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Impact of Heterogeneous Environmental Regulation on Carbon Emissions: Firm-Level Evidence from China's Manufacturing Industry

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Abstract

Government implementation of environmental regulatory measures is typically an efficacious means of mitigating carbon emissions from firms, and the diversification of regulatory forms provides producers with diversified choice space so that enterprises can choose ecologically favorable production methods according to their own circumstances. Based on the unbalanced panel data of 2140 listed manufacturing companies in China from 2011 to 2019, this study uses a fixed-effects model to investigate the impact and mechanisms of command-and-control, market-based, and public participation environmental regulations on corporate carbon emissions. The study finds that all three types of environmental regulations significantly reduce corporate carbon emissions, and the results are robust. Mechanism tests suggest that environmental regulations can reduce corporate carbon emissions by increasing research and development (R&D) investment. Heterogeneity analysis indicates that the carbon reduction effect of environmental regulations is more pronounced in samples of enterprises in the eastern region, heavily-polluting industries, and highly marketized industries. Further analysis reveals that digital transformation negatively moderates the impact of command-and-control and public participation environmental regulations on corporate carbon emissions. The aforementioned findings offer policymakers significant empirical evidence on effectively promoting the development of low-carbon initiatives and enhancing coordination in China' s government regulations for environmental governance.

Keywords: environmental regulations, corporate carbon emissions, R&D investment, heterogeneity analysis, digital transformation

1. Introduction

Carbon emissions are a significant contributor to environmental pollution and climate instability, posing a serious challenge to both global ecosystems and socioeconomic development (Pei et al., 2019; Wu et al., 2023). China' s energy demand is increasing rapidly due to accelerated industrialization and rapid economic development (Cui et al., 2022a). As a result, there has been a sharp rise in the consumption of oil, coal, and other energy sources, leading to high carbon emissions. (Wang et al., 2019). Given the escalating carbon emission crisis, the Chinese government must establish and enforce a set of stringent environmental rules in order to address environmental pollution and drive the country towards energy conservation, emission reduction, and sustainable growth (Zou & Zhang, 2022). Achieving the "carbon peak and carbon neutrality" target in China necessitates a thorough examination of the ways in which environmental regulations aid in the reduction of carbon emissions and the mechanisms through which they facilitate this goal.

The word "environmental regulation" refers to a wide range of statutes and regulations enacted to preserve natural ecosystems (Yin et al., 2022). Carbon emissions are a result of production and consuming activities and have an impact on the environment. The market mechanism alone is not sufficient to effectively control carbon emissions. Therefore, the use of a third-party instrument is necessary to effectively limit carbon emissions (Wang & Zhang, 2022). In order to control carbon emissions and achieve the goal of reducing emissions, governments institute and enforce regulatory laws while intervening in the financial operations of relevant financial institutions (Ge et al., 2022). Existing research has substantiated that environmental regulation serves as a potent tool in overseeing environmental and developmental issues, prompting governments worldwide to deploy environmental regulatory measures prudently to manage carbon emissions effectively (Zhang et al., 2020).

Despite the substantial advancements in China' s manufacturing sector following economic reforms and opening-up policies, the rapid expansion of the business is frequently accompanied by substantial carbon emissions and energy consumption (An et al., 2023; Avenyo & Tregenna, 2022; Wang et al., 2022b). Between 2007 and 2019, the manufacturing sector experienced a typical yearly increase of 4.14% in energy use and a carbon emissions growth rate of 3.01% per year on average (Wang et al., 2023b). These figures present significant challenges and pressures for China' s overall carbon emission reduction efforts. Furthermore, they contribute to a range of issues such as deteriorating environmental conditions, negative effects on public health, and the promotion of unsustainable economic growth (Chontanawat, 2020; Lee & Choi, 2021). Therefore, prioritizing emission reductions and energy conservation in the manufacturing sector is imperative. Government initiatives aimed at carbon control should predominantly focus on enterprises, as they serve as the primary sources of both individual-level economic growth and carbon emissions. Lowering carbon emissions is an essential endeavor that China must undertake (Shang et al., 2023).

Porter' s theory posits that carrying out reasonable environmental rules can incentivize businesses to seek improvements in production technologies and bolster their environmental protection measures. Cost reductions resulting from technological innovations have the potential to offset or even outweigh cost increases resulting from environmental regulations, increase resource efficiency and reduce carbon emissions (Wu & Lin, 2022). Among various methods to foster technological progression, augmenting investments in research and development emerges as the pragmatic and crucial approach to driving technological innovation (Huang et al., 2020). A firm' s research and development (R&D) activities can significantly influence its environmental sustainability, especially in terms of reducing energy consumption and minimizing carbon emissions (Hailemariam et al., 2022; He et al., 2021; Hoang, 2022; Yang et al., 2021). Furthermore, to achieve a harmonious combination of mitigating carbon emissions and promoting financial efficiency, it becomes crucial to foster technological advancements and enhance overall productivity efficiency (Wang et al., 2021). In light of this, societal sustainable development goals can be advanced by the application of various techniques that push businesses to increase their spending on R&D and the intensity with which they approach it (Cubillos & Cardoso, 2020).

Porter' s hypothesis is frequently widely employed to investigate how environmental regulations affect carbon emissions. Numerous studies have been conducted at both the meso- and macro-levels, yielding relatively mature research findings. Nonetheless, there is a lack of literature addressing the implications of both formal and informal environmental legislation on carbon emissions on a micro level. This study differentiates between formal environmental regulation, which entails the government' s establishment of environmental regulations and legislation, and market-driven regulatory systems include both command-and-control and market-driven techniques. Contrarily, informal environmental regulation heavily relies on public' s consciousness of environmental protection and individuals' and society' s voluntary regulation and oversight of environmental pollution. This is exemplified through public participation (Zhang et al., 2022a). Enterprises are the primary contributors to environmental pollution. Surveys conducted at the enterprise level provide more detailed insights and diverse findings compared to surveys conducted at the province or industry level. The objective of this study is to examine the influence of various environmental regulation measures on carbon emissions at a small level. The study categorizes environmental regulatory tools into three groups, providing a theoretical foundation for governments to implement more focused environmental regulations.

The prospective impacts of this work predominantly appear in two crucial domains. Firstly, by examining the effects of various environmental regulatory tools on micro-level carbon emissions and classifying them into three categories, this research illuminates the low-carbon effects of diverse environmental regulations and their diverse impacts, essential for understanding the positive outcomes of low-carbon development facilitated by these regulations. It assists governments in crafting supportive policies aligned with environmental regulations, improving the carbon emission performance of businesses, and promoting low-carbon development. Secondly, building on Porter' s theory, this study delves into the mechanisms that underlie the effects of different environmental regulations on carbon emissions at the micro level. In contrast to conventional research methodologies, this study incorporates the unique research context, exploring not just the mediating role of R&D investments but also the moderating impact of digital transformation, enriching the ongoing discussion on reducing carbon emissions at the micro level.

2. Theoretical Analysis and Research Hypothesis

2.1 Environmental Regulation and Corporate Carbon Emissions

Environmental regulation pertains to the governmental framework put in place to supervise and alleviate the adverse impacts of market activity on the environment. Its goal is to address environmental challenges resulting from economic operations through administrative structures, market mechanisms, and public engagement (Hao et al., 2018). To curb emissions effectively, governmental intervention through environmental regulatory measures is crucial to restrict polluting industries, as environmental laws' primary goal is environmental protection, offering significant potential to mitigate carbon emissions broadly (Liu et al., 2023b; Xu & Xu, 2022). While previous research predominantly scrutinized environmental regulation as a unified entity to gauge its influence on carbon emissions, the intricate nature of regulatory tools and diverse behavioral factors involved often constrains the explanatory power of findings derived from this analytical approach (Wang et al., 2022a). This research categorizes environmental regulating instruments into three distinct forms: command-and-control, market incentive, and public engagement (Ren et al., 2018). These types are analyzed to determine their respective impacts on corporate carbon emissions.

Command-and-control environmental regulation (ER1) encompasses governmental laws, regulations, policies, and standards intended to curtail and oversee businesses' polluting activities, with these regulations carrying legal authority and imposing obligations on enterprises. Non-compliance with these regulations can result in penalties or even the closure of the offending businesses (Xie et al., 2017). The government may effectively control high carbon emissions and pollution production by enforcing a stricter environmental protection system and implementing more stringent and professional identification of carbon emissions and ecological damages. This approach will result in a large increase in the economic costs borne by firms (Zhao et al., 2022). Furthermore, to circumvent substantial penalties, companies may be motivated to adapt, modernise, and enhance their equipment or technology, as well as enhance energy efficiency and productivity to diminish carbon emissions (Bu & Shi, 2021).

Market-incentivized environmental regulation (ER2) is a government approach that utilises market-based methods instead of forceful measures to regulate the polluting actions of companies and internalise their environmental pollution. This is achieved through tools like environmental taxes, financial subsidies, and carbon emissions trading systems (Shi et al., 2022). Unlike ER1, ER2 is more flexible in that it does not force firms to improve their carbon performance, but mainly encourages them to reduce emissions by raising their pollution costs or providing economic incentives (Huang & Tian, 2023). Through imposing taxes and fees on enterprises and offering subsidies for cleaner energy sources, the government can effectively reduce carbon emissions by enhancing costs, internalizing negative externalities, and promoting cleaner energy adoption (Bai et al., 2023; Huang & Yi, 2023).

Public-participation environmental regulation (ER3) entails voluntary efforts by the public and economic entities independent of governmental enforcement, with adoption and effectiveness dependent on environmental awareness within these groups. ER3 motivates public engagement in environmental protection activities, potentially reducing government costs for oversight (Shen et al., 2023). This regulatory approach involves environmental actions like submitting letters, oversight by NGOs, and proposals from legislative bodies, aiming to highlight pollution issues to prompt enterprises to address environmental concerns and achieve energy conservation goals (Liu et al., 2023c). ER3 exercises pressure on local environmental governance to enforce regulations, leading to tangible carbon control outcomes. In summary, this study posits the following hypotheses.

H1a: Implementing ER1 can effectively decrease corporate carbon emissions.

H1b: Implementing ER2 can effectively decrease corporate carbon emissions.

H1c: Implementing ER3 can effectively decrease corporate carbon emissions.

2.2 Mediating Role of R&D Investment

Environmental regulation is widely acknowledged as a critical driver for promoting technological innovation (Yu & Zhang, 2022). The Porter' s theory suggests that stringent and well-crafted environmental restrictions can motivate corporations to participate in the development of new technical advancements. In response to the requirements imposed by environmental regulations, profit-driven firms will strive to find the most efficient and cost-effective methods of compliance. This, in turn, fosters technological innovation and enhances competitiveness in the market, resulting in a mutually beneficial outcome (Porter & Linde, 1995). Early neoclassical economic theory argued that the imposition of government regulation leads to the internalization of external costs, increases firm costs, reduces industry size, and ultimately negatively affects the innovation and competitiveness of the regulated firms (Palmer, 1995). From the perspective of businesses, environmental restrictions such as technological standards, environmental charges, or tradable emissions that necessitate the allocation of resources towards pollution control are frequently viewed as insufficient, notwithstanding the potential environmental and societal advantages they could provide. The reason for this is that if enterprises are mandated to decrease or internalise an externality such as pollution, it will inevitably limit their choices or resources in the manufacturing procedure, redirecting capital away from profitable projects (Zhou et al., 2021). Therefore, if environmental restrictions have the potential to create profitable opportunities for reducing pollution, enterprises that prioritise maximising profits should have already capitalised on these chances (Huang et al., 2021). Hence, enterprises' technical innovation may be adversely affected by environmental legislation. Furthermore, certain studies indicate that there is a complex relationship between environmental regulations and corporations' expenditure on R&D, which is mostly influenced by the level of environmental regulation (Guo et al., 2018; Wang et al., 2018).

Enterprise R&D is crucial in fostering technical progress that enhances manufacturing efficiency while minimizing energy usage. This includes the comprehensive utilization of resources, the creation of low-carbon or zero-carbon technologies through innovative processes, energy conservation initiatives, carbon emission reduction, and enterprise carbon performance enhancement (Alam et al., 2019; Churchill et al., 2019). Theoretically, technical innovation is crucial for carbon emission reduction in businesses, with increased R&D investment standing out as a practical and fundamental means to achieve innovation (Chang et al., 2019). Notably, scholars have investigated the green attributes of R&D spending and empirically demonstrated its inverse relationship with corporate carbon dioxide emissions, indicating that higher R&D expenditures significantly reduce carbon dioxide emission intensity in listed companies (Li et al., 2022a). The relationship between R&D investment and carbon emissions might show nonlinearity, with a clear inverted U-shaped pattern in addition to linear correlations (Li et al., 2021).

Effective environmental regulations necessitate that companies conserve energy and decrease carbon emissions. To comply with these regulations without incurring financial losses, companies may focus on enhancing technology and equipment to reduce expenses and actively pursue technological innovations through R&D (Pan et al., 2021). Therefore, in principle, environmental legislation incentivizes resource allocation to R&D, leading to the beneficial outcome of carbon emission reduction. By conducting data analysis, it becomes clear that investments in R&D have a significant influence on the relationship between environmental rules and the amount of carbon emissions produced by corporations. Consequently, this study presents the following hypotheses.

H2a: R&D investment serves as an intermediary in the connection between ER1 and corporate carbon emissions.

H2b: R&D investment serves as an intermediary in the connection between ER2 and corporate carbon emissions.

H2c: R&D investment serves as an intermediary in the connection between ER3 and corporate carbon emissions.

3. Research Design

3.1 Research Samples and Data Sources

This study focuses on Chinese A-share listed companies in the manufacturing sector during the period from 2011 to 2019. The year 2010 was a pivotal juncture in China' s economic progression, as it signaled the onset of comprehensive data collection and recording for Chinese A-share listed companies. This streamlined data acquisition for researchers post-2010, prompting the initiation of this study from the year 2011 onwards. Excluding Hong Kong, Macau, Taiwan, and Tibet due to data unavailability, this study applies several measures during primary data collection: 1) Exclusion of firms under special treatment labels from the SSE and SZSE, such as ST and *ST. 2) Elimination of listed companies with significant data deficiencies from 2011 onwards. 3) To address extreme values, all continuous variables are winsorized at the 1% level. Ultimately, the study consists of 11,993 sample observations.

Data for calculating corporate carbon emissions are sourced from the China Statistical Yearbook and China Industrial Statistical Yearbook, while financial data are obtained from the China Stock Market and Accounting Research Database (CSMAR). Environmental regulation data are extracted from various sources, including the China Statistical Yearbook 2011-2019, China Environmental Statistics Yearbook, China Environmental Yearbook, China Industrial Statistics Yearbook, and China Energy Statistics Yearbook. The data calculation process was completed by Stata 16.0 software.

3.2 Research Variables

3.2.1 Dependent Variable

Corporate carbon emissions (CE). Due to data limitations, direct access to the carbon emission data of Chinese enterprises is not possible. Therefore, building on the research by Wang et al. (2023a), this paper estimates CE by utilizing industry carbon emissions obtained from operating costs. Industry carbon emissions are derived from industry energy consumption data published and the CO_2 conversion factor provided by the Xiamen Energy Conservation Center, as detailed in the study by Lin & Jia (2019).The formula for estimating carbon emissions of enterprises is shown below:

$$CE_{i,t} = C_{j,t} \times 2.493 \times cost\_ f_{i,t} / cost\_ i_{j,t} \quad (1)$$

Among them: $CE_{i,t}$ represents the carbon emissions of company *i* in period *t*; $C_{j,t}$ represents the energy consumption of industry *j* in period *t*; 2.493 represents the carbon dioxide conversion coefficient of 1 ton of standard coal; $cost\_f_{i,t}$ represents the cost of the main business of company *i* in period *t*, and $cost\_ i_{j,t}$ represents the cost of main business of the industry *j* that company *i* belongs to in period *t*.

3.2.2 Independent Variables

The independent variables in this study consist of three distinct types of environmental regulations: command-and-control environmental regulation, market incentive environmental regulation, and public participation environmental regulation. The details are as follows.

Command-and-control environmental regulation (ER1). Employing the indicators from Cui et al. (2022b) and Wang et al. (2022), this study utilizes industrial wastewater emissions, industrial sulfur dioxide emissions, public sector soot emissions, the number of environmental protection laws and regulations issued by provinces, and the number of administrative penalty cases accepted to quantify ER1.

Market incentive environmental regulation (ER2). Following the research by Li et al. (2019), this paper adopts industrial pollution control investment as a portion of regional GDP, environmental infrastructure construction investment as a percentage of regional GDP, sewage charges (environmental tax), and environmental expenditure as a fraction of local general public budget expenditures to gauge ER2.

Public participation environmental regulation (ER3). Drawing from the study by Yang & Wang (2022), this research utilizes the number of recommendations and proposals from the two sessions of the National People’ s Congress (NPC), the count of key pollutant-emitting units implementing automated monitoring, and the number of nature reserves to assess ER3.

In summary, the entropy weight method is used to calculate the three types of environmental regulation tools mentioned above (Fang & Shao, 2022).

3.2.3 Mediating Variable

Research and development (R&D) investment. R&D within a company encompasses intangible aspects that are challenging to precisely measure, such as the innovative ideas and knowledge of R&D personnel. Nevertheless, companies need to allocate significant resources to attain these subjective elements. Hence, the magnitude of a company’ s R&D investment, indicated by the ratio of R&D investment to core business revenue, can serve as a measure of the firm’ s R&D investment level (Pan et al., 2021).

3.2.4 Control Variables

Referring to Chen (2023) and Dai et al. (2022), the control variables in this study comprise firm size (Size), firm age (Age), asset-liability ratio (Lev), capital intensity (Capin), sales growth rate (Growth), cash ratio (Cflow), net profit margin on total assets (ROA), proportion of independent directors (Idr), and two positions (Dual). Additionally, this research adjusts for time and industry-fixed effects.The definition of each variable is shown in Table 1.

Table 1. Variable definitions

Variable type	Variable name	Symbols	Definition
Dependent variable	Carbon emissions	CE	Industry energy consumption x 2.493 x business operating costs/industry operating costs.
Independent variables	Command-and-control environmental regulation	ER1	Industrial wastewater emissions, industrial sulfur dioxide emissions, industrial soot emissions; number of environmental protection laws and regulations issued by provinces; number of administrative penalty cases received.
	Market incentive environmental regulation	ER2	Ratio of investment in industrial pollution control to regional GDP; ratio of investment in environmental infrastructure construction to regional GDP; sewage charges (environmental tax); ratio of environmental expenditure to local general public budget expenditure.
	Public participation environmental regulation	ER3	Number of recommendations and proposals of the two sessions; number of key pollutant emission units implementing automatic monitoring; number of nature reserves.

Mediating variable	R&D investment	RD	Ratio of corporate R&D investment to operating revenue.
Control variables	Firm size	Size	Natural logarithm of total enterprise assets.
	Firm age	Age	Natural logarithm of current year - year of establishment + 1.
	Cash ratio	Cflow	Net cash flow to total assets ratio.
	Capital density	Capin	Ratio of capital expenditures to total assets at the beginning of the period
	Asset-liability ratio	Lev	Total liabilities at year-end to total assets at year-end.
	Total assets net profit margin	ROA	Net profit to total assets.
	Sales growth rate	Growth	Ratio of change in sales revenue for the current period to sales revenue for the previous period.
	Proportion of independent directors	Idr	Ratio of the number of independent directors to the size of the board.
	Whether the chairman and general manager are one person	Dual	The chairman of the board and the general manager are the same person as 1, otherwise 0.

3.2.5 Model Setting

To examine the influence of various environmental regulatory tools on corporate carbon emissions, referring to Qi et al. (2022), this paper establishes the following fixed effect model:

$$CE_{i,t} = \alpha_0 + \alpha_1 ER_{i,t} + \alpha_2 Con_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \tag{2}$$

Among them: $CE_{i,t}$ represents the carbon emissions of firm i in period t; $ER_{i,t}$ represents the environmental regulations in the province where firm i is located in period t; $Con_{i,t}$ represents a set of control variables, θ_i and μ_t represents industry and year fixed effects, and $\varepsilon_{i,t}$ represents a random disturbance term.

To investigate the influence of environmental regulation on corporate carbon emissions, this paper introduces R&D investment as a mediating variable and formulates the following mediating effect model (Tan & Zhu, 2022) :

$$RD_{i,t} = \alpha_0 + \alpha_1 ER_{i,t} + \alpha_2 Con_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \tag{3}$$

$$CE_{i,t} = \alpha_0 + \alpha_1 ER_{i,t} + \alpha_3 RD_{i,t} + \alpha_2 Con_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \tag{4}$$

Among them: $RD_{i,t}$ represents the level of R&D investment of firm i in period t; the other variables are as described above.

4. Empirical Results and Analysis

4.1 Descriptive Statistics

Table 2 presents the descriptive statistical data for the variables. From the table, it can be seen that the average value of CE is 40.36, with a significant range, reflecting that many sample companies are facing energy conservation and emission reduction issues. Among the three environmental regulation tools, ER2 has the smallest standard deviation, ER3 has the smallest mean value, and the ranges of the three environmental regulations are relatively large, indicating that there is a significant difference in the intensity of environmental regulations among provinces in China, providing a realistic background for studying the impact of heterogeneous environmental regulations on CE. The mean value of RD is 0.0427, indicating that sample companies are more focused on technological or product innovation. Additionally, the variance of most variables is less than the mean value, indicating relatively small coefficients of variation and good stability of the sample.

Table 2. Descriptive statistical results

Variables	Obs	Mean	SD	Min	Max
ER1	11,993	0.276	0.110	0.122	0.795
ER2	11,993	0.216	0.0796	0.0737	0.493
ER3	11,993	0.196	0.120	0.00441	0.508
CE	11,993	40.36	161.6	0.149	2,944
RD	11,993	0.0427	0.0342	0	0.242
Size	11,993	21.90	1.124	19.78	26.04
Age	11,993	2.723	0.365	1.099	3.584

Cflow	11,993	1.036	1.943	0.0182	27.65
Capin	11,993	2.089	1.189	0.401	8.840
Lev	11,993	0.376	0.193	0.0291	0.906
ROA	11,993	0.0432	0.0574	-0.381	0.213
Growth	11,993	0.169	0.333	-0.481	2.330
Idr	11,993	37.46	5.319	30	60
Dual	11,993	0.314	0.464	0	1

4.2 Empirical Results

4.2.1 Basic Regression Analysis

Table 3 displays the benchmark regression outcomes regarding the impact of three types of environmental regulations on carbon emissions. From the results in column (1), it can be seen that ER1 has a significant negative impact on CE at the 5% significance level, indicating that ER1 has a suppressive effect on CE. This is mainly reflected in that for every 1 percentage point increase in the intensity of ER1, CE decrease by 0.182 percentage points, confirming H1a. The results in column (2) show that the regression coefficient of ER2 on CE is negative and passes the 5% significance test. From the coefficient value, for every 1 percentage point increase in the intensity of ER2, CE decrease by 0.249 percentage points, confirming H1b. The results in column (3) for ER3 on CE regression show a negative coefficient at the 1% significance level. This indicates that ER3 has a suppressive effect on CE, meaning that for every 1 percentage point increase in the intensity of ER3, CE decrease by 0.359 percentage points, thus confirming H1c. These results are consistent with the research conclusions of Huang and Yi (2023) and Zhang et al. (2022).

Table 3. Benchmark regression results

Variables	(1) CE	(2) CE	(3) CE
ER1	-0.182**		
	(0.075)		
ER2		-0.249**	
		(0.103)	
ER3			-0.359***
			(0.070)
Size	0.299***	0.300***	0.297***
	(0.016)	(0.016)	(0.016)
Age	0.024	0.022	0.021
	(0.016)	(0.016)	(0.016)
Cflow	0.021***	0.021***	0.020***
	(0.003)	(0.003)	(0.002)
Lev	-0.255***	-0.252***	-0.258***
	(0.063)	(0.062)	(0.062)
Growth	-0.013	-0.014	-0.014
	(0.017)	(0.017)	(0.017)
Capin	-0.063***	-0.063***	-0.065***
	(0.006)	(0.006)	(0.006)
Idr	0.006***	0.006***	0.006***
	(0.001)	(0.001)	(0.001)
Dual	0.019**	0.016*	0.021**
	(0.009)	(0.009)	(0.009)
ROA	-0.182	-0.193	-0.165
	(0.140)	(0.140)	(0.139)
_cons	-6.795***	-6.785***	-6.737***
	(0.354)	(0.354)	(0.348)
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
N	11993	11993	11993
Adj-R^2	0.452	0.452	0.453

Note. t values are shown in brackets, ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively, and the same below.

4.2.2 Robustness Test

This study conducted robustness tests using two methods: (1) Changing the sample period. On January 1, 2015, China implemented the "Strictest Ever Environmental Protection Law of the People' s Republic of China," which further clarified the government's supervisory responsibilities for environmental protection, improved systems such as ecological protection red lines and total pollutant control, and established penalty measures such as daily fines, production restrictions, and suspensions. Considering that the enactment of the new environmental protection law may have an impact on the regression results, this study shortened the sample period to 2015-2019. (2) Lagging the explained variable. Recognizing that environmental regulations may have lagged effects on a company' s carbon emissions, this study regressed the model using the lagged one-period carbon emissions data. From Table 4 and Table 5, it is evident that the outcomes of these assessments align with the baseline regression results, thereby showcasing the robustness of the conclusions drawn from this study.

Table 4. Changing the sample interval

Variables	(1) CE	(2) CE	(3) CE
ER1	-0.191**		
	(0.081)		
ER2		-0.237*	
		(0.128)	
ER3			-0.331***
			(0.078)
_cons	-6.672***	0.086***	-6.646***
	(0.439)	(0.008)	(0.433)
Controlled variables	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
N	7484	7484	7484
Adj-R^2	0.434	0.374	0.434

Table 5. Lagged one-period dependent variable

Variables	(1) L.CE	(2) L.CE	(3) L.CE
ER1	-0.198***		
	(0.064)		
ER2		-0.291***	
		(0.086)	
ER3			-0.346***
			(0.056)
_cons	-7.287***	0.069***	-7.275***
	(0.322)	(0.006)	(0.321)
Controlled variables	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
N	9697	9697	9697
Adj-R^2	0.606	0.390	0.606

4.2.3 Mechanism Analysis

Table 6, Table 7, and Table 8 present the results of the regression analysis on the mediating role of R&D investment. From Table 6, the results in column (1) show that ER1 increases a company' s R&D investment, indicating that companies tend to engage in technological innovation to improve their current production conditions in order to meet environmental policy standards (Zhang et al., 2021). Analysis of the mediating effect in column (2) shows that even when ER1 and RD are included in the model simultaneously, the coefficient remains significantly negative, suggesting that ER1 can reduce a company' s carbon emissions by increasing R&D investment. In other words, R&D investment acts as a partial mediator, supporting H2a.

In Table 7 the results in column (1) show that ER2 decreases a company' s R&D investment, indicating that a certain level of environmental regulations can divert resources from R&D investment (Huang et al., 2020). Following the analysis of the mediating effect in column (2), it is found that the coefficient remains significant when ER2 and RD are included in the model simultaneously, revealing that there is a masking effect of R&D investment. Drawing on the method used by Li et al. (2022b) for testing mediating effects, the calculation shows that the masking effect accounts for 15.6%, indicating that R&D investment masks 15.6% of the impact and indeed plays a role in the main causal relationship. Therefore, H2b is supported.

In Table 8 the results in column (1) show that ER3 decreases a company’ s R&D investment, although not significantly. Analysis of the mediating effect in column (2) when ER3 and RD are simultaneously included in the model reveals that the coefficient of ER3 remains significantly negative, indicating that R&D investment acts as a partial mediator, supporting H2c.

Table 6. Results for the mediating effect of R&D investment between ER1 and CE

Variables	(1) RD	(2) CE
ER1	0.010***	-0.179**
	(0.003)	(0.075)
RD		-0.350**
		(0.178)
_cons	0.069***	-6.771***
	(0.006)	(0.349)
Controlled variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
N	11993	11993
Adj-R^2	0.390	0.452

Table 7. Results for the mediating effect of R&D investment between ER2 and CE

Variables	(1) RD	(2) CE
ER2	-0.010***	-0.253**
	(0.003)	(0.103)
RD		-0.394**
		(0.180)
_cons	0.073***	-6.756***
	(0.006)	(0.348)
Controlled variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
N	11993	11993
Adj-R^2	0.390	0.452

Table 8. Results for the mediating effect of R&D investment between ER3 and CE

Variables	(1) RD	(2) CE
ER3	-0.000	-0.359***
	(0.002)	(0.070)
RD		-0.374**
		(0.180)
_cons	0.071***	-6.710***
	(0.006)	(0.343)
Controlled variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
N	11993	11993
Adj-R^2	0.390	0.453

4.2.4 Heterogeneity Analysis

Heterogeneity of regions. The Chinese provinces display marked disparities in economic development, resource availability, and industrial structure, leading to significant divergence in the nature, extent, and enforcement of environmental regulatory frameworks across regions. By scrutinizing these regional disparities in the impacts of environmental regulations, insights into the potential ramifications of such regulations can be gleaned, serving as a basis for tailored regulatory strategies. In general, the eastern region is notable for its early embrace of the coastal openness policy and higher level of economic development, whereas the middle and western regions are typified by relatively lower economic advancement (Zhang, 2021). Consequently, this study classifies the sample into two groups: eastern enterprises and central/western enterprises, which are then analysed further using regression analysis (Wang et al., 2023c). The regression results in Table 9 highlight that the impact of environmental regulations on mitigating carbon emissions is particularly evident in the economically developed eastern region. Specifically, all three types of environmental regulations play a significant role in decreasing carbon emissions. In contrast, in the central and western regions, only ER3 demonstrates a substantial effect on reducing carbon emissions at a 10% significance level, while the impact of the other regulatory measures is minimal. These distinctions can be attributed to the advanced economy, technological prowess, and innovative culture prevalent in the eastern region. Enterprises here are proactive in environmental stewardship, emphasizing energy conservation efforts and leveraging low-carbon policies with notable results. Conversely, the central and western regions encounter obstacles stemming from constrained economic development capacity, limited resources, financial support, and environmental awareness. Additionally, their environmental governance systems, including management mechanisms, are less sophisticated, possibly hindering full compliance with carbon emission regulations and diminishing the efficacy of environmental mandates in curbing carbon emissions (Liu et al., 2023a).

Heterogeneity of industries. Highly polluting firms are distinguishable by their resource-intensive operations, involving protracted manufacturing procedures that necessitate substantial energy and resource usage, consequently escalating pollution emissions (Sun & Zeng, 2023). Therefore, heavy polluters should prioritize the achievement of a “double carbon” goal. According to neoclassical economic theory, heavy polluters face heightened environmental compliance costs compared to lighter polluters, impeding their inclination to invest in green energy efficiency initiatives (Cao et al., 2022). This study further classifies the sample into two groups: heavy polluters and non-heavy polluters (Peng et al., 2021). The aim is to investigate how industrial heterogeneity affects the reduction of carbon emissions, as illustrated in the regression results presented in Table 10. The analysis reveals that all three forms of environmental regulations significantly diminish carbon emissions in heavily polluting enterprises, indicating that stricter government regulations for these entities lead to more effective emission reductions. On the contrary, the effect of environmental regulations on carbon emissions in non-heavily polluting enterprises is less prominent, with only ER3 showing a significant decrease at the 10% significance level. These results may be attributed to the greater number of carbon emission sources and links in the production processes of heavily polluting firms, resulting in heightened energy consumption and emissions that necessitate a stronger push for emission reduction. Consequently, stringent policy demands, increased market competition, and larger economic scales motivate heavily polluting companies to adopt cleaner, renewable energy sources. They also commit to substantial investments in pollution control projects and green innovation initiatives to curtail long-term production costs and achieve substantial reductions in carbon emissions (Lin & Zhang, 2023). Conversely, non-heavily polluting firms encounter lesser environmental pressures during routine manufacturing operations and may exhibit lower compliance with government environmental regulations, hence experiencing challenges in reducing carbon emissions.

Heterogeneity in the degree of marketization. Marketization is the degree to which the market impacts the allocation of resources, including different economic, social, legal, and political institutional transformations (Zhang, 2024). Corporates, as active participants in the market, are significantly affected by the institutional context. Therefore, by utilizing China’ s marketization index, this study categorizes the samples into high and low groups based on the median of each province’ s average marketization index value. The objective is to evaluate how variations in marketization levels impact carbon emission reduction by enterprises. The specific outcomes of the regression analysis are presented in Table 11. The results reveal that in regions with high marketization, the influence of environmental regulations on CE is noteworthy, whereas in low marketization areas, this influence is not statistically significant. This disparity may arise from more advanced legal and environmental frameworks in highly marketized areas, leading to stricter carbon emission regulations for businesses. Additionally, increased marketization levels could improve resource allocation efficiency and facilitate optimal utilization of production elements, thereby enhancing companies’ carbon performance and enabling them to leverage environmental regulations for greater benefits (Wang et al., 2023a).

Table 9. Regression results of heterogeneity of regions

		Carbon emissions		
		ER1	ER2	ER3
Eastern	coefficient	-0.203**	-0.282**	-0.412***
		(0.099)	(0.133)	(0.097)
	_cons	-6.926***	-6.921***	-6.840***
		(0.438)	(0.439)	(0.425)
	Con/Industry/Year	Yes	Yes	Yes
	N	8455	8455	8455
	Adj-R^2	0.437	0.437	0.439
Midwestern	coefficient	-0.239	-0.045	-0.288*
		(0.155)	(0.171)	(0.150)
	_cons	-6.638***	-6.660***	-6.635***
		(0.616)	(0.617)	(0.616)
	Con/Industry/Year	Yes	Yes	Yes
	N	3538	3538	3538
	Adj-R^2	0.444	0.443	0.444

Table 10. Regression results of heterogeneity of industries

		Carbon emissions		
		ER1	ER2	ER3
Heavy polluting industries	coefficient	-0.273***	-0.359***	-0.524***
		(0.096)	(0.133)	(0.092)
	_cons	-8.493***	-8.472***	-8.463***
		(0.471)	(0.471)	(0.462)
	Con/Industry/Year	Yes	Yes	Yes
	N	4646	4646	4646
	Adj-R^2	0.585	0.585	0.587
Non-heavy polluting industries	coefficient	-0.042	-0.112	-0.223*
		(0.129)	(0.177)	(0.117)
	_cons	-4.575***	-4.559***	-4.517***
		(0.652)	(0.650)	(0.642)
	Con/Industry/Year	Yes	Yes	Yes
	N	7347	7347	7347
	Adj-R^2	0.139	0.139	0.139

Table 11. Regression results of heterogeneity in degree of marketization

		Carbon emissions		
		ER1	ER2	ER3
Highly marketization	coefficient	-0.168	-0.682***	-0.288**
		(0.186)	(0.183)	(0.122)
	_cons	-8.202***	-8.073***	-8.162***
		(0.474)	(0.471)	(0.469)
	Con/Industry/Year	Yes	Yes	Yes
	N	5836	5836	5836
	Adj-R^2	0.485	0.488	0.486
Low marketization	coefficient	-0.058	0.036	-0.124
		(0.078)	(0.140)	(0.098)
	_cons	-6.666***	-6.680***	-6.654***
		(0.439)	(0.439)	(0.437)
	Con/Industry/Year	Yes	Yes	Yes
	N	6157	6157	6157
	Adj-R^2	0.467	0.467	0.467

4.2.5 Further Analysis

The advent of Industry 4.0 has led to the widespread impact of digital technologies and digital transformation across various aspects of enterprises. This include modifications in the organizational framework, manufacturing capabilities, operational and commercial frameworks, construction of platform systems, and plans for enterprise growth (Warner & Wager, 2019). Research has confirmed that the progress and implementation of digital technologies have a beneficial effect on promoting urban innovation and decreasing urban carbon emissions (Jing et al., 2023). The reason for this is that in order to improve environmental performance, companies must take sustainability into account when designing products, producing them, and managing emissions. Digital technologies offer effective solutions for creating environmentally-friendly products, optimising production processes, and reducing carbon emissions (Li et al., 2020). Researchers have also analysed the detailed mechanisms of enterprise digital transformation, considering both its direct and indirect impacts. They found that businesses' carbon emission performance drops as a direct result of digital transformation, which increases power usage and energy intensity. Conversely, digital transformation has the unintended consequence of motivating businesses to reduce their production and energy consumption, boost their total productivity, and free up capital. As a result, businesses' carbon emissions and the intensity of their emissions are reduced (He & Chen, 2023). Moreover, the progress of the digital economy can promote low-carbon innovation within businesses by mitigating their financial constraints and environmental risks. In general, the mitigation of carbon emissions in enterprises mainly entails incorporating technological advancements to conserve energy, lower emissions, mitigate pollutant discharges throughout the industrial operations, and bolster the firm' s carbon efficiency. Hence, in the context of technological advancement, digital transformation facilitates prompt engagement and supplementary benefits in innovation, empowering businesses to overcome obstacles and ultimately diminish carbon emissions (Yang et al., 2023). The advent and application of digital technology have yielded intricate ramifications for the sustainable expansion of enterprises. Consequently, digital transformation holds immense importance for firms in attaining the objective of environmentally friendly development.

Drawing from the approach outlined by Shang et al. (2023), this study employs Python for text analysis of annual reports from listed companies. It calculates and evaluates the occurrence of keywords related to enterprises' digital transformation, such as "Artificial Intelligence Technology," "Blockchain Technology," "Cloud Computing Technology," and "Big Data Technology" and their applications. The total word frequency is computed, followed by the application of the logarithm function to derive the final digital transformation index (Lndigital). The measurement model can be summarized as (Chen & Ma, 2021) :

$$CE_{i,t} = \beta_0 + \beta_1 ER_{i,t} + \beta_2 Lndigital_{i,t} + \beta_3 ER_{i,t} \times Lndigital_{i,t} + \beta_4 Con_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \tag{5}$$

Among them: $Lndigital_{i,t}$ represens the level of digital transformation of company *i* in period *t*; other variables are as described above.

We assess whether digital transformation moderates the impact of environmental regulation on corporate carbon emissions, as outlined in Equation (5). The regression results are presented in Table 12, where the column headings align with the previously discussed meanings. The interaction between ER2 and digital transformation exhibited a positive yet insignificant effect on corporate carbon emissions, as indicated by the test outcomes across the three types of environmental regulation. Conversely, the interactions of ER1 and digital transformation, as well as ER3 and digital transformation, demonstrated negative effects on CE at a significant level of 1%. These findings suggest that digital transformation attenuates the influence of ER1 and ER3 on CE, while it does not significantly impact the relationship between ER2 and these emissions. The potential explanation for the aforementioned outcomes may lie in governments implementing environmental regulations to drive advancements in pollution control and production technologies within companies. Energy demands and carbon emissions are intricately intertwined with the production, utilization, and disposal of digital devices and equipment. The process of digitalization requires significant data storage and processing, which results in heightened energy consumption and escalated electricity needs. Therefore, the elevated energy demands and power consumption of digital services and products, alongside economic growth, eventually lead to the rise in carbon emissions (Zheng et al., 2023).

Table 12. Regression results of the moderating effect of digital transformation

Variables	(1) CE	(2) CE	(3) CE
ER1	-0.186**		
	(0.076)		
ER2		-0.245**	
		(0.103)	
ER3			-0.334***
			(0.069)
Lndigital_ER1	-0.186***		
	(0.043)		
Lndigital_ER2		0.047	
		(0.060)	
Lndigital_ER3			-0.148***
			(0.043)
_cons	-6.790***	-6.782***	-6.734***
	(0.354)	(0.354)	(0.349)
Controlled variables	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
N	11993	11993	11993
Adj-R^2	0.452	0.452	0.453

5. Conclusions and Policy Implications

This article is predicated on sample data from listed manufacturing companies on the A-share market in China spanning from 2011 to 2019. It classifies environmental regulations into three categories: command and control (ER1), market-based incentives (ER2), and public participation (ER3). The study delves into their influence on corporate carbon emissions (CE) and elucidates their operational mechanisms.The research findings are as follows: 1) the primary outcome of implementing ER1, ER2, and ER3 is the partial mitigation of firms' carbon emissions, which is robust across various tests; 2) R&D investment serves as a mediator in the pathway through which all three types of environmental regulations affect company carbon emissions in terms of their mechanisms; 3) heterogeneity analysis indicates that the influence of environmental regulations on corporate carbon emissions is more pronounced in the eastern region, heavily polluting industries, and highly marketized firms; 4) additional analysis reveals that digital transformation acts as a negative moderator, offsetting the adverse effects of ER1 and ER3 on CE, but it does not moderate the relationship between ER2 and CE.

This study presents policy recommendations based on the previous research findings. Firstly, it is imperative to establish a market-oriented environmental regulatory framework and develop customized environmental laws that resonate with local circumstances. The study results underscore the substantial influence of all three forms of environmental regulations in reducing corporate carbon emissions. Hence, strategic formulation and enforcement of specific environmental regulations tailored to regional characteristics are essential. This involves strengthening incentives' efficacy and optimizing regulatory frameworks to foster environmental preservation. Secondly, bolster governmental support for enterprise R&D investment. It is paramount for governments at various levels to augment investments in emission reduction technologies. This initiative should focus on cultivating scientific and technological capabilities in R&D, enhancing incentivization schemes for R&D professionals, and integrating economic objectives with eco-friendly practices seamlessly within enterprises' strategic management. By emphasizing R&D innovation, businesses can fortify their core competitive advantage and long-term growth prospects. Establishing diverse R&D facilities and actively promoting non-profit R&D platforms are crucial steps, leveraging tax benefits and financial aid provided by governmental bodies to propel innovative R&D pursuits. Thirdly, considering the regional and corporate disparities, efficient enforcement of environmental laws by the government is crucial, while actively promoting carbon emission reduction. As indicated by heterogeneity analysis results, the government should leverage the eastern region as a pioneer area and target heavily polluting, market-driven industries. Tailored measures to curtail carbon emissions for enterprises with varying profiles should be developed. Additionally, in light of the relatively underdeveloped economies in central and western regions, boosting tax and financial aid is vital to establish a unified national framework for carbon dioxide emission reduction. Fourthly, leveraging digital infrastructure to promote eco-friendly, low-emission lifestyles and consumption patterns, as well as encouraging the adoption of sustainable energy sources, is essential. Prioritizing low-carbon regulations and enhancing market and incentive mechanisms for utilizing renewable energy in the digital infrastructure sector will steer digital development in an environmentally sustainable direction and bolster carbon emission reduction efforts.

While this study is innovative and pioneering, it does have certain limitations. The examination of the influence of environmental regulations on corporate carbon emissions in this paper lacks comprehensive detail. Additionally, there may be additional mechanisms, apart from R&D investment and digital transformation, that warrant further investigation. Moreover, the data on firm’ s carbon emissions in this article are indirectly measured, primarily due to data constraints, rather than being directly sourced from listed firms.It is necessary to conduct further updates in this regard. Ultimately, this article specifically examines China, which is the most prominent emerging country, hence restricting the applicability of its conclusions to other emerging economies. Further research is essential to explore the similarities and variations in the impacts of environmental regulations on corporate carbon emission in emerging countries, especially since many of these countries are substantial contributors to carbon emissions.

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