sustainability

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Do Heterogeneous Environmental Policies Improve Environmental Quality While Promoting Economic Growth?

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Abstract: The long-standing model of high energy consumption growth of China has put the country at a market disadvantage in terms of clean technological innovation and clean goods production. With the support of national policies, China's environmental industry has achieved rapid development. However, the key to establishing a long-term effective mechanism is how to encourage enterprises to develop and use green and clean technologies. Thus, we construct a theoretical model related to environmental policies and then derive the impact of heterogeneous environmental policies on different research and development (R&D) approaches. The environmental and economic effects of heterogeneous environmental policies are then explored by incorporating environmental quality and economic growth into the model. Next, we evaluate the policy effect based on the panel data of prefecture-level cities in China from 2009 to 2016. In a further discussion, we measure the decoupling indices of carbon emissions and economic growth for each of the 281 prefecture-level cities in China using the Tapio model. Through theoretical derivation and empirical analysis, this paper provides a more comprehensive study of the green bias effect of environmental policies. The results show that environmental policies can significantly promote green technological innovation regardless of the R&D approach adopted by firms. The difference is that when firms conduct their own R&D, the sector's R&D efficiency parameters determine the direction of technological innovation steering. When technological innovation is introduced externally, the substitution relationship between sectoral products determines whether environmental policy is effective. Finally, the combination of environmental regulation and government subsidies is more effective in green-biasing technological innovation.

Keywords: environmental regulation; subsidies; clean technology; technological innovation; environmental quality

Citation: Chang, H. Do Heterogeneous Environmental Policies Improve Environmental Quality While Promoting Economic Growth? *Sustainability* **2023**, *15*, 1162. https://doi.org/10.3390/su15021162

Academic Editor: Elena Cristina Rada

Received: 25 November 2022
Revised: 20 December 2022
Accepted: 4 January 2023
Published: 7 January 2023

1. Introduction

On 8 October 2018, the United Nations Intergovernmental Panel on Climate Change (IPCC) released the IPCC Special Report on Global Warming of 1.5 °C in Incheon, Republic of Korea. The report argues that limiting global warming to 1.5 °C will reduce its challenging impacts on ecosystems, human health and well-being, and make it easier to achieve the UN Sustainable Development Goals than limiting global warming to 2 °C. Excessive greenhouse gas emissions are a direct contributor to global climate change. Under the background of global warming, carbon reduction has become a hot issue of concern to the international community.

China is the world's largest energy producer and largest energy consumer. It is estimated that the economic losses caused by environmental pollution in China already account for approximately 8% of GDP, and in some developed regions, the pollution losses are as high as 10% of GDP or more. Unfortunately, even with the high cost of pollution control and environmental costs, not only have the environmental problems of China not been fundamentally addressed, but they have also even exacerbated the contradiction between high-quality economic development and the constraints of energy and the environment. As a result, the problems caused by energy use have become a serious threat to China's high-quality economic development. Since China's environmental performance index ranks lower in the world, we must rethink the question of whether it is wrong to rely on carbon emissions to drive economic growth. Facing increasingly serious environmental problems, China has promulgated and formulated a series of rectification measures. After the state promulgated the Environmental Protection Law in 2015, the report of the 19th National Congress of China even pointed out that "Lucid waters and lush mountains are invaluable assets". To implement the concept of green development, on 22 September 2020, at the 75th UN General Assembly, China formally put forward the "double carbon" goal of achieving peak carbon dioxide emissions in 2030 and carbon neutrality in 2060. To achieve the "double carbon" goal and to restrain environmental pollution without limiting the economic development of enterprises, China urgently needs to formulate an effective environmental regulation policy. However, the incentives for the research and development of clean technologies in the Chinese market are insufficient. In addition, dirty production has occupied the first-mover advantage. Although the Chinese government has issued relevant environmental policies, their effects are not satisfactory. The harmonious development of economic growth and environmental quality through government intervention is an urgent problem to be solved.

This paper makes three marginal contributions: (1) Compared to the previous literature, we construct a theoretical model based on different presuppositions, gain a theoretical understanding of whether autonomous R&D or exogenous introduction are more biased towards green technological progress, and discuss how heterogeneous environmental policies affect environmental quality and promote economic growth based on the identification of technology bias effects. (2) We access the websites of provincial and municipal governments to collect information on the time of the specific implementation of environmental regulations in different cities. Based on this, we use the progressive difference–in-difference (DID) approach to precisely delineate the treatment and control groups. (3) The traditional literature does not fully consider the decoupling state of carbon emissions and economic growth in each prefecture-level city, which may lead to a biased assessment of policy tests and growth effects. To avoid this bias, we re-examine prefecture-level municipalities with different decoupling statuses.

The paper is organized and presented as follows. Section 2 discusses a disaggregated body of literature on environmental policy and environmental innovation. Section 3 constructs a relevant theoretical framework, and within this section, the effects of heterogeneous environmental policies on environmental quality and economic growth are discussed. Section 4 presents the questions of our empirical framework, which can be used to identify the effects of environmental regulation and subsidies on environmental innovation; it also introduces the data. Section 5 provides a brief overview of our empirical results on environmental regulation and subsidies for environmental innovation. Section 6 revisits the issue of environmental policy in terms of environmental quality and economic growth using the Tapio decoupling model to make our empirical results more robust. The final section discusses our conclusions and provides policy implications.

2. Review of the Literature

To observe the environmental effects of environmental policies of different countries around the world, this paper selected several representative countries from several continents at the transnational level. At the national level, the research reports of provincial and prefecture-level cities and listed companies in China, as well as the representatives of the fastest-growing provinces (Guangdong Province) and municipalities directly under the Central Government (Beijing) in China were selected. The significance of such a wide selection of national samples is that we can intuitively observe the commonalities of environmental policies through different data.

Table 1 illustrates that scholars have shown a keen interest in issues related to economic growth and environmental quality. By using different data, different methods and different research perspectives, they have tried to co-ordinate the relationship between economic growth and environmental quality. In the long term, companies that create pollution must take responsibility for its control. Through environmental policies, the government promotes enterprises to research and develop clean technologies and replace polluting products with environmentally friendly ones. This is an important means to achieve the compatible development of the environment and economy [1]. However, in the short term, environmental policies require enterprises to bear the costs of pollution control activities, as well as the consequences of environmental damage. Economic growth and environmental quality have fallen into a state of trade-offs [2].

Table 1. Review of the relevant literature.

Authors	Country/Scope	Period	Methodology	Conclusion
Cross-country and national studies:				
Apergis and Payne (2014) [3]	7 Central American countries	1980–2010	Error correction model	Energy mix→CO_2 ↓
Jaforullah and King (2015) [4]	United States	1965–2012	Cointegration test, granular causality test	Energy mix→CO_2 ↓
Lasisi et al. (2022) [5]	7 European countries	1990–2020	Moment quantile regression approach, Granger causality approaches	Fuel consumption →CO_2 ↑ GDP ↑
Wang et al. (2014) [6]	China	1995–2011	Panel data model	Urbanization rate, industrialization →CO_2 ↑ GDP ↑
Zhang et al. (2022) [7]	33 countries	1990–2015	Two-way fixed effects model	Environmental policy → Green patents ↑
Zoundi (2017) [8]	25 African countries	1980–2012	Additional autoregressive distribution lags	Energy mix→CO_2 ↓
Regional-, city- and enterprise-level research:				
Bai et al. (2020) [9]	29 provincial capitals in China	2000–2015	Fixed effect regression model	Renewable energy technological innovation →CO_2 ↓
Cui et al. (2022) [10]	Listed companies in China	1990–2010	DID	Environmental regulation → Green patent ↑
Ji and Chen (2017) [11]	29 provincial capitals in China	1998–2010	STIRPAT model	Urbanization rate →CO_2 ↑ GDP ↑
Miao (2017) [12]	216 prefecture-level cities in China	2013	2SLS	Urbanization rate →CO_2 ↑ GDP ↑
Ren et al. (2022) [13]	Listed companies in China	2011–2015	IV-2SLS	Environmental subsidies → Environmental management innovation ↑
Shen et al. (2021) [14]	244 prefecture-level cities in China	2004–2016	IV	Economic growth target constraints → Green technology innovation ↑
Wang et al. (2012) [15]	Beijing	1997–2010	STIRPAT model	Urbanization rate, industrialization →CO_2 ↑ GDP ↑, R&D → CO_2 ↓
Wang et al. (2013) [16]	Guangdong Province	1980–2010	STIRPAT model, ridge regression	Urbanization rate, industrialization →CO_2 ↑ GDP ↑

Notes: "↑": positive effect, "↓": negative effect. Variables: per capita gross domestic product (GDP).

Scholars disagree on the idea of whether economic growth and environmental quality can be jointly improved. Some scholars argue that environmental regulation causes problems such as higher costs for enterprises and lower international competitiveness in the long run. Other scholars argue that the increased production costs due to regulation can be compensated by government subsidies. They argue that a reasonable means of environmental regulation can improve the productivity and competitiveness of enterprises, make up for the R&D costs of enterprises, and create a win–win opportunity for energy conservation and economic growth [17,18]. In this context, green technological innovation plays an important role in regulating the relationship between the two, and green technological progress, which is an important driver in addressing environmental externalities and overcoming path dependency [19], plays a key role in achieving a green transition. Environmental regulation and government subsidies can contribute to the green transformation of an economy through green technological innovation [20]. Therefore, the key to creating this win–win situation lies in whether the environmental policy can stimulate the green technological innovation ability of enterprises.

Environmental regulation is usually manifested as administrative orders and regulatory policies, while government subsidies are manifested as government support for firms' science, technology and innovation (STI) projects. Although firm profitability is negatively affected when green products are initially introduced, green product innovation positively affects profitability in the long run [21], and the underlying theory can be explained by the Porter hypothesis [17]. Using relevant data from the Organisation for Economic Co-operation and Development (OECD), some scholars have found that environmental regulations can accelerate corporate clean technological innovation and cause firms to invest more resources in clean technological innovation activities [22]. Several scholars from China have examined the impact of environmental policies on green innovation in renewable energy technologies, using data from 33 countries over the period 1990–2015, finding that strict environmental policies promote green innovation in renewable energy technologies [7]. Meanwhile, the higher the tax price of energy, the more firms tend to innovate green technologies [23], and the higher the price of environmental taxes, the more pronounced the positive effect of pollution control [24]. Regarding subsidies, both government subsidies and environmentally oriented government subsidies significantly promote environmental innovation among Chinese listed companies, with cleaner production companies benefiting more from them [25].

The US scholar Acemoglu examined the relationship between environmental policy and clean technology, and found that the simultaneous implementation of environmental taxes and R&D subsidies can both improve clean technological innovation and reduce pollution emissions while ensuring economic growth [26]. Empirical studies based on Chinese listed companies confirm this point and confirm that government governance is indeed effective in reducing environmental pollution and improving the quality of economic development [13].

In summary, the literature generally focuses on the impact of policy interventions on technological progress as a whole but does not specifically break down how environmental regulations and government subsidies affect environmental quality and economic growth by changing the direction of technological progress in different R&D contexts. Specifically, promoting compatible economic growth and environmental quality requires exploring what policy mix and what policy intensity, under different R&D scenarios, can better stimulate the green innovation potential of firms while ensuring economic growth, which remains a key and cutting-edge issue in academic research.

3. Theoretical Models

At the early stage of the implementation of environmental regulation, under the pressure of environmental governance costs, enterprises will choose low-cost, low-difficulty, quick-effect technology to improve productivity and to promote the rapid realization of green transformation. For example, in the process of rapid green transformation, highly polluting enterprises introduce pollution control, prevention technology, purification technology, and recycling technology through external purchases. However, with the narrowing of the gap between China and developed countries, technology introduction no longer has a comparative advantage. Realizing the transformation from a traditional technological innovation mode to an independent innovation mode has become the main direction of China's technological development. For example, at present, with the availability of capital, talents, and information, most enterprises choose independent innovations to improve the R&D capability of green technology and enhance their international competitiveness. Using a mathematical deduction of the technology bias effect caused by heterogeneous policies, we extend the model of Acemoglu and Aghion to identify the dynamic processes through which biased technological progress affects economic growth and environmental quality through a mathematical deduction of the technology bias effect caused by heterogeneous policies [23,26]. Specifically, this paper first constructs a production sector model that explores how environmental policy affects the technology bias effect and environmental quality when firms undertake autonomous R&D by incorporating technological progress into the profit function of producers of intermediate goods. Furthermore, assuming that clean technological innovation is carried out by an independent R&D sector, this paper examines the similarities and differences in the mechanisms of environmental policy under different economic scenarios.

3.1. Basic Model

Assume that the amount of labour input in the clean sector is L_{ct}, the dirty sector labour input is L_{Nt}, and the total labour input size is L_t; therefore, $L_{Nt} + L_{ct} = L_t$. Let the clean sector be C and the level of output of the clean sector be Y_{ct}. Additionally, let the dirty sector be N and the level of output of the dirty sector be Y_{Nt}. The production function of the total social product Y satisfies the constant elasticity of substitution (CES) production function:

$$\begin{gathered} Y = \left[{Y_{ct}}^{\frac{\varepsilon-1}{\varepsilon}} + {Y_{Nt}}^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \\ Y_{ct} = L_{ct}^{\alpha} \int_0^1 A_c^{\alpha}(j) x_c^{1-\alpha}(j) dj; Y_{Nt} = L_{Nt}^{\alpha} \int_0^1 A_N^{\alpha}(j) x_N^{1-\alpha}(j) dj \end{gathered} \tag{1}$$

where x_i is intermediate goods, A_c is the clean sector technology level, A_N is the dirty sector technology level, ε is the elasticity of substitution between the two sectors $(\varepsilon > 1)$, and α is the share parameter. Assuming that firms are motivated to innovate by monopoly profits, let the market for intermediate goods be a monopoly market. Y_{ct} is the price of p_c, and Y_{Nt} is the price of p_N.

Assuming that only the production and consumption of dirty products cause environmental pollution, the government uses the means of environmental regulation to limit dirty sector N emissions, where environmental regulation τ_N includes the imposition of environmental taxes and the implementation of carbon trading policies. To simplify the analysis, the price of the final good Y is normalised to 1. Thus, when the market is in equilibrium, the following is satisfied:

$$\left[{p_c}^{1-\varepsilon} + (1+\tau_N)^{1-\varepsilon} {p_N}^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} = 1 \tag{2}$$

$$\frac{p_c}{(1+\tau_N)p_N} = \left(\frac{Y_{ct}}{Y_{Nt}} \right)^{-1/\varepsilon} \tag{3}$$

Assuming that government subsidies for the clean sector are at a level of τ_c, the profit maximisation problem for the sector is as follows:

$$\max_{w_c, x_c} p_c Y_c - w_c L_{ct} - (1-\tau_c) p_{cj} x_c \tag{4}$$

$$\max_{w_N, x_N} p_N Y_N - w_N L_N - p_{Nj} x_N \tag{5}$$

where w_i is the wage and p_{ij} is the price of intermediate goods. According to the profit maximisation principle, the expression for the demand for intermediate goods is obtained as follows:

$$(1-\tau_c) p_{cj} = p_c L_{ct}^{\alpha} A_c^{\alpha} {x_c}^{-\alpha} \tag{6}$$

$$p_{Nj} = p_N L_{Nt}^{\alpha} A_N^{\alpha} {x_N}^{-\alpha} \tag{7}$$

Since the intermediate goods market is a monopoly market, to simplify the analysis, assume that the marginal cost of intermediate goods is $1-\alpha$. Thus, the profit of the producer of intermediate goods is $\left[p_{ij} - (1-\alpha) \right] x_i$, and since $0 < \alpha < 1$, the price of intermediate goods is obtained by solving the maximisation problem based on $p_{cj} = p_{Nj} = 1$. Thus, the profits of intermediate goods manufacturers are obtained as follows:

$$\pi_c = \alpha (1-\tau_c)^{\frac{1}{\alpha}} {p_c}^{\frac{1}{\alpha}} A_c L_c \tag{8}$$

$$\pi_N = \alpha p_N^{\frac{1}{\alpha}} A_N L_N \tag{9}$$

Combining the above equations yields the relative prices of the two sectors:

$$\frac{p_c}{p_N} = \left(\frac{1}{1+\tau_N}\right)^{-\frac{\varepsilon\alpha}{\psi}} (1-\tau_c)^{\frac{\alpha-1}{\psi}} \left(\frac{A_c}{A_N}\right)^{-\frac{\alpha}{\psi}} \left(\frac{L_c}{L_N}\right)^{-\frac{\alpha}{\psi}} \tag{10}$$

where the elasticity of substitution between the clean and dirty sectors is $\psi = \varepsilon\alpha - \alpha + 1$ when $\varepsilon > 1$ and when $\psi > 1$.

3.2. R&D Market Balance When Technological Progress Relies on Independent R&D

We set up a government innovation subsidy for the clean technology R&D sector alone: $R_{ct} = \tau_c p_{cj} x_c$. μ_{ct} is the probability that machines in the clean production sector are improved, β is the level after improvement $(\beta > 1)$, and τ_c is the intensity of the clean technology R&D subsidy. Based on previous research, such as Aghion and Howitt [27,28], the probability of R&D $\mu_{ct} = \xi_c \left(\frac{\tau_c R_{ct}}{L_{ct} A_{ct}}\right)^{\varphi}$, and ξ_i is the R&D efficiency parameter $(i = c, N)$. φ is the output elasticity of R&D inputs; its value is greater than 0 and less than 1. The expected return of technological innovation is $\mu_{ct}\pi_{ct}$, and the maximisation objective function is $\max\left[\mu_{ct}\pi_{ct} - p_{ct}R_{ct}\right]$. Thus, the optimal innovation probability is as follows:

$$\mu_{ct} = \xi_c^{\frac{1}{1-\varphi}} \varphi^{\frac{\varphi}{1-\varphi}} \tau_c^{\frac{\varphi}{1-\varphi}} (1-\alpha)^{\frac{\varphi}{1-\varphi}} \alpha^{\frac{(1+\alpha)\varphi}{1(1-\alpha)(1-\varphi)}} \tag{11}$$

Thus, the following are the technology level functions:

$$A_{ct} = \int_0^1 \beta A_{ct-1}\mu_{ct} dj + \int_0^1 A_{ct-1}(1-\mu_{ct}) dj = \beta A_{ct-1}\mu_{ct} + A_{ct-1}(1-\mu_{ct}) \tag{12}$$

From the above equation, the rate of technological progress in the clean intermediate goods production sector is obtained as follows:

$$g_{ct} = \frac{(A_{ct} - A_{ct-1})}{A_{ct-1}} = \beta\mu_{ct} + 1 - \mu_{ct} - 1 = (\beta - 1)\mu_{ct} \tag{13}$$

Substituting the optimal innovation probability into the above equation yields the following:

$$g_{ct} = \vartheta \xi_c^{\frac{1}{1-\varphi}} \tau_c^{\frac{\varphi}{1-\varphi}} \tag{14}$$

where $\vartheta = (\beta - 1)\varphi^{\frac{\varphi}{1-\varphi}} (1-\alpha)^{\frac{\varphi}{1-\varphi}} \alpha^{\frac{(1+\alpha)\varphi}{(1-\alpha)(1-\varphi)}}$. Similarly, the rate of progress of dirty technologies is obtained as follows:

$$g_{Nt} = \vartheta \xi_N^{\frac{1}{1-\varphi}} (1-\tau_N)^{\frac{\varphi}{(1-\alpha)(1-\varphi)}} \tag{15}$$

Thus, when the clean sector conducts its own R&D, environmental technology advances in the direction a_{t1}:

$$a_{t1} = \frac{A_{ct}}{A_{Nt}} = \frac{A_{ct-1}(1+g_{ct})}{A_{Nt-1}(1+g_{Nt})} = \frac{A_{ct-1}\left(1 + \vartheta \xi_c^{\frac{1}{1-\varphi}} \tau_c^{\frac{\varphi}{1-\varphi}}\right)}{A_{N_{t-1}}\left[1 + \vartheta \xi_N^{\frac{1}{1-\varphi}} (1-\tau_N)^{\frac{\varphi}{(1-\alpha)(1-\varphi)}}\right]} \tag{16}$$

In the above equation, a_{t1} is the direction of technological progress when firms conduct their own R&D, and its magnitude depends on the R&D efficiency parameter ξ, the intensity of R&D subsidies τ_c and the intensity of environmental regulation τ_N. The above equation shows that the higher the intensity of environmental regulation and the higher the intensity of R&D subsidies, the more technological progress occurs in the direction of clean technology. At the same time, technological progress moves in the direction of high R&D efficiency parameters.

Conclusion C1. When firms conduct their own R&D, there are differences in heterogeneous R&D efficiency and technology bias effects under heterogeneous environmental policies. Specifically, the higher the policy intensity is, the higher the R&D efficiency in the clean sector and the more technological progress towards green technological innovation.

3.3. R&D Market Equilibrium When Technological Progress Relies on Exogenous Introduction

Drawing on Acemoglu, the technological innovation equation is set as follows [29]:

$$\dot{T}_i = \xi_i T_i^{\delta} S_i \tag{17}$$

In the above equation, ξ_i is the R&D efficiency parameter, and S_i is a scientist engaged in R&D. $S_c + S_N \leq S$, and $\delta \in [0,1]$ denotes the degree of technology spillover and defines the value of the firm as V_i. The marginal productivity of the scientist is $\xi_i T_i$. From the Bellman equation, it follows that $V_i(j) - \dot{V}_i(j) = \pi_i$. At a steady state, $\dot{V}_i(j) = 0$, at which point there is $V_i(j) = \frac{\pi_i}{r}$. From the Bellman equation and the free entry and exit conditions for the R&D market, $\xi_c T_c V_c(j) - w = 0$. The relative value of labour in the clean and dirty sectors is obtained as follows:

$$\frac{V_c}{V_N} = (1-\tau_c)^{\frac{1}{\alpha}} \left(\frac{p_c}{p_d}\right)^{\frac{1}{\alpha}} \frac{L_c T_c}{L_N T_N} \tag{18}$$

When the R&D market is balanced, $\xi_c T_c V_c = \xi_N T_N V_N$, at which point firms hire scientists and decide on the direction of R&D based on market value. Bringing the R&D market equilibrium conditions into the above equation yields the following:

$$a_{t2} = \frac{T_{ct}}{T_{Nt}} = \left(\frac{\xi_N}{\xi_c}\right)^{-\frac{\psi}{\delta\psi+\psi-1}} \left[\frac{1+\tau_N}{(1-\tau_c)^{\frac{\varepsilon}{\alpha}}}\right]^{\frac{\psi}{\delta\psi+\psi-1}} \left(\frac{L_c}{L_N}\right)^{\frac{1-\psi}{\delta\psi+\psi-1}} \tag{19}$$

From the above equation, it follows that $\frac{\partial\left(\frac{T_{ct}}{T_{Nt}}\right)}{\partial(\tau_N)} > 0$, which shows that environmental regulation inhibits the level of technology in the dirty sector while promoting an increase in the relative level of technology in the clean sector. At the same time, $\frac{\partial\left(\frac{T_{ct}}{T_{Nt}}\right)}{\partial(\tau_c)} > 0$, which suggests that environmental subsidies increase technological innovation in the clean sector more and that technological progress moves in the direction of clean technology.

Conclusion C2. The green technology bias of heterogeneous environmental policies is effective when firms introduce technological advances exogenously, and the simultaneous implementation of environmental regulation and government subsidy policies is more effective in promoting clean technological innovation.

3.4. Environmental Quality and Economic Growth Effects

The analysis above shows that heterogeneous environmental policies significantly contribute to the green technology bias of technological progress, regardless of the R&D approach chosen by the firm. The difference is that when firms choose to conduct their own R&D, the higher the intensity of environmental policies is, the higher the R&D efficiency parameter, and the more significant the green technology bias effect. In addition, green technological innovation is more influenced by the intensity of environmental policies. When technological progress is introduced exogenously, the simultaneous implementation of environmental policies promotes green technology bias more than the single implementation of environmental policies.

Having completed the theoretical analysis at the firm level, the issue of environmental quality and economic growth arising from heterogeneous environmental policies is further examined. First, we investigate how environmental policy affects environmental quality by assuming that individuals have no savings and that all current output is used for consumption. Thus, consumption equals the amount of output, i.e., $C_t = c_t L_t = Y$. Additionally, the utility of an individual is determined by consumption and environmental quality. c_t denotes the individual's consumption, and Q_t indicates environmental quality. The individual's utility function satisfies the following equation:

$$U_t = \ln c_t + \ln Q_t \tag{20}$$

The effectiveness function satisfies $\lim_{c_t \to 0} \frac{\partial U_t}{\partial c_t} = \infty$, $\lim_{Q_t \to 0} \frac{\partial U_t}{\partial Q_t} = \infty$. Environmental quality Q_t is based on stock pollution in the previous period S_{t-1} and flow pollution in the current period P_t. The relationship between S_t and Q_t satisfies $S_t = (1-\theta)S_{t-1} + P_t; Q_t = {S_t}^{\rho}$. Clean technology A_{ct} has a purifying effect on pollution emissions such that $P_t = rY_{Nt}/{A_{ct}}^{\frac{A_{ct}}{A_{Nt}}}$, where r is the carbon emission intensity factor for the dirty sector, θ represents the self-restoring capacity of the environment, and ρ is the transformation parameter between stock pollution and environmental quality ($\rho < 0$). The environmental quality Q_t and R&D subsidies τ_c can be obtained. The following relationship can be observed:

$$\frac{\partial Q_t}{\partial \tau_c} = \rho {S_t}^{\rho-1} {A_{ct}}^{-\frac{A_{ct}}{A_{Nt}}} r \left[-A_{Nt}^{-1} (\ln A_{ct} + 1) \frac{\partial A_t}{\partial \tau_c} Y_{Nt} + \frac{\partial Y_{Nt}}{\partial \tau_c} \right] \tag{21}$$

where

$$\frac{\partial A_{ct}}{\partial \tau_c} = A_{ct-1} \vartheta \frac{\varphi}{1-\varphi} \xi_c^{\frac{1}{1-\varphi}} {\tau_c}^{\frac{2\varphi-1}{1-\varphi}}; \frac{\partial Y_{Nt}}{\partial \tau_c} = \alpha^{\frac{2\alpha}{1-\alpha}} (1-\tau_N)^{\frac{\alpha}{1-\alpha}} A_{Nt} \frac{\partial L_{Nt}}{\partial \tau_c}; \tag{22}$$

$$\frac{\partial L_{Nt}}{\partial \tau_c} = \frac{-(\varepsilon-1) A_{Nt}^{\varepsilon-1} A_{ct}^{\varepsilon-2} (1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}} \frac{\partial A_{ct}}{\partial \tau_c}}{\left[A_{Nt}^{\varepsilon-1} + A_{ct}^{\varepsilon-1} (1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}} \right]^2} \tag{23}$$

Therefore,

$$\frac{\partial A_a}{\partial \tau_c} = A_{ct-1} \vartheta \frac{\varphi}{1-\varphi} \xi_c^{\frac{1}{1-\varphi}} {\tau_c}^{\frac{2\varphi-1}{1-\varphi}} > 0 \text{ and } \rho < 0 \tag{24}$$

when $\varepsilon > 1$, $\partial Y_{Nt}/\partial \tau_c < 0$, $\partial A_{ct}/\partial \tau_c > 0$. That is, as the intensity of R&D subsidies τ_c increases, the production of dirty product Y_{Nt} decreases, and pollutant emissions are reduced. In contrast, as the intensity of R&D subsidies τ_c decreases, the level of clean technology increases, and the quality of the environment improves. This is followed by a discussion of environmental quality Q_t and environmental regulation τ_N. The following relationship exists:

$$\frac{\partial Q_t}{\partial \tau_N} = \rho {S_t}^{\rho-1} \left[r A_{Nt}^{-2} \ln A_{ct} {A_{ct}}^{1-\frac{A_{ct}}{A_{Nt}}} \frac{\partial A_{Nt}}{\partial \tau_N} Y_{Nt} + r {A_{ct}}^{-\frac{A_{ct}}{A_{Nt}}} \frac{\partial Y_{Nt}}{\partial \tau_N} \right] \tag{25}$$

where

$$\frac{\partial A_{Nt}}{\partial \tau_N} = -A_{Nt-1} \vartheta \frac{\varphi}{(1-\varphi)(1-\alpha)} \xi_N^{\frac{1}{1-\varphi}} (1-\tau_N)^{\frac{\varphi}{(1-\varphi)(1-\alpha)}-1}; \tag{26}$$

$$\frac{\partial Y_{Nt}}{\partial \tau_N} = \alpha^{\frac{2\alpha}{1-\alpha}} \left[-\frac{\alpha}{1-\alpha} (1-\tau_N)^{\frac{2\alpha}{1-\alpha}} A_{Nt} L_{Nt} + (1-\tau_N)^{\frac{\alpha}{1-\alpha}} \left(\frac{\partial L_{Nt}}{\partial \tau_N} A_{Nt} + L_{Nt} \frac{\partial A_{Nt}}{\partial \tau_N} \right) \right]; \tag{27}$$

$$\frac{\partial L_{Nt}}{\partial \tau_N} = \frac{(1-\tau_N)^{\frac{2\alpha-\varepsilon-1}{1-\alpha}} A_{Nt}^{\varepsilon-2} A_{ct}^{\varepsilon-1} \left[(1-\tau_N)(\varepsilon-1) \frac{\partial A_{Nt}}{\partial \tau_N} + \frac{\alpha-\varepsilon}{1-\alpha} A_{Nt} \right]}{\left[A_{Nt}^{\varepsilon-1} + A_{ct}^{\varepsilon-1} (1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}} \right]^2} \tag{28}$$

Therefore,

$$\frac{\partial A_{Nt}}{\partial \tau_N} = -A_{Nt-1} \vartheta \frac{\varphi}{(1-\varphi)(1-\alpha)} \xi_N^{\frac{1}{1-\varphi}} (1-\tau_N)^{\frac{\varphi}{(1-\varphi)(1-\alpha)}-1} < 0 \text{ and } \rho < 0 \tag{29}$$

when $\varepsilon > 1$ and when $\partial Y_{Nt}/\partial \tau_N < 0$, $\partial A_{Nt}/\partial \tau_N < 0$. That is, as the intensity of environmental regulation τ_N increases, the output of dirty products decreases, along with the level of dirty technologies, thus improving environmental quality.

Thus, heterogeneous environmental policies significantly improve environmental quality by influencing the production of dirty goods as well as clean technological innovation. Again, the economic growth effects of environmental regulation are tested.

By simplifying Y_{ct}, Y_{Nt}, we substitute into (1) to obtain the final product Y:

$$Y = \alpha^{\frac{2\alpha}{1-\alpha}} A_t (1-\tau_N)^{\frac{\alpha}{1-\alpha}} L_t \tag{30}$$

where $A_t = \left[\frac{A_{ct}^{\varepsilon-1}(1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}+1} + A_{Nt}^{\varepsilon-1}}{\left[A_{Nt}^{\varepsilon-1} + A_{ct}^{\varepsilon-1}(1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}}\right]^{\frac{\varepsilon-1}{\varepsilon}}} \right]^{\frac{\varepsilon}{\varepsilon-1}}$ and both sides of the equation are for time t. Derive and organise to obtain the growth rate of the final good, i.e., the economic growth rate.

$$g = \frac{\dot{A}_t}{A_t} = n + \frac{\varepsilon e_t (1-\tau_N) g_{ct} + \varepsilon g_{Nt}}{e_t(1-\tau_N)+1} - \frac{e_t(\varepsilon-1) g_{ct} + (\varepsilon-1) g_{Nt}}{e_t+1} \tag{31}$$

In the above equation, $e_t = \frac{A_{Nt}^{\varepsilon-1}}{A_{ct}^{\varepsilon-1}}(1-\tau_N)^{\frac{\alpha-\varepsilon}{1-\alpha}}$.

- If $g_{ct} > g_{Nt}$, technological progress is in a clean direction; when $\lim\limits_{t\to\infty} g = n + g_{ct}$, the first-order partial derivative yields $\frac{\partial g}{\partial \tau_c} = \frac{\partial g_{ct}}{\partial \tau_c} > 0$. In the long run, government subsidies contribute to economic growth, while economic growth under environmental regulation cannot be determined.
- If $g_{ct} = g_{Nt}$, at this point, $\lim\limits_{t\to\infty} g = n + g_{ct} = n + g_{Nt}$. The first-order partial derivative yields $\frac{\partial g}{\partial \tau_c} = \frac{\partial g_{ct}}{\partial \tau_c} > 0$. Furthermore, the first-order partial derivative yields $\frac{\partial g}{\partial \tau_N} = \frac{\partial g_{ct}}{\partial \tau_N} < 0$. Government subsidies promote economic growth, but environmental regulation has a negative effect on economic growth in the long run.
- If $g_{ct} < g_{Nt}$, at this point, $\lim\limits_{t\to\infty} g = n + g_{Nt}$, the first-order derivative of this is $\frac{\partial g}{\partial \tau_N} = \frac{\partial g_{ct}}{\partial \tau_N} < 0$. That is, environmental regulation inhibits economic growth when technological progress is chronically biased towards dirty technological innovation.

Conclusion C3. Heterogeneous environmental policies improve environmental quality and promote economic growth by changing the direction of technological progress, and the effects of environmental policies on environmental quality under different technological endowments are significant. Appropriate environmental regulation and government subsidy policies will promote the compatible development of economic growth and environmental quality only when technological progress is biased towards clean technologies. Otherwise, environmental regulation will only put environmental quality and economic growth in a dilemma.

4. Econometric Model Design and Data

4.1. Variable Construction

There are three main types of measurements of green technological innovation in the clean sector: traditional measures to decompose technological progress based on the production decomposition rate; the Solow residual approach to express technological progress using regression residuals, such as the principal component method and data envelopment analysis; or selecting the number of green technology invention patents granted to express green technological progress. We used the number of green patents granted to represent green technological progress in the clean sector. We do so because green factor inputs and outputs are difficult to distinguish from production and the statistics of green patents well reflect the overall level and scale of green technological innovation. Thus, this paper obtains different city-level patent data from the State Intellectual Property Office's

China Patent Distribution Bulletin website by setting the type of patent, International Patent Classification (IPC) classification code and the address of the inventing unit based on the IPC code of green patents.

To calculate the intensity of environmental regulation, we drew on the common practice of scholars. To determine environmental regulations, we chose the concept of local regulations. First, pollutant emissions per unit of economic output are calculated to ensure comparability, standardising the formula $\mathrm{DE}_{\mathrm{ij}}^{\mathrm{s}} = \frac{\left[\mathrm{DE}_{\mathrm{ij}} - \min\left(\mathrm{DE}_{\mathrm{j}}\right)\right]}{\left[\max\left(\mathrm{DE}_{\mathrm{j}}\right) - \min\left(\mathrm{DE}_{\mathrm{j}}\right)\right]}$, where $\mathrm{DE}_{\mathrm{ij}}^{\mathrm{s}}$ is the emissions after standardisation and $\mathrm{DE}_{\mathrm{ij}}$ is the pre-standardised emissions. $\max\left(\mathrm{DE}_{\mathrm{j}}\right)$ and $\min\left(\mathrm{DE}_{\mathrm{j}}\right)$ represent the maximum and minimum emissions of pollutant j per year, respectively. Second, the differences in pollution between individual cities are specifically reflected using an adjustment parameter, calculated as $\omega_{\mathrm{ij}} = \frac{\mathrm{E}_{\mathrm{ij}}}{\sum \mathrm{E}_{\mathrm{ij}}}$, where ω_{ij} denotes the adjustment factor and E_{ij} denotes the initial emissions of the pollutant. Finally, the environmental regulation intensity is calculated for each city: $\mathrm{ER}_{\mathrm{i}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{j}=1}^{\mathrm{n}} \omega_{\mathrm{ij}} \mathrm{DE}_{\mathrm{ij}}^{\mathrm{s}}$.

The environmental pollution Q is expressed as the average of unit sulphur dioxide emissions, unit industrial soot emissions and industrial wastewater emissions. In addition, government subsidies are expressed in terms of scientific R&D expenditure at the prefecture level, and the level of economic development is expressed in terms of GDP per capita at the prefecture level. To reduce bias in the results, various control variables, such as the share of secondary production, the innovation index and regional fixed assets, were also controlled.

4.2. Data Sources and Descriptive Statistics

In Table 2, we describe the basic statistical information related to our main variables. The variables were obtained from the China Statistical Yearbook, the China Environment Yearbook and the China Patent Full Text Database. We excluded cities with severe amounts of missing data. Finally, 2009–2016 panel data on 281 prefecture-level cities in China were used.

Table 2. Summary statistics of the main variables.

Variable Symbol	Variable Name	Mean	Std. Dev.	Min	Max	Obs
Green patent	Green technological innovation	3.674	1.706	0	8.782	2248
Q	Environmental quality	57.811	26.687	11.916	264.171	2248
E_regulation	Environmental regulation	0.659	0.168	0	1.252	2248
Subsidy	Government subsidy	10.042	1.319	6.624	15.202	2248
Financial freedom	Financial freedom	2.705	1.911	0.647	31.853	2248
S_GDP	Share of secondary production in GDP	49.496	10.373	14.95	89.75	2248
Population	Total population at year end	5.877	0.693	2.970	8.129	2248
Innovation Index	Innovation Index	11.292	50.901	0.01	1061.37	2248
Fixed assets	Fixed assets	16.871	0.952	14.403	19.925	2248
E_develop	Level of economic development	16.358	0.927	13.687	19.457	2248

5. Empirical Results

As Conclusions C1 and C2 show that there is a technology bias effect in heterogeneous environmental policies, we first tested whether environmental policies can drive technological progress in a clean direction. In doing so, we explored the bias effect of environmental regulation and government subsidies separately and simultaneously, and the degree of bias. On this basis, the impact of environmental policy on environmental quality and economic growth was further tested to verify Conclusion C3.

5.1. A Test of the Direction of Technological Progress in Heterogeneous Environmental Policies

According to Conclusion C1, heterogeneous environmental policies influence environmental policy effects by shifting the direction of technological progress. Therefore, we first examined the relationship between environmental policy and green technological innovation. It has been argued that the relationship between the two does not show a simple linear relationship and that government policy effects are often in a dynamic state of flux. Thus, we constructed linear and nonlinear models of environmental policy, government subsidies and the direction of technological progress under a single policy:

$$\begin{gathered}
\text{Green Patent}_{i,t} = \alpha_0 + \beta_0\text{E\_regulation}_{i,t} + \gamma_0 X_{it} + V_i + U_i + \varepsilon_{it} \\
\text{Green Patent}_{i,t} = \alpha_1 + \beta_1\text{E\_regulation}_{i,t} + \beta_2(\text{E\_regulation}_{i,t})^2 + \gamma_1 X_{it} + V_i + U_i + \varepsilon_{it} \\
\text{Green Patent}_{i,t} = \alpha_0 + \beta_0\text{Subsidy}_{i,t} + \gamma_0 X_{it} + V_i + U_i + \varepsilon_{it} \\
\text{Green Patent}_{i,t} = \alpha_1 + \beta_1\text{Subsidy}_{i,t} + \beta_2\left(\text{Subsidy}_{i,t}\right)^2 + \gamma_1 X_{it} + V_i + U_i + \varepsilon_{it}
\end{gathered} \tag{32}$$

where the explanatory variable Green Patent indicates the direction of technological progress in the environment, X_{it} are the control variables, V_i are area fixed effects, U_i is a time fixed effect, α_0 is an intercept term that does not vary with individuals, and ε_{it} is a random error term. We also investigated the impact of environmental policies on 281 prefecture-level cities in Eastern, Western and Central China because each region has different levels of economic development and pays different levels of attention to the environment. Furthermore, since the "One Belt, One Road" initiative was proposed in 2013, China has been committed to improving the livelihoods of the countries along the route and promoting green development over the past eight years, and has signed co-operation agreements on ecological and environmental protection with many countries along the route. We further classified prefecture-level cities into "Belt and Road" cities (B&R) and non-Belt and Road cities (Neither). The results of the test are shown in Table 3.

Table 3. Direction of technological progress.

Explained Variable: Green Patent						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	East	**Central**	**Western**	**B&R**	**Neither**	**All**
Panel A: Directions for technological progress under environmental regulation						
Linear model:						
E_regulation	−0.0968	0.3615	−1.5219 ***	0.0724	−0.7134 ***	−0.6604 ***
	(0.2452)	(0.4038)	(0.3158)	(0.3810)	(0.1896)	(0.1767)
Nonlinear models:						
E_regulation	−0.1372	1.3266	1.1727	−0.7442	1.1425 **	0.8518 *
	(0.6032)	(1.1477)	(0.8963)	(0.7682)	(0.5220)	(0.4663)
$(\text{E\_regulation})^2$	0.0797	−1.4463	−2.9364 **	1.0146	−2.1706 **	−1.7447 **
	(0.8154)	(1.6176)	(1.1385)	(1.0559)	(0.6972)	(0.6246)
Panel B: The direction of technological progress with government subsidies						
Linear model:						
Subsidy	0.1679 ***	0.2868 ***	0.2543 ***	0.1749 **	0.2726 ***	0.2700 ***
	(0.0472)	(0.0773)	(0.0721)	(0.0858)	(0.0371)	(0.0347)
Nonlinear models:						
Subsidy	0.0301 **	0.0088	−0.0739 **	0.0740 ***	−0.0133	−0.0067
	(0.0140)	(0.0285)	(0.0298)	(0.0174)	(0.0130)	(0.0107)
$(\text{Subsidy})^2$	−0.4266	0.0959	1.6464 **	−1.4958 ***	0.5204 **	0.3890 *
	(0.2859)	(0.5827)	(0.5672)	(0.4046)	(0.2601)	(0.2166)
X_{it}	Yes	Yes	Yes	Yes	Yes	Yes
Year Control	Yes	Yes	Yes	Yes	Yes	Yes
Region Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	960	624	664	200	2048	2248

Notes: Robust standard errors in parentheses; *** denotes significance at 1%, ** at 5%, and * at 10%.

As shown in Panel A of Table 3, the effectiveness of environmental regulation in shifting technological progress is significantly negative under the linear model scenario. In particular, green technological innovation is negatively affected by environmental regulation in the Western region and cities classified as Neither. This may be due to the lack of a mechanism to identify the categories of enterprises in the initial environmental policies, which affected the clean sector. In the discussion of the nonlinear model, the quadratic coefficient of environmental regulation is significantly negative, and the primary coefficient is significantly positive, showing an inverted U-shaped relationship between environmental regulation and green technological innovation in the overall sample. This result suggests that as the intensity of environmental regulation increases, the level of green technological innovation first increases and then decreases, and that at higher levels of regulation-like policy intensity, environmental regulation inhibits both dirty technological innovation and green technological innovation.

The linear model in Panel B of Table 3 shows that the effect of government subsidies on green technological progress is significantly positive at the 1% level. The positive effect of government subsidies on green technological innovation is significant in the sample as a whole and in the heterogeneous sample subgroups. In the nonlinear model, Western cities and Belt and Road cities show very different results, with government subsidies and green technological progress in Western cities showing a U-shaped relationship. That is, as the intensity of government subsidies increases, green technological progress first decreases and then increases. In the Belt and Road cities, government subsidies and green technological progress show an inverted U-shaped relationship. That is, as the intensity of government subsidies increases, green technological innovation first increases and then decreases. The above phenomenon may occur because, due to the backwards development of green technology in Western cities, R&D subsidies were used more often to improve basic R&D facilities in the early stage of government subsidies. Only when the intensity of R&D subsidies reached a certain level and the infrastructure support was complete did the level of green technology meet the conditions for rapid development. A U-shaped relationship can be observed in Western cities. In Belt and Road cities, however, the initial government subsidies have a significant effect on the improvement of green technological innovation due to the long-standing green development concept and the high level of green technology. Therefore, for Belt and Road cities, government subsidies should be kept within a reasonable range to rationalize the allocation of resources.

5.2. Testing the Environmental and Economic Effects of Heterogeneous Policies

After verifying that heterogeneous environmental policies change the direction of technological progress, the model was extrapolated to show that environmental policies reduce environmental pollution and promote economic growth by changing the direction of technological progress. To test whether heterogeneous environmental policies can affect environmental quality and economic development, we further modeled the environmental quality and economic growth effects of heterogeneous policies:

$$\begin{aligned} \mathrm{Q_{it}} &= \alpha_0 + \beta_1 \mathrm{E\_regulation}_{i,t} + \beta_2 (\mathrm{E\_regulation}_{i,t})^2 + \beta_3 \mathrm{Subsidy}_{i,t} + \beta_4 \left(\mathrm{Subsidy}_{i,t}\right)^2 + \gamma_0 \mathrm{X_{it}} + \mathrm{V_i} + \mathrm{U_i} + \varepsilon_{it} \\ \mathrm{E\_evelop}_{i,t} &= \alpha_0 + \beta_1 \mathrm{E\_regulation}_{i,t} + \beta_2 (\mathrm{E\_regulation}_{i,t})^2 + \beta_3 \mathrm{Subsidy}_{i,t} + \beta_4 \left(\mathrm{Subsidy}_{i,t}\right)^2 + \gamma_0 \mathrm{X_{it}} + \mathrm{V_i} + \mathrm{U_i} + \varepsilon_{it} \end{aligned} \tag{33}$$

Table 4 shows that the primary coefficient of environmental regulation is significantly positive and that the secondary coefficient is significantly negative. This result indicates that as the intensity of environmental regulation increases, the emission of pollutants first increases and then decreases, and that there is a threshold for the emission reduction effect of environmental regulation. At the same time, the primary and secondary coefficients of environmental regulation are not significant in Belt and Road cities, which may be related to the fact that Belt and Road cities have been promoting the concept of green development for a long time. In addition, the primary coefficient of government subsidies in Table 4 is significantly negative, and the secondary coefficient is significantly positive. However, as the intensity of government subsidies continues to increase, government subsidies increase productivity while reducing emissions, thus increasing pollutant emissions. Thus, there is an optimal subsidy intensity for government subsidies. In addition, Table 4 shows that the innovation index significantly reduces the emission of environmental pollutants, while the remaining control variables all aggravate environmental pollution to varying degrees. The economic growth effect of the direction of technological progress is further tested as follows.

Table 4. Environmental effects test.

Variables	**Explained Variable: Environmental Quality Q**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	East	**Central**	**Western**	**B&R**	**Neither**	**All**
$(\text{E\_regulation})^2$	−1.4181	−2.2011 **	−3.0522 **	−0.2061	−2.3076 ***	−2.3970 ***
	−0.9229	−0.7375	−1.0925	−2.2846	−0.5593	−0.5641
E_regulation	6.3473 ***	6.6623 ***	7.8581 ***	2.3477	7.3661 ***	7.3096 ***
	−1.2436	−1.0389	−1.3723	−3.063	−0.743	−0.7501
$(\text{Subsidy})^2$	0.2008 ***	0.0683 ***	0.1916 ***	0.2310 ***	0.1035 ***	0.1539 ***
	−0.0216	−0.0186	−0.0363	−0.0555	−0.0141	−0.0131
Subsidy	−3.9875 ***	−1.4797 ***	−3.8612 ***	−5.2134 ***	−2.0988 ***	−3.1117 ***
	−0.443	−0.3788	−0.6918	−1.2813	−0.2817	−0.2649
Fixed assets	1.9631 ***	−0.4902 **	−0.0862	4.7996 ***	0.2972 *	0.6066 ***
	−0.2686	−0.2304	−0.3184	−0.9899	−0.1534	−0.1617
S_GDP	−0.0123	0.0183 **	0.0166 **	0.0567	0.0129 **	0.0131 **
	−0.0087	−0.0071	−0.0083	−0.0419	−0.0046	−0.0049
Innovation Index	−0.0103 ***	0.0124 ***	−0.0161 **	−0.0072 ***	−0.0086 ***	−0.0092 ***
	−0.0007	−0.003	−0.0059	−0.0021	−0.0007	−0.0006
Financial freedom	0.0241	0.0512	0.0352 *	−0.6446 *	0.0281 **	0.0337 **
	−0.0356	−0.0329	−0.0209	−0.3666	−0.0139	−0.0151
Population	0.0133 ***	0.0026 ***	0.0042	0.0047 **	0.0042 ***	0.0036 ***
	−0.0024	−0.0006	−0.0027	−0.0018	−0.0011	−0.0009
Constant	−3.8076	15.9626 ***	31.4974 ***	−45.9903 *	14.3979 ***	14.8070 ***
	−5.819	−4.6151	−6.5285	−23.3768	−3.0485	−3.2003
Year Control	Yes	Yes	Yes	Yes	Yes	Yes
Region Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	960	624	664	200	2048	2248
R-squared	0.585	0.795	0.578	0.685	0.589	0.575

Notes: Robust standard errors in parentheses; *** denotes significance at 1%, ** at 5%, and * at 10%.

Table 5 shows the economic effects of environmental regulation and government subsidies. If the intensity of environmental regulation continues to increase in the future, it may inhibit output growth and hinder economic growth. Table 5 also shows the impact of government subsidies on the level of economic development. The primary coefficient of government subsidies is significantly negative, and the secondary coefficient is significantly positive, while government subsidies and the level of economic development show a U-shaped relationship. This result indicates that government subsidies do not boost economic growth in the short term; however, in the long term, government subsidies are significantly advantageous for economic growth. In addition, the regression coefficient of fiscal freedom is significantly negative, indicating that the higher the fiscal ratio is, the less favourable the local economic growth. All the control variables, except for the fiscal ratio GOV, significantly contribute to economic growth.

Table 5. Tests of the economic growth effect.

Variables	**Explanatory Variable: Level of Regional Economic Development (E_Develop)**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	East	**Central**	**Western**	**B&R**	**Neither**	**All**
$(\text{E\_regulation})^2$	−0.1383 *	0.0994	−0.0853	−0.2476 **	−0.1098 *	−0.1395 **
	−0.0824	−0.0975	−0.0877	−0.1013	−0.0564	−0.0524
E_regulation	0.2040 *	−0.1504	0.2534 **	0.3066 **	0.1920 **	0.2331 ***
	−0.111	−0.1374	−0.1102	−0.1358	−0.0749	−0.0697
$(\text{Subsidy})^2$	0.0091 ***	−0.0022	0.0144 ***	0.004	0.0084 ***	0.0083 ***
	−0.0019	−0.0025	−0.0029	−0.0025	−0.0014	−0.0012
Subsidy	−0.1218 **	0.0798	−0.2551 ***	−0.082	−0.1138 ***	−0.1132 ***
	−0.0396	−0.0501	−0.0555	−0.0568	−0.0284	−0.0246
Fixed assets	0.0906 ***	0.1246 ***	0.2399 ***	0.2740 ***	0.1679 ***	0.1700 ***
	−0.024	−0.0305	−0.0256	−0.0439	−0.0155	−0.015
S_GDP	0.0190 ***	0.0131 ***	0.0148 ***	0.0017	0.0167 ***	0.0163 ***
	−0.0008	−0.0009	−0.0007	−0.0019	−0.0005	−0.0005
Innovation Index	0.0001 **	0.0023 ***	−0.0003	0.0003 ***	0.0001	0.0002 ***
	−0.0001	−0.0004	−0.0005	−0.0001	−0.0001	−0.0001
Financial freedom	−0.0161 ***	−0.0199 ***	0.0030 *	−0.0330 **	−0.0052 ***	−0.0053 ***
	−0.0032	−0.0043	−0.0017	−0.0163	−0.0014	−0.0014
Population	0.0007 ***	0.0005 ***	0.0014 ***	0.0002 **	0.0012 ***	0.0007 ***
	−0.0002	−0.0001	−0.0002	−0.0001	−0.0001	−0.0001
Constant	−7.7840 ***	−7.8980 ***	−8.6859 ***	−8.7632 ***	−8.2530 ***	−8.1453 ***
	−0.5195	−0.6103	−0.5241	−1.0368	−0.3074	−0.2974
Year Control	Yes	Yes	Yes	Yes	Yes	Yes
Region Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	960	624	664	200	2048	2248
R-squared	0.952	0.978	0.968	0.985	0.959	0.959

Notes: Robust standard errors in parentheses; *** denotes significance at 1%, ** at 5%, and * at 10%.

The above analysis shows that the effect of heterogeneous policies on environmental quality and economic development is significant. The impact of environmental regulation on environmental quality and economic development has an inverted U-shaped relationship, with a minimum threshold for emission reduction and a maximum ceiling for promoting economic growth for the intensity of regulations. When these two points correspond to different levels of environmental regulation intensity, economic growth and environmental quality are hardly compatible. Similarly, the impact of government subsidies on environmental quality and economic development has a U-shaped relationship, with a maximum upper limit for government subsidies to reduce emissions and a minimum threshold point to promote economic development. Therefore, a single implementation of environmental regulation or government subsidies can easily lead to a dilemma between economic growth and environmental quality, which confirms Conclusion C3.

5.3. Testing for Policy Mix Effects

To test Conclusion C2 and to test whether a combination of policies is more significant than a single policy effect, the following regression analysis was constructed using the cross-product ES of subsidies and environmental regulations:

$$\begin{gathered}\text{Green Patent}_{i,t}=\alpha_0+\beta_1\text{ES}_{i,t}+\gamma_0\text{X}_{it}+\text{V}_i+\text{U}_i+\varepsilon_{it}\\ \text{Q}_{it}=\alpha_1+\beta_2\text{ES}_{i,t}+\gamma_1\text{X}_{it}+\text{V}_i+\text{U}_i+\varepsilon_{it}\\ \text{E\_develop}_{i,t}=\alpha_2+\beta_3\text{ES}_{i,t}+\gamma_2\text{X}_{it}+\text{V}_i+\text{U}_i+\varepsilon_{it}\end{gathered}\quad(34)$$

As shown in column (3) of Table 6, the coefficient of the interaction term between government subsidies and environmental regulations is significantly positive at the 1% level.

These results indicate that the combination of government subsidies and environmental regulations has a positive effect on technological innovation and that the shift effect of the combined policy is better than that of a single policy. The coefficient of the cross-product of government subsidies and environmental regulations in column (6) is significantly negative at the 1% level, and the interaction term between government subsidies and environmental regulations significantly reduces the emission of environmental pollutants. When the economic effects of environmental regulations and government subsidies were examined in isolation, it was found that both significantly contribute to an increase in the level of economic development. However, the coefficient of the interaction term is not significant, indicating that the combined effect of environmental regulations and government subsidies is not enhanced when testing the level of economic development. The above analysis suggests that the implementation of environmental regulations along with appropriate R&D subsidies will reinforce the shift in the direction of green technological progress and be more conducive to reducing regional pollutant emissions, thus validating Conclusion C2.

Table 6. Tests of the effects of the policy mix.

Variables	**Green Patent**			**Q**			**E_Develop**		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
E_regulation	−0.6378 ***		−3.5057 ***	0.0359 *		0.0656 **	0.0502 **		0.0570 **
	(0.1647)		(0.1090)	(0.0216)		(0.0242)	(0.0209)		(0.0224)
Subsidy		0.2599 ***	−0.1338 ***		−0.0039	0.0004		0.0520 ***	0.0520 ***
		(0.0317)	(0.0200)		(0.0042)	(0.0044)		(0.0039)	(0.0041)
ES			0.1003 ***			−0.0010 **			0.0002
			(0.0017)			(0.0004)			(0.0003)
Fixed assets	0.1503	0.0830	0.2782 ***	0.1148 ***	0.1147 ***	0.1139 ***	0.1705 ***	0.1490 ***	0.1519 ***
	(0.1229)	(0.1216)	(0.0728)	(0.0161)	(0.0162)	(0.0162)	(0.0156)	(0.0150)	(0.0150)
S_GDP	0.0180 ***	0.0109 **	0.0065 **	0.0019 ***	0.0020 ***	0.0021 ***	0.0173 ***	0.0160 ***	0.0159 ***
	(0.0037)	(0.0037)	(0.0022)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Innovation Index	−0.0003	−0.0005	0.0003	−0.0004 ***	−0.0004 ***	−0.0004 ***	0.0004 ***	0.0003 ***	0.0003 ***
	(0.0005)	(0.0005)	(0.0003)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Financial freedom	0.0215 *	0.0252 **	0.0030	−0.0031 **	−0.0032 **	−0.0029 *	−0.0057 ***	−0.0055 ***	−0.0053 ***
	(0.0117)	(0.0116)	(0.0069)	(0.0015)	(0.0015)	(0.0015)	(0.0015)	(0.0014)	(0.0014)
Population	0.0010	0.0005	−0.0013 **	0.0001	0.0001	0.0001	0.0009 ***	0.0008 ***	0.0008 ***
	(0.0007)	(0.0007)	(0.0004)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Constant	−2.8638	−3.0016	−2.2640	0.7578 **	0.8036 **	0.7485 **	−8.7541 ***	−8.4859 ***	−8.5866 ***
	(2.4050)	(2.3609)	(1.4181)	(0.3151)	(0.3136)	(0.3149)	(0.3046)	(0.2904)	(0.2917)
Year Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2248	2248	2248	2248	2248	2248	2248	2248	2248
R-squared	0.638	0.648	0.875	0.710	0.710	0.711	0.954	0.958	0.958

Notes: Robust standard errors in parentheses; *** denotes significance at 1%, ** at 5%, and * at 10%.

6. Robustness Tests

6.1. Parallel Trend Test

This part of the empirical evidence aimed to test whether environmental regulation policies have improved environmental quality while promoting green technological progress. DID models are considered one of the most effective ways to assess policy effects. Since the years of implementation of environmental regulations vary from city to city, we used a time-varying DID approach with the following parallel trend test results.

As shown in Figure 1, green technological innovation was on a downwards trend prior to the implementation of environmental regulation, and emissions of environmental pollutants were on an upwards trend until 2011, slowing after 2012. Following the implementation of environmental regulation, the downwards trend in green technological innovation and the upwards trend in pollutant emissions were broken, and the trend in green technological innovation changed significantly, accompanied by a slowdown in pollutant emissions. On the other hand, the economic growth trend changed in approximately 2012. The above trends continued until the end of the sample period, and the above analysis shows a passing result of the parallel trend test.

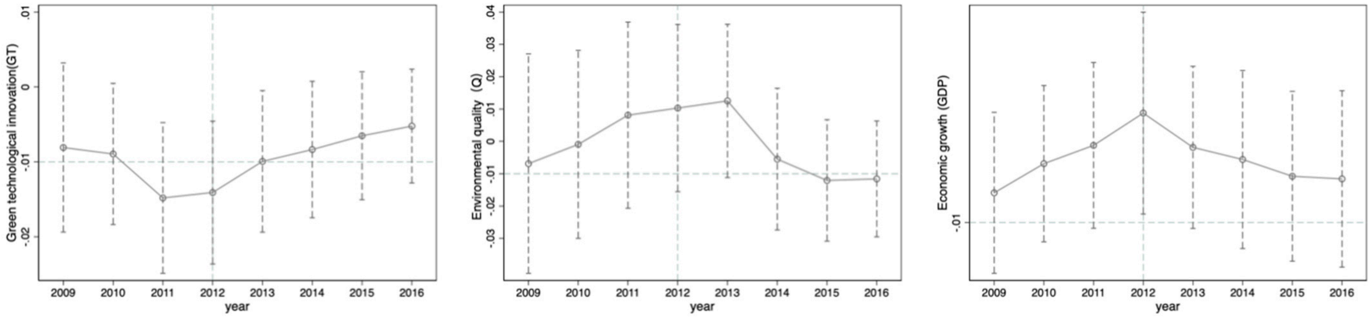

Figure 1. Parallel trend test.

6.2. Further Discussion

As shown in Table 1 in the literature review section, a rise in GDP is always accompanied by a rise in CO_2. What is the relationship between China's economic growth and CO_2 emissions? Different prefecture-level cities have different levels of development and policy choices due to their different factor endowments. Therefore, after verifying the above findings, the decomposition of economic growth and carbon emissions growth of China's prefecture-level cities from 2009 to 2016 is immediately followed by a discussion of the decoupling based on the decoupling state of each prefecture-level city.

The decoupling index method is widely used in studies to analyse economic growth, resource consumption, and pollutant emissions, and there are currently two main approaches to decoupling models in academia: the OECD approach and the Tapio decoupling approach [30]. The Tapio decoupling model was chosen in this paper, and the formula is derived as follows: $\mathrm{e(C)} = \frac{\Delta \mathrm{CO_2\%}}{\Delta \mathrm{GDP\%}}$, where $\mathrm{e(C)}$ denotes the elasticity of decoupling economic growth from carbon emissions and ΔCO_2 indicates the increase in total carbon emissions from the base period to the end of the period. The growth rate of the total volume of ΔGDP% denotes the growth rate of regional GDP from the base period to the end of the period. In reference to Wang, the decoupling states were subdivided into eight states based on the magnitude of the decoupling elasticity values [31], as shown in Figure 2.

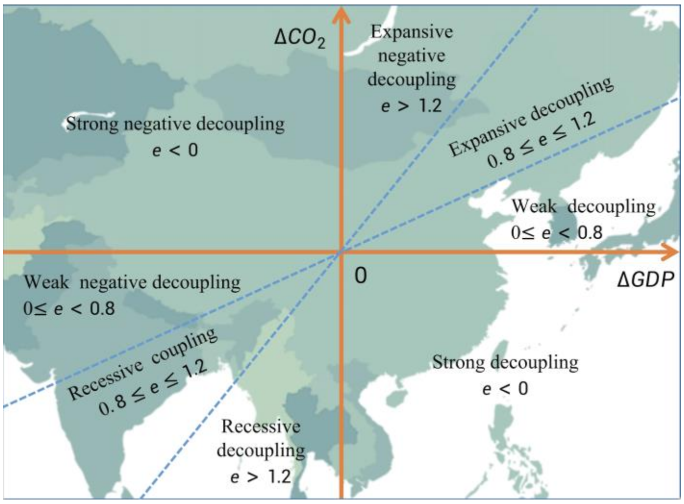

Figure 2. Schematic diagram of the decoupling states.

The only five categories of decoupling status measured for China's prefecture-level cities for the time periods 2009–2012, 2013–2016 and 2009–2016 were as follows: strong negative decoupling, expansive negative decoupling, expansive decoupling, weak decoupling and strong decoupling.

As shown in Figure 3, with 2012 as the cut-off point, the strong decoupling status increased significantly after the implementation of environmental policies. Except for a very few cities where the decoupling state worsened after the implementation of environmental policies, the decoupling state in most cities developed in a positive direction. Figure 3 illustrates that heterogeneous environmental policies accelerated the decoupling of economic growth and carbon emissions. The decoupling states of cities are shown in Table 7.

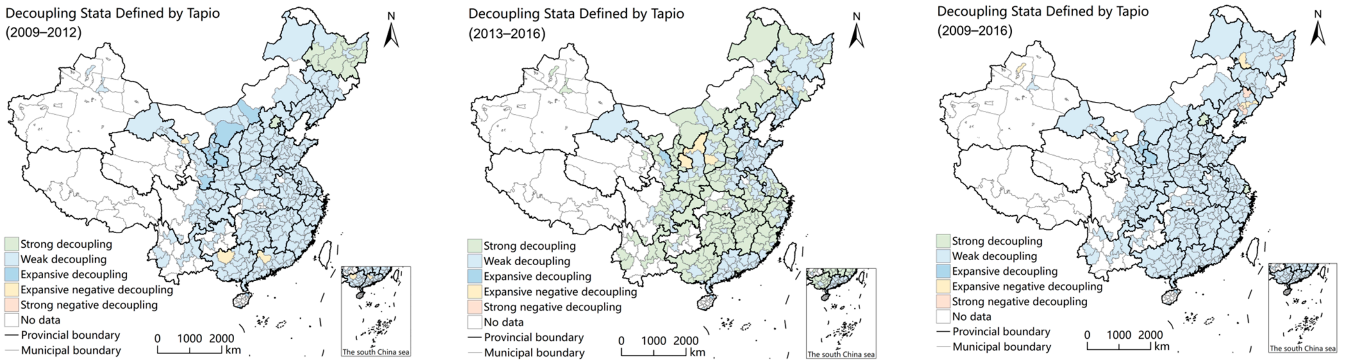

Figure 3. Decoupling states of carbon-related and economic output for 281 Chinese cities. Note: The basic map comes from the National Geomatics Centre of China and the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.

Table 7. Urban decoupling states.

e	Degree of Decoupling	ΔCO_2	ΔY	City Representatives
$(e < 0)$	Worst	Positive	Negative	Anshan, Jiayuguan, Qitaihe, Tieling
$(e \geq 1.2)$	Slightly worse	Positive	Positive	Benxi, Daqing, Jinchang, Karamay, Liaoyang
$(0.8 \leq e < 1.2)$	General	Positive	Positive	Haikou, Qingyang, Shizuishan, Wuzhong
$(0 \leq e < 0.8)$	Better	Positive	Positive	266 prefecture-level cities, including Ankang, Anqing and Anshun
$(e < 0)$	Best	Negative	Positive	Beijing, Shanghai

The table above shows that the four cities with the worst decoupling states in China from 2009–2016 were Anshan, Jiayuguan, Qitaihe and Tieling, while Benxi, Daqing, Jinchang, Karamay and Liaoyang had a slightly worse decoupling state. Anshan, Tieling, Benxi, Daqing, Liaoyang and Qingyang are all old heavy industrial bases and demonstrated difficulty in breaking away from their traditional development patterns. Other cities, such as Jiayuguan, have a secondary production rate of over 60%, with a large proportion of traditional manufacturing industries dominated by steel and aluminium and a low proportion of new industries and modern services, making the transition relatively slow. As a coal industry city born from coal, Qitaihe is a typical coal resource city. As cities with large mineral resources, Karamay, Wuzhong and Shizuishan also had difficulty breaking away from the traditional model of relying on energy for economic development. The decoupling relationship between carbon emissions and economic growth in the cities above varies, as does the effectiveness of the implementation of environmental policies. Therefore, when discussing the effects of environmental policies, it is necessary to categorise them, defining the cities with a good decoupling state as S1, those with a worst, slightly worse and average decoupling state as S2, and excluding the cities where there has been complete decoupling (Beijing and Shanghai).

As shown in Table 8, the empirical results for cities with better decoupling states are consistent with the previous section, and the heterogeneity test is further validated.

Furthermore, environmental regulation is not significant in all columns of S2, indicating that environmental regulation does not have a significant effect on cities with poor decoupling states. In poorer cities, as the intensity of government subsidies increases, the level of economic development first decreases and then increases, and the economic effect of government subsidies is significant. The share of secondary industries in the control variables also has a significant impact on economic development and environmental quality. Specifically, the share of secondary industries promotes economic growth while aggravating environmental pollution. Therefore, for old industrial cities and cities with large resources, to make economic growth and environmental quality compatible, environmental policies should be adjusted in the future based on their actual situation in terms of their industrial structure.

Table 8. Further discussion.

Variables	Green Patent		Q		E_Develop	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	S1	**S2**	**S1**	**S2**	**S1**	**S2**
ES	0.2850 **	−0.2764	0.4319 ***	−0.3912	−0.0168	−0.0273
	(0.0957)	(0.4331)	(0.1154)	(0.4433)	(0.0108)	(0.0573)
(E_regulation)^2	0.3071	1.4583	−2.8168 ***	−1.7222	−0.0495	−0.5230
	(0.4613)	(2.4589)	(0.5559)	(2.5166)	(0.0519)	(0.3253)
E_regulation	−3.7474 ***	−1.0634	3.7884 **	7.8588	0.2761 **	0.9932
	(0.9811)	(4.9864)	(1.1825)	(5.1035)	(0.1103)	(0.6598)
(Subsidy)^2	0.0242 **	−0.0575	0.1268 ***	−0.0238	0.0065 ***	0.0438 ***
	(0.0110)	(0.0755)	(0.0133)	(0.0772)	(0.0012)	(0.0100)
Subsidy	−0.4035 *	1.2991	−2.8817 ***	0.7451	−0.0720 **	−0.7639 ***
	(0.2314)	(1.4715)	(0.2789)	(1.5061)	(0.0260)	(0.1947)
Fixed assets	0.0504	0.2214	0.6605 ***	−0.4286	0.1774 ***	−0.0494
	(0.1283)	(0.5269)	(0.1547)	(0.5393)	(0.0144)	(0.0697)
S_GDP	0.0149 ***	−0.0097	0.0158 **	0.0303 **	0.0142 ***	0.0213 ***
	(0.0042)	(0.0137)	(0.0050)	(0.0140)	(0.0005)	(0.0018)
Innovation Index	−0.0011	−0.0089	−0.0033 ***	−0.0055	0.0004 ***	−0.0101 *
	(0.0008)	(0.0412)	(0.0010)	(0.0422)	(0.0001)	(0.0055)
Financial freedom	−0.0000	−0.0001	−0.0001 **	0.0004	0.0000 ***	0.0001 **
	(0.0000)	(0.0003)	(0.0000)	(0.0003)	(0.0000)	(0.0000)
Population	0.0002	0.0297	0.0035 ***	0.0357	0.0006 ***	0.0229 ***
	(0.0007)	(0.0279)	(0.0008)	(0.0285)	(0.0001)	(0.0037)
Constant	2.2004	−9.9899	13.5634 ***	−9.1963	−8.2086 ***	−5.7763 **
	(2.5999)	(13.4025)	(3.1335)	(13.7170)	(0.2924)	(1.7733)
Year Control	Yes	Yes	Yes	Yes	Yes	Yes
Region Control	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2128	104	2128	104	2128	104
R-squared	0.657	0.568	0.606	0.721	0.965	0.942

Notes: Robust standard errors in parentheses; *** denotes significance at 1%, ** at 5%, and * at 10%.

7. Conclusions and Implications

Against the backdrop of the trend towards green and low-carbon sustainable development, this paper argues for the environmental and economic effects of heterogeneous policies from the perspective of technology bias, with a view to providing more theoretical explanations and empirical evidence for green and sustainable development in China. First, enterprises are realistically faced with the question of whether technological innovation should be independently developed or purchased and introduced. By constructing a model of the green technology bias effect due to heterogeneous environmental policies, this paper explores which R&D approach is more biased towards green technological progress under what factor endowment. We found that environmental policies significantly promote enterprises' green technological innovation regardless of which approach they adopt. The difference is that the sectoral R&D efficiency parameter determines the direction of technological innovation steering when firms conduct their own R&D. Additionally, the substitution relationship between sectoral products determines the effectiveness of environmental policy when firms purchase and introduce technological innovations. Furthermore, when environmental regulations and government subsidies are implemented simultaneously, the green technology bias increases. We then incorporated environmental quality into the utility function and considered the economic and environmental effects of a heterogeneous mix of environmental policies. We found that heterogeneous environmental policies can improve environmental quality and promote economic growth by changing the direction of technological progress, and that an appropriate mix of policies can make economic growth and environmental quality compatible; otherwise, environmental policies will only lead to a dilemma for environmental quality and economic growth. The model findings were then empirically tested based on the perspective of regional differences based on 2009–2016 panel data on 281 prefecture-level cities. In addition, following a parallel trend test using the DID approach, we measured and discussed the decoupling index between carbon emissions and economic growth for prefecture-level cities using the Tapio model, and the findings remained robust.

In response to the above findings, this paper offers the following policy implications:

Firstly, environmental regulation can work only within a reasonable range, and too high a level of regulation may promote green technological innovation but inhibit economic growth, while too low a level of regulation may not have an emission reduction effect. Therefore, to overcome this dilemma, the government should fully consider the financial situation of enterprises to afford green technological innovation when formulating environmental regulation policies, reasonably formulate environmental tax and carbon emission trading rights policies, fully consider the relative benefits of emission reduction and growth, and meet emission reduction targets while minimising the negative impact of environmental regulation on economic growth. In addition, in view of the failure of the current environmental regulation policies in old and heavily industrial cities, the government should reasonably formulate differentiated environmental regulation policies based on the actual situation of regions.

Secondly, the cost of developing green technological innovations is enormous; excessive R&D costs may force enterprises to choose to purchase pollution quotas externally, and pollutant emissions will increase rather than decrease. The government should increase subsidies for enterprise R&D, but there are also papers that suggest that increased R&D investment will increase productivity and thus aggravate pollutant emissions [32]. Therefore, government R&D subsidies should have a green bias to prevent enterprises from using them to expand production. For cities in the Central and Western regions and non-"the belt and road initiative" cities with low levels of green technology innovation and development, it is imperative to improve the local basic R&D facilities as soon as possible. Specifically, there are two steps for old industrial cities and heavy industrial enterprises to improve policy levels of green technology innovation. The first step could be organized by the government to implement and finance high-tech industrial parks; the second could be undertaken by the companies to develop independent R&D and collaborative R&D, or to introduce new external technologies. At the same time, the government should carefully screen the subsidy targets, avoid rent-seeking, and give full play to the latecomer advantage of government subsidies.

Thirdly, although the simultaneous implementation of environmental regulations and government subsidies is more conducive to the green bias of technological progress, they have very different policy effects in terms of emission reduction and growth promotion. The local government should accurately calculate the optimal policy intensity according to local data, strengthen the co-ordination between policies, adjust the policy mix in a targeted and dynamic manner based on different local factor endowments, and establish a diversified policy mix system.

This paper also has some limitations. First, the amount of state subsidies depends on the specific situation of the industry and the technological level of the company. We cannot control the problem of policy bias caused by these factors through prefecture-level data. Secondly, the technological innovation effect of regional environmental regulation will spread from the region where it is located to the surrounding areas, particularly affecting the direction of technological innovation in the surrounding areas. This article does not analyse whether cross-sectoral and cross-regional linkages affect the effectiveness of environmental policies. In the future, we will further refine relevant research.

Funding: Graduate teaching reform project of Capital University of Economics and Business: "Research on the Innovation of Professional Degree Postgraduates' Training Mode with the Goal of Improving Practical Ability" initial results.

Institutional Review Board Statement: "Not applicable" for studies not involving humans or animals.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data used to support the findings of this study will be available from the author upon request.

Acknowledgments: The author would like to thank the anonymous reviewers and the editor for their constructive comments and suggestions for this paper.

Conflicts of Interest: The author declares no conflict of interest.

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