent to which the economic structure tends toward service-oriented development [45,46].

3.2.2. Independent Variables

Command-and-Control Environmental Regulation (ER1):

This type of regulation enforces compliance with green and environmental standards through strict legal mandates, achieving environmental protection goals by setting pollution limits or reduction standards. Non-compliance results in legal or administrative penalties. Several scholars use logarithms of pollutant fee revenues or environmental protection taxes as measurement indicators [47]. Local governments may implement a “basket” of measures, combining administrative and economic tools for environmental governance [48]. In this study, the number of environmental administrative penalties disclosed is used as the proxy variable (ER1). This approach is consistent with recent studies that use environmental penalties, punishment records, or punished-enterprise data to capture the enforcement or penalty dimension of environmental regulation, especially within mandatory environmental regulation frameworks [26]. Therefore, ER1 is interpreted as a proxy for revealed regulatory enforcement pressure rather than a comprehensive measure of environmental regulation.

Guidance-Oriented Environmental Regulation (ER2):

Guidance-oriented environmental regulation refers to policy signals and supportive measures through which government departments guide future environmental efforts. These measures are often reflected in policy documents, work reports, fiscal subsidies, tax incentives for green enterprises, and direct investment in environmental protection. In this study, guidance-oriented regulation is captured using the proportion of pollution control investment to the added value of the secondary industry, following Lanoie [49] et al.

Although guidance-based environmental regulation is commonly associated with incentive instruments such as subsidies, tax preferences, and policy guidance, government environmental protection investment also reflects an important fiscal channel of policy intervention. Unlike command-and-control instruments that directly impose constraints on firms, fiscal environmental expenditure represents a form of governmental commitment to green development and sends credible signals regarding policy priorities.

In this sense, government-funded pollution control investment does not directly substitute for firm-level subsidies, but it reflects a broader fiscal policy orientation that may influence firms' expectations and investment decisions. Therefore, it can be interpreted as

an indirect policy signal through which the government guides environmental behavior, rather than merely providing public environmental services.

Moreover, prior studies showing that command-and-control regulation increases environmental investment usually focus on firm-level green investment or environmental investment as a behavioral response to regulatory pressure [50]. By contrast, ER2 in this study is measured by the ratio of pollution control investment to the added value of the secondary industry, which captures city-level pollution control investment intensity relative to the scale of industrial economic activity. Therefore, the possible effect of command-and-control regulation on firm-level environmental investment does not necessarily undermine the validity of ER2.

This study focuses on command-and-control and guidance-oriented environmental regulations because both are formal regulatory instruments implemented through governmental policies. They therefore have a more direct influence on firms' production decisions, resource allocation, and environmental behavior. By contrast, public participation-oriented regulation mainly reflects informal social pressure generated by public environmental awareness and participation. Since the study aims to investigate environmental regulation from the perspective of government governance, public participation-oriented regulation is not included in the analysis. This choice helps maintain conceptual consistency across the regulatory variables.

3.2.3. Mediating Variable

This study employs the aggregate number of green patent applications to represent green technological innovation.

Green technology innovation can be measured from two perspectives: input and output.

Input Perspective:

Green technology innovation is evaluated through R&D expenditure, which measures the intensity of innovation efforts. However, this perspective may overlook conversion efficiency and other factors.

Output Perspective:

The green patent counts are used as a proxy for green technology innovation. Patent applications and maintenance involve significant time and costs, and applicants file patents when they anticipate economic returns [51]. Even unapproved patent applications represent inventors' creative achievements.

Based on the World Intellectual Property Organization (WIPO) classification of green patents (IPC codes), this study uses green patent application data obtained from the Chinese Patent Gazette website of the State Intellectual Property Office as the proxy indicator for green technology innovation [52]. Several scholars use the total number of granted green patents categorized by application date [53,54].

3.2.4. Control Variables

The level of industrial structure upgrading is also influenced by other factors. Referring to existing studies [55,56], the following control variables are selected:

The level of economic development is measured by real GDP per capita (PGDP).

Science and Technology Expenditure (TS):

The ratio of science and technology expenditure to GDP represents the fiscal support for science and technology.

Human Capital Level (HC):

Measured using the logarithmic value of the number of students attending standard higher education institutions. The high cost of R&D activities creates a need for government financial support and investment in skilled labor [57].

Fixed-Asset Investment (IFA):

Fixed-asset investment promotes the development of high-tech industries. It is measured by the ratio of fixed-asset investment to GDP.

Level of Openness (FDI):

Measured by the ratio of actual utilized foreign investment to GDP. Increased foreign direct investment (FDI) in high-tech products or services contributes to local firms' technological and production innovation through learning and competition effects. FDI facilitates regional technological spillovers [13].

Urbanization Level (U):

Represented by the proportion of the urban permanent population. Urbanization involves labor migration and industrial reorganization. As urbanization progresses, technological innovation and resource reallocation optimize industrial structural changes [58].

3.2.5. Moderating Variable

Digital Finance (DF):

Inclusive digital finance provides the necessary funding, hardware facilities, and innovation environment for technological research and development as well as the transformation of technological achievements. Data is employed from the Peking University Digital Financial Inclusion Index of China. This index was developed by the Institute of Digital Finance, Peking University, together with Ant Group Research Institute, and has been widely used to measure the development of digital inclusive finance in China [59]. The index is constructed from three dimensions: coverage breadth, usage depth, and degree of digitization. It also provides data at the provincial, city, and county levels, which makes it suitable for city-level empirical analysis.

3.3. Sample Selection and Data Sources

This study focuses on the Chengdu–Chongqing, Middle Reaches of the Yangtze River, and Yangtze River Delta urban agglomerations because urban agglomerations have become important spatial carriers of regional integration and high-quality development in China [60]. Additionally, these agglomerations represent distinct stages of China's regional development, spanning western, central, and eastern regions. They differ systematically in economic development level, industrial structure, innovation capacity, and environmental governance intensity. Thus, this heterogeneity provides a natural comparative setting for identifying the relationships among environmental regulation, green technological innovation, and industrial structure upgrading.

In addition, city-level data better capture the actual implementation of environmental regulation and digital finance policies, which are primarily designed and enforced at the municipal level in China. Compared with provincial or regional aggregates, city-level observations allow for greater variability, reduce aggregation bias, and improve identification accuracy by capturing within-region heterogeneity.

Considering data availability and reliability, this project selects data from three urban clusters for the period 2011–2023. Data sources include statistical yearbooks of provinces and prefecture-level cities, China Statistical Yearbook, China Urban Construction Statistical Yearbook, China Science and Technology Statistical Yearbook, China Environmental Statistical Yearbook, the China Research Data Services Platform (CNRDS), the Economic Forecasting System database, and the Chinese Patent Gazette website of the State Intellectual Property Office. Incomplete yearly data was addressed by applying interpolation methods.

Empirical analysis was conducted using Stata 18.0.

4. Results

4.1. Descriptive Statistics of Variables

Table 1 reports the descriptive statistics for 923 observations. The dependent variable (ISU) shows moderate variation, indicating heterogeneity in industrial structure upgrading across regions. The mediating variable (GTI) also exhibits considerable dispersion, suggesting uneven levels of green innovation. Among the explanatory variables, ER1 displays substantial variability, reflecting differences in the intensity of command-and-control regulation, whereas ER2 remains at a relatively low level with limited variation, indicating that guidance-based regulation is generally less developed. For the control variables, human capital (HC) shows pronounced regional disparities, while real GDP per capita (PGDP) and urbanization (U) are relatively more concentrated. Notably, digital finance (DF) presents significant variation across regions, highlighting heterogeneous development levels and providing a solid basis for examining its moderating role. Overall, the variables exhibit sufficient dispersion to support subsequent empirical analysis.

Table 1. Descriptive statistics.

Variable Type	Variable Symbol	Variable Definition	Maximum	Minimum	Mean	Std. Dev	Observed Value
Explained variable	ISU	Upgrading of industrial structure	3.058	0.023	0.995	0.382	923
Intermediate variable	GTI	Green technology innovation	9.876	1.792	5.771	1.624	923
Explanatory variable	ER1	Environmental administrative punishment	8.196	0.000	2.574	2.339	923
	ER2	Environment-related investment/Value added of the secondary industry	0.035	0.000	0.002	0.003	923
Control variable	IFA	Investment in fixed assets/GDP	13.511	0.006	0.817	0.525	923
	FDI	Foreign Direct Investment/GDP	0.181	0.000	0.019	0.018	923
	HC	Human capital level	116.105	0.000	14.329	22.757	923
	TS	Scientific and technological/GDP	0.020	0.000	0.004	0.003	923
	U	Urbanization rate	1.000	0.230	0.588	0.133	923
	PGDP	real GDP per capital	12.237	7.902	10.977	0.604	923
Moderating variable	DF	Digital finance	373.22	35.08	210.830	80.688	923

Figure 2A shows the kernel density plot of ISU and ER1. The solid line represents the mean and the dashed line represents the median. ISU is highly concentrated around its central value, indicating that industrial structure upgrading is relatively clustered across observations. In contrast, ER1 exhibits a flatter and more dispersed distribution, suggesting that command-and-control environmental regulation varies more substantially across regions and years.

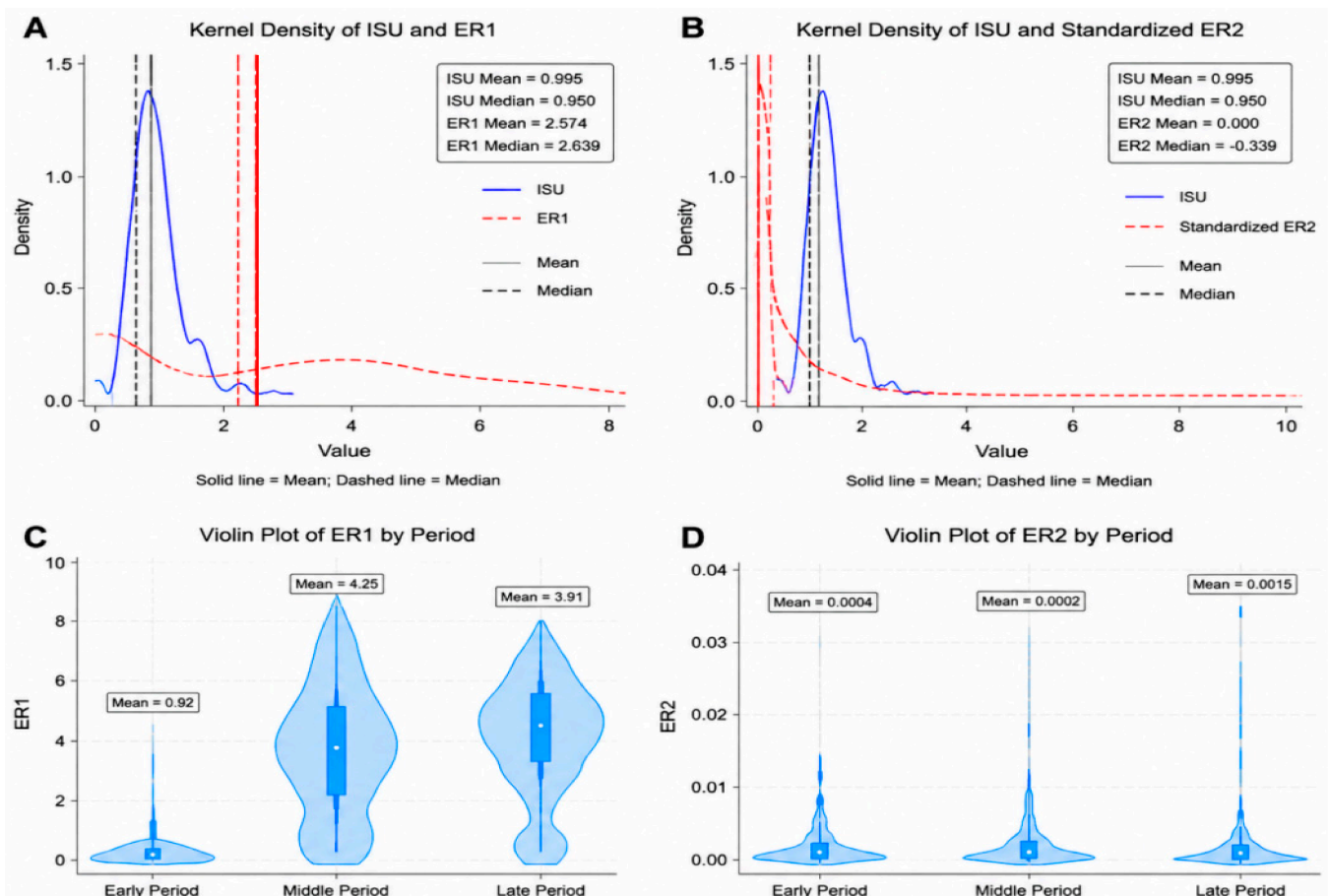


Figure 2. (A) Kernel Density of ISU and ER1. (B) Kernel Density of ISU and ER2. (C) Violin Plot of ER1 by Period. (D) Violin Plot of ER2 by Period.

Figure 2B shows the kernel density plot of ISU and standardized ER2. The solid line represents the mean and the dashed line represents the median. ER2 is standardized before plotting because its original distribution is highly concentrated near zero, producing an extremely high density peak and compressing the ISU density curve when both variables are plotted on the same scale. This approach just makes the curve easier to exhibit but does not change the shape. Standardized ER2 exhibits a sharp peak on the left side and a long right tail, indicating that guidance-based environmental regulation is concentrated among most observations but has a small number of substantially higher values. This suggests greater heterogeneity and right-skewness in ER2 compared with ISU.

Figure 2C shows that the violin plot of ER1 is highly concentrated at low levels during the early period, suggesting relatively weak command-and-control environmental regulation at the beginning of the sample period. In the middle period, the distribution shifts upward and becomes more dispersed, indicating a substantial increase in ER1 as well as greater heterogeneity across observations. In the late period, ER1 remains at a relatively high level, while its distribution becomes more concentrated, suggesting that command-and-control regulation became more stable and consistently stronger over time.

Figure 2D shows the violin plot of ER2 remaining relatively stable across the three periods. However, the distributions are highly concentrated near low values in all periods, with long upper tails indicating the presence of a small number of observations with substantially higher ER2 levels. The late period exhibits a longer upper tail, suggesting greater heterogeneity and more pronounced high-ER2 observations in the later stage.

4.2. Baseline Regression Analysis

CER is mean-centered on ER, which helps remove scale-related differences and makes the annual trend easier to compare around its average level. Figure 3A presents the changes in the mean values of ISU and CER1 over time. It can be observed that when the mean value of CER1 increases, the mean value of ISU also tends to rise. However, the specific effect of CER1 on ISU still needs to be further examined through formal baseline regression analysis. Figure 3B is the same but for CER2.

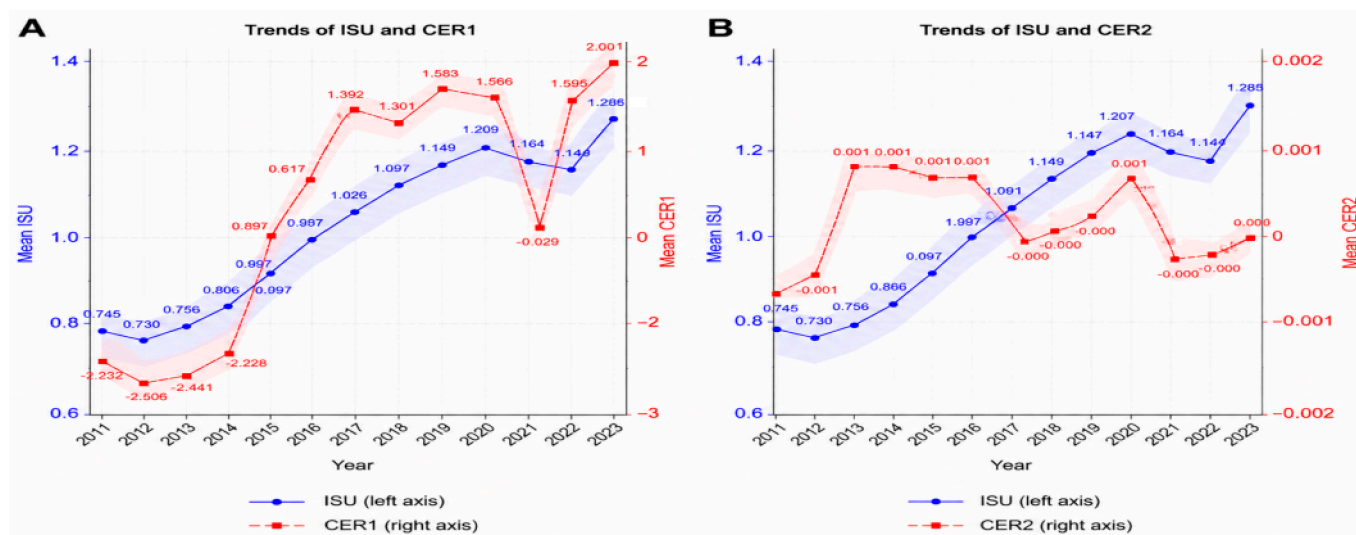


Figure 3. (A) Trends of ISU and CER1. (B) Trends of ISU and CER2.

Table 2A reports three regression specifications for the relationship between CER1 and ISU. Model 1 estimates the baseline association without control variables or fixed effects. Model 2 adds control variables while excluding fixed effects. Model 3 further incorporates both control variables and fixed effects to account for unobserved heterogeneity. Table 2B is the same but for CER2.

According to Table 2A, the significance of CER1 in both Model 2 and Model 3 suggests that the association between CER and ISU is not driven solely by observable control variables or time-invariant individual heterogeneity. Thus, the persistence of the CER coefficient across specifications provides evidence of specification robustness.

Meanwhile, the coefficient of CER2 changes sign across the stepwise specifications. In Model 1, the positive coefficient reflects the unconditional association between guidance-based regulation and ISU. In Model 2, the coefficient becomes negative, suggesting that city-level characteristics may absorb part of the variation between ER2 and ISU. This sign change may be related to the correlation between guidance-based regulation and local economic conditions, industrial scale, financial development, or government intervention. In Model 3, after controlling for fixed effects, the coefficient becomes positive again. Therefore, the positive effect of ER2 should be interpreted cautiously as evidence from the fixed-effects specification, rather than as a fully stable relationship across all model settings.

Figure 4A,B show the result. The “√” mark indicates that the corresponding specification is included, whereas the “×” mark indicates that it is not applied.

Table 2. Baseline Regression Results.

(A) Baseline Regression Results of CER1			
Variables	Model 1	Model 2	Model 3
Constant	0.995 *** (0.011)	−1.016 *** (0.242)	−2.605 *** (0.276)
CER1	0.078 *** (0.005)	0.046 *** (0.005)	0.026 *** (0.003)
Controls	No	Yes	Yes
Fixed effect	No	No	Yes
R ²	0.230	0.378	0.559
(B) Baseline Regression Results of CER2			
Variables	Model 1	Model 2	Model 3
Constant	0.995 *** (0.012)	−1.802 *** (0.236)	−3.601 *** (0.254)
CER2	23.167 *** (4.168)	−8.278 *** (4.061)	7.076 ** (2.971)
Controls	No	Yes	Yes
Fixed effect	No	No	Yes
R ²	0.032	0.330	0.532
(C) Summarized Baseline Regression Results			
Variables	(1) ISU	(2) ISU	
Constant	−2.605 *** (0.276)	−3.601 *** (0.254)	
CER1	0.026 *** (0.003)		
CER2		7.076 ** (2.971)	
IFA	0.017 (0.013)	0.015 (0.014)	
FDI	0.409 (0.529)	0.244 (0.546)	
HC	0.006 (0.001)	0.006 *** (0.002)	
TS	18.057 *** (3.741)	21.173 *** (3.835)	
U	0.132 (0.143)	0.262 * (0.147)	
PGDP	0.304 *** (0.029)	0.387 *** (0.028)	
Fixed effect	YES	YES	
R ²	0.559	0.532	

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Values in () represent standard errors.

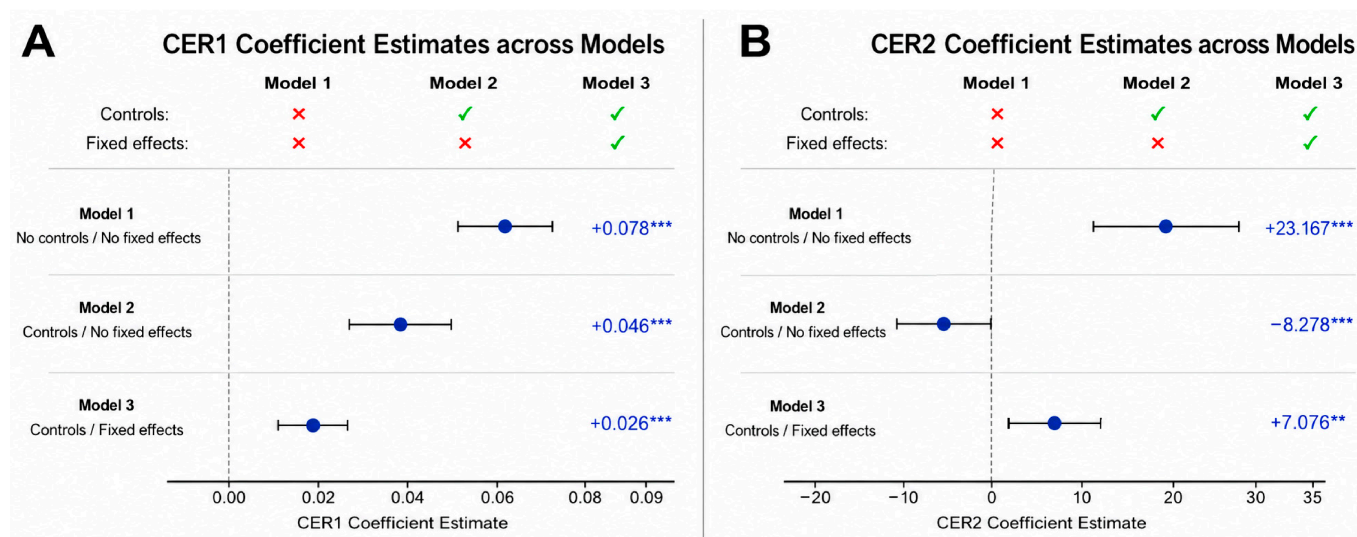


Figure 4. (A) CER1 Coefficient estimates across models. (B) CER1 Coefficient estimates across models. Notes: ** and *** indicate significance at the 5% and 1% levels, respectively.

Table 2C summarizes the fixed-effect regression results of both environmental regulations. As shown in Table 2C, the regression coefficient of command-and-control environmental regulation on industrial structure upgrading is positive and significant at the 1%

level, indicating that Hypothesis H1 is supported. One possible explanation is that enterprises marked by substantial energy demand and high pollution intensity are relatively sensitive to environmental administrative penalties. The high costs of such penalties may consume firms' innovation resources, prompting them to invest in green R&D and improve their level of technological innovation in order to avoid penalties.

The regression coefficient of guidance-based environmental regulation on industrial structure upgrading is positive and significant at the 5% level, indicating that Hypothesis H1 is supported. Government authorities mainly promote this through measures such as green fiscal subsidies, tax reductions or exemptions for qualified green enterprises, direct tax credits for the purchase of environmental protection equipment, and additional tax deductions for green innovation and R&D expenditures, thereby increasing firms' sources of innovation funding, stimulating green innovation activities, improving resource utilization efficiency and labor productivity, and guiding the transformation and upgrading of industrial structure.

4.3. Robustness Test

Robustness tests are conducted on the baseline regression results by using the extreme-value exclusion method and by replacing the dependent variable (Table 3). In the extreme-value exclusion test column (1–2), the baseline model is re-estimated after applying 1% winsorization to both the explanatory and dependent variables, and the empirical results confirm the robustness of the baseline regression results.

Table 3. Robustness Test Results.

Variables	Extreme-Value Exclusion		Shorten Sample Period			Add Control Variables		
	(1) ISU	(2) ISU	(3) ISU	(4) ISU	(5) ISU	(6) ISU	(7) ISU	(8) ISU
Constant	−2.757 *** (0.280)	−3.714 *** (0.260)	−2.809 *** (0.331)	−3.710 *** (0.303)	−2.398 *** (0.312)	−3.934 *** (0.281)	−2.591 *** (0.278)	−3.592 *** (0.256)
CER1	0.026 *** (0.003)		0.019 *** (0.003)		0.035 *** (0.004)		0.026 *** (0.003)	
CER2		6.606 * (3.699)		7.599 ** (2.997)		5.538 * (3.243)		7.058 ** (2.974)
Controls	—	—	—	—	—	—	—	—
Fixed effect	YES	YES	YES	YES	YES	YES	YES	YES
R ²	0.585	0.556	0.538	0.522	0.588	0.539	0.560	0.550

Notes: Estimation results for control variables is omitted for simplicity. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

In addition, this study re-estimates the model using a shorter sample period (excluding 2011 and 2023, columns (3–4), and excluding the COVID-19 period 2021–2022, columns (5–6)). This approach aims to mitigate the potential influence of specific time effects, such as structural breaks or extreme observations in certain years. If the main results remain consistent across different time windows, it indicates that the results are not shaped by specific time intervals but reflect a stable relationship. Another approach is including additional control variables to reduce omitted variable bias and to ensure that the estimated relationship is not driven by other confounding factors, columns (7–8). After running these robustness tests, the regression coefficients of ER1 and ER2 remain significantly positive, which is consistent with the baseline regression results.

4.4. Endogeneity Test

To alleviate potential reverse causality between environmental regulation and industrial structure upgrading, this study further employs the one-period lagged environmental regulation variable in the regression. This approach helps strengthen the temporal ordering between the explanatory variable and the dependent variable, thereby reducing the possibility that current industrial structure upgrading reversely affects current environmental regulation. If the coefficient of the lagged environmental regulation remains consistent with the baseline results, the main findings can be regarded as robust [61,62]. Table 4 shows the result of the lagged regression. The coefficients of LCER1 and LCER2 are positive, which are consistent with the result of baseline regression. The *p*-value of LCER2 is 0.107, which is close to 10% significance.

Table 4. One-period lagged environmental regulation regression.

Variables	(1) ISU	<i>p</i> -Value	(2) ISU	<i>p</i> -Value
Constant	−3.012 *** (0.284)	0.000	−3.853 *** (0.265)	0.000
LCER1	0.023 *** (0.003)	0.000		
LCER2			4.792 (2.970)	0.107
Controls	—	—	—	—
Fixed effect	YES		YES	
R ²	0.580		0.556	

Notes: Estimation results for control variables is omitted for simplicity. *** indicate significance at the 1% levels, respectively.

4.5. Mediation Effect Analysis

Table 5 shows the results of the mediating regression. According to Table 5, command-and-control environmental regulation drives industrial structure upgrading by forcing enterprises to engage in green technology innovation. The coefficient of the direct effect of this regulation on industrial structure upgrading is 0.019, which is significantly positive at the 1% level. The mediation effect coefficient, calculated as the indirect effect divided by the total effect ($0.101 \times 0.075/0.019 = 39.87\%$), indicates that green technological innovation accounts for the partial mediating effect.

Table 5. Mediation Effect Results.

Variables	(1) GTI	(2) GTI	(3) GTI	(4) ISU	(5) ISU	(6) ISU
Constant	−5.276 *** (0.803)	−9.047 *** (0.758)	−7.585 *** (0.817)	−2.207 *** (0.277)	−2.749 *** (0.264)	−3.250 *** (0.271)
GTI				0.075 *** (0.012)	0.094 *** (0.011)	0.080 *** (0.011)
CER1	0.101 *** (0.010)			0.019 *** (0.004)		
CER2		12.676 (8.862)			5.881 ** (2.857)	
LCER			30.302 *** (9.142)			2.380 (2.901)
Control variable	—	—	—	—	—	—
Fixed effect	YES	YES	YES	YES	YES	YES
R ²	0.574	0.523	0.460	0.581	0.569	0.583

Notes: Estimation results for control variables is omitted for simplicity. ** and *** indicate significance at the 5% and 1% levels, respectively.

Additionally, the coefficient of ER2 on GTI is 12.676 ($p = 0.153$) beyond the 10% level, which is insignificant, suggesting that the green technological innovation cannot function as a mediating role in the contemporaneous-data test. However, considering that it takes time for firms to move from receiving subsidies to conducting R&D and ultimately generating patent outputs, this study lags CER2 by one period to examine the effect of lagged CER2 on GTI and the mediating effect under this dynamic specification.

From columns (3) and (6), the lagged CER2 has a significantly positive coefficient on GTI and passes the mediation effect test. This suggests that the impact of guidance-based environmental regulation on industrial structure upgrading does not occur directly but is mainly achieved indirectly through promoting green technological innovation. Figure 5A–C visualize the above results.

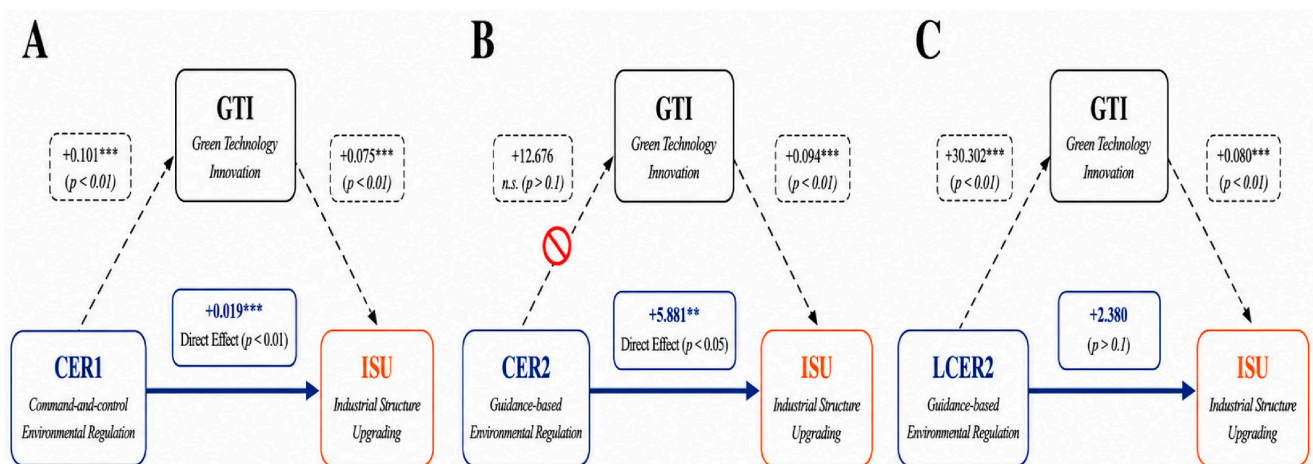


Figure 5. (A) Mediating regression results for CER1. (B) Mediating regression results for CER2. (C) Mediating regression results for lagged CER2. Notes: ** and *** indicate significance at the 5% and 1% levels, respectively.

In summary, H2 is partly verified. Green technological innovation plays a partial mediating role in the relationship between command-and-control environmental regulation and industrial structure upgrading. Although the mediation test based on contemporaneous CER2 data is not statistically significant, the mediation effect becomes significant when a one-period lag of CER2 is introduced. A possible explanation is that firms need time to move from receiving policy support to engaging in R&D activities, and finally to transforming R&D inputs into observable innovation outputs such as patents. Moreover, guidance-based regulation usually operates through softer mechanisms such as policy guidance, information disclosure, market signals, and voluntary adjustment, rather than direct compulsory pressure [63,64].

4.6. Moderating Effect Analysis

Environmental regulation and inclusive digital finance are mean-centered to reduce the influence of multi-collinearity. In addition, digital finance works as a slow-moving institutional and economic factor, whose influence on firm behavior operates with a temporal lag. Firms' strategic choices are thus conditioned by previously formed environmental perceptions and resource endowments, rather than contemporaneous fluctuations. Therefore, it is lagged by one period to alleviate simultaneity bias and to better reflect the pre-existing financial conditions under which firms make strategic decisions. By incorporating the interaction terms between environmental regulation and inclusive digital finance into the model, this study empirically tests the moderating effect of inclusive digital finance on the effect of environmental regulation on industrial structure upgrading.

According to Table 6 columns (1)–(2), the coefficient of the interaction term between command-and-control environmental regulation and inclusive digital finance is -0.001 , indicating that inclusive digital finance serves a negative moderating role in the effect of environmental regulation on industrial structure upgrading. One possible explanation for the negative result is that in areas where the digital economy is more advanced, well-functioning market mechanisms and improved corporate governance reduce the marginal effectiveness of command-and-control regulations. Conversely, in less developed environments, where market mechanisms are weaker and firms exhibit stronger short-termism, mandatory regulations serve as a more important disciplining force. Therefore, the effectiveness of command-and-control regulations is stronger in low DF regions [65].

Table 6. Moderating Effect Results.

Variables	(1) ISU	(2) ISU	(3) ISU	(4) ISU
Constant	-1.284^{***} (0.377)	-1.282^{***} (0.376)	-1.354^{***} (0.374)	-1.448^{***} (0.375)
LCDF	0.001^{***} (0.001)	0.001 (0.001)	0.001^{***} (0.001)	0.001^{***} (0.001)
CER1	0.007^{**} (0.004)	0.008^{***} (0.004)		
CER1 $\times$ LCDF		-0.0001^{***} (0.000)		
CER2			9.178^{***} (2.694)	6.377^{**} (2.920)
CER2 $\times$ LCDF				0.062^{**} (0.025)
Controls	—	—	—	—
Fixed effect	YES	YES	YES	YES
R ²	0.599	0.600	0.602	0.605

Notes: Estimation results for control variables is omitted for simplicity. ** and *** indicate significance at the 5% and 1% levels, respectively.

Based on columns (3)–(4), the coefficient of the interaction term between guidance-based environmental regulation and inclusive digital finance is 0.062 , and the coefficients of the main effects of guidance-based environmental regulation and inclusive digital finance are both positive. The results show that inclusive digital finance positively strengthens the relationship in the process by which guidance-based environmental regulation promotes industrial structure upgrading, which is consistent with Hypothesis H3. This indicates that inclusive digital finance promotes industrial structure upgrading by directing funds to green industries and guiding polluting industries to reduce carbon emissions.

Moreover, the effectiveness of guidance-based regulations depends on firms' absorptive capacity and resource endowments. In high-DF regions, where firms possess stronger human capital, better financing access and more advanced information-processing capabilities, policy signals can be more effectively internalized and transformed into concrete actions. In contrast, under low-DF conditions, these enabling factors are largely absent. As a result, guidance-based regulations tend to be less effective, as firms face greater difficulties in translating policy signals into concrete actions [66,67].

Figure 6A,B are constructed based on Table 6. As seen in Figure 6A, since the original slope of no-interaction is positive, while the slope of the interaction term line is flatter, indicating that DF plays a negative moderating role. Conversely, in Figure 6B, when the slope of the interaction term line is sharper, it indicates that DF plays a positive moderating role.

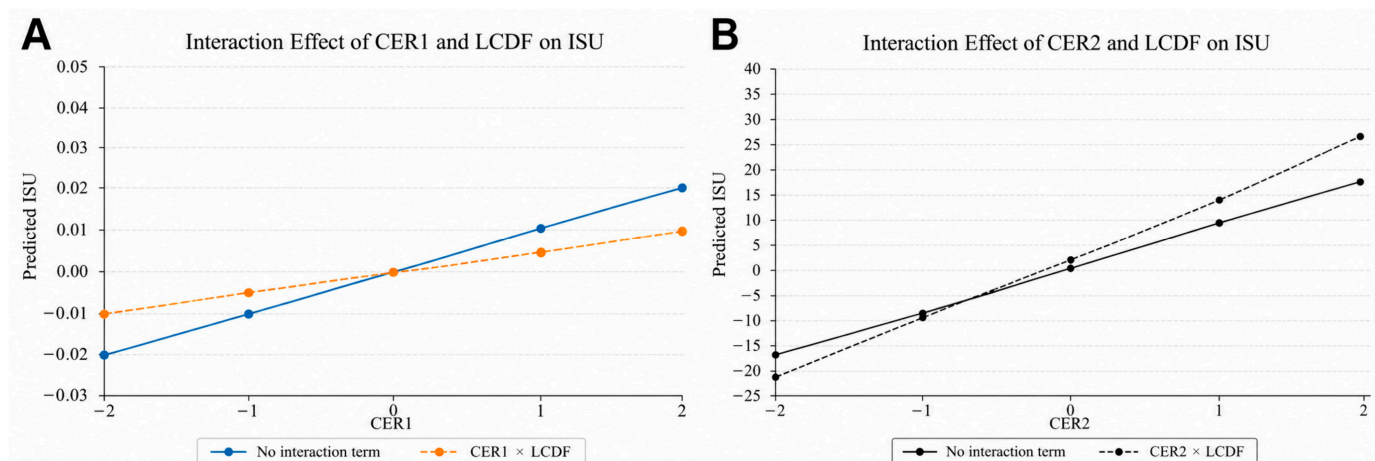


Figure 6. (A) Interaction effect of CER1 and LCDF on ISU. (B) Interaction effect of CER1 and LCDF on ISU.

4.7. Regional Heterogeneity Test of Environmental Regulation

The Chengdu–Chongqing urban cluster primarily includes Chongqing and core cities in Sichuan Province, such as Chengdu. The Middle Reaches of the Yangtze River urban cluster includes core cities in Hubei, Hunan, and Jiangxi provinces. According to the national regional development policy approved by the State Council in 2016, the Yangtze River Delta urban cluster covers Shanghai and parts of Jiangsu, Zhejiang, and Anhui provinces. Using sample data from the three regions, Equation (1) was re-estimated (Tables 7–9).

Table 7. Chengdu–Chongqing Urban Test Results.

Variables	(1) ISU	(2) ISU
Constant	4.435 *** (1.221)	4.127 *** (1.239)
ER1	0.021 ** (0.007)	
ER2		15.862 (11.013)
Controls	—	—
Fixed effect	YES	YES
R2	0.734	0.725

Notes: Estimation results for control variables is omitted for simplicity. ** and *** indicate significance at the 5% and 1% levels, respectively.

Table 8. Yangtze River Urban Test Results.

Variables	(1) ISU	(2) ISU
Constant	−2.178 *** (0.418)	−3.015 *** (0.412)
ER1	0.035 *** (0.007)	
ER2		3.663 (5.771)
Controls	—	—
Fixed effect	YES	YES
R2	0.557	0.524

Notes: Estimation results for control variables is omitted for simplicity. *** indicate significance at the 1% levels.

In the Chengdu–Chongqing urban agglomeration, command-and-control environmental regulations can significantly promote industrial structure upgrading, whereas guidance-based instruments contribute to the improvement of industrial system upgrading, although the effect is not significant. A possible reason is that the increase in investment in environmental pollution control in the Chengdu–Chongqing urban agglomeration may

squeeze innovation funding, or that pollution control investment has a lagged effect and has not yet fully played its role.

Table 9. Yangtze River Delta Urban Test Results.

Variables	(1) ISU	(2) ISU
Constant	−1.971 *** (0.519)	−3.352 *** (0.459)
ER1	0.024 *** (0.005)	
ER2		7.359 ** (3.591)
Controls	—	—
Fixed effect	YES	YES
R2	0.549	0.519

Notes: Estimation results for control variables is omitted for simplicity. ** and *** indicate significance at the 5% and 1% levels, respectively.

Similar to the Chengdu–Chongqing urban agglomeration, in the urban agglomeration in the middle reaches of the Yangtze River, command-and-control environmental regulations can significantly promote industrial structure upgrading, while guidance-based environmental regulation has a positive effect on industrial structure upgrading, but the effect is not significant.

In the Yangtze River Delta urban agglomeration, command-and-control and guidance-based environmental regulations can all significantly promote industrial structure upgrading, which is consistent with the baseline regression results. The above empirical evidence suggests that the contribution of environmental regulation to industrial structure upgrading exhibits regional heterogeneity; therefore, Hypothesis H4 is supported.

5. Discussion

5.1. Key Findings

Based on an investigation of the pathways through which ecological policy measures and eco-oriented innovation shape industrial transformation, this study conducted an empirical investigation using fixed effects, mediation effect models, and regulating effect models, as well as a regional heterogeneity analysis of environmental regulation. The key findings are as follows:

Firstly, command-and-control and guidance-oriented environmental regulation can both promote industrial structure upgrading, but their effects differ. Former regulation mainly works through mandatory constraints and compliance pressure, forcing firms to reduce inefficient and polluting production activities. Later regulation, in contrast, relies more on policy incentives, market signals, and supportive measures, encouraging firms to improve production efficiency and move toward cleaner and higher-value activities.

Secondly, green technology innovation acts as a mediating mechanism in the process by which command-and-control environmental regulation facilitates industrial structure upgrading, which suggests that regulatory policies work more than directly reshaping the industrial structure. Instead, they operate by inducing firms to engage in innovation activities that enhance production efficiency, facilitate technological upgrading, and promote the reallocation of resources toward more sustainable sectors [40].

Thirdly, the effect of environmental regulation on industrial structure upgrading may vary because of differences in the moderating effect of digital finance. For command-and-control regulation, higher DF weakens its effect because firms in high-DF regions already face stronger market discipline, better governance, and more efficient information mechanisms. In contrast, guidance-based regulation is more effective in high-DF regions, where firms possess stronger absorptive capacity, financing conditions, human capital,

and information-processing capabilities, enabling them to translate policy guidance into concrete actions.

Finally, the effects of different types of environmental regulation on industrial structure upgrading exhibit regional heterogeneity. This suggests that the effectiveness of environmental regulation depends not only on the policy instrument itself, but also on regional conditions. Differences in economic development, industrial foundation, innovation capacity, digital finance development, and policy enforcement may affect how firms respond to environmental regulation.

5.2. Implications

In the context of China's emphasis on green and low-carbon transformation and the promotion of green technology innovation, these findings provide significant policy implications and offer a reference for similar regions pursuing both environmental protection and industrial upgrading.

Building an Appropriate Local Environmental Regulation System. Local governments should tailor the intensity of guidance-oriented environmental regulation to local conditions, clarify environmental governance responsibilities, and increase fiscal investment in environmental protection. Policy support such as tax and fee reductions for enterprises engaged in environmental governance should be strengthened, while an integrated ecological governance mechanism should be established. In addition, a big data platform should be developed to analyze pollution sources and mitigation efforts, thereby enhancing the participation and supervision of government, society, and enterprises. The punitive effect of command-and-control environmental regulation can also be leveraged to promote regional green technology innovation. Meanwhile, local governments should also avoid excessively stringent regulation that may cause productivity losses.

Promoting Green Technology Innovation to Drive Industrial Structure Upgrading. Regional technology innovation collaboration platforms should be established to strengthen technology exchange and cooperation within and between urban clusters. The leading role of technology-oriented enterprises should be used to create a favorable innovation environment for small and medium-sized technology enterprises. At the same time, traditional manufacturing should be modernized to accelerate industrial transformation and upgrading. The core role of green innovation in industrial structure upgrading should be further strengthened to achieve coordinated development between green technology innovation and industrial upgrading across regions.

Improving the Capacity of Digital Finance. In the digital economy era, governments should help release the enabling effect of digital finance on green technological innovation. For example, a green information statistical platform involving enterprises, government, and the public can be established to support real-time collection and analysis of green business information. Digital financial technology should also be used to promote R&D investment in blockchain and the Internet of Things in green industries, thereby supporting industrial structure upgrading and strengthening the positive interaction among environmental regulation, digital finance, green technology innovation, and industrial structure upgrading.

5.3. Limitations

This study also has several limitations. First, the measurement of variables may not fully capture the actual characteristics of the indicators. Therefore, the empirical results should be interpreted within specific conditions, and their representativeness and generalizability should be treated with caution. Second, the research sample does not

cover all regions of China. Future studies may extend the data scope and conduct a more comprehensive analysis based on a broader sample.

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Abbreviations

The following abbreviations are used in this manuscript:

ISU	Upgrading of industrial structure
GTI	Green technology innovation
ER1	Environmental administrative punishment
ER2	Environment-related investment/ Value added of the secondary industry
IFA	Investment in fixed assets/GDP
FDI	Foreign Direct Investment/GDP
HC	Human capital level
TS	Scientific and technological/GDP
U	Urbanization rate
PGDP	real GDP per capital
DF	Digital finance
LCDF	Lagged and centered Digital finance
GDP	Gross Domestic Product

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