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Can Fintech Lead to the Collaborative Reduction in Pollution Discharges and Carbon Emissions?

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Abstract: Pollutants and greenhouse gases are major challenges to regional and global sustainability, respectively, and regulatory policies always target one of them. Using panel data, including those of fintech, economy, society, and environment for the prefecture-level cities in China, this study aimed to investigate the role of fintech in regional pollution control and carbon emission reduction. It was found that fintech not only significantly reduces pollutant and carbon dioxide emissions, but can also significantly promote the coordination between pollution control and carbon reduction. This study also adopted a pilot policy of integrating technology and finance for a differences-in-differences regression and identified the causal effects of fintech on the collaborative reduction in pollution and carbon emissions. In addition, innovation factors play a crucial role in the collaborative implementation process of pollution control and carbon reduction driven by fintech. Specifically, fiscal technology expenditure and regional innovation have significant moderating effects on pollution control and carbon reduction, while green innovation has a significant mediating effect. Our findings contribute to optimizing financial and regulatory policies, thereby enabling fintech to leverage the momentum of regional pollution control and carbon reduction.

Keywords: fintech; pollution control; carbon emissions; innovation; green innovation

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1. Introduction

In the past century, various countries have not only faced the impact of regional pollutants on their residents' health in the process of industrialization, but also faced the challenge of ecosystem health caused by global climate change [1]. Various types of environmental and carbon regulation policies have been designed and implemented to reduce regional pollutants and carbon emissions [2]. Although these environmental and carbon regulatory policies have achieved positive results in promoting sustainable development, there are always issues with inconsistent multiple objectives and tasks, as well as increasing pressure on micro enterprises to transform and finance [3]. These issues also lead to a decrease in the effectiveness of corresponding environmental and carbon regulatory policies. For example, many regions are gradually promoting green and low-carbon transformation, which has led to a large number of repeated investments and increased pressures for enterprises. Especially for developing countries, the conflict between green transformation and low-carbon development further leads to an insufficient financing support capacity for industrial transformation [4,5].

Innovation plays a crucial role in leading industrial transformation and upgrading, and it is the ultimate determining force for achieving green and low-carbon goals [6]. Therefore, many countries actively promote fintech development in order to improve the innovative development capability of financial services, which is bound to play a positive role in leading technological innovation and industrial development in the field of green, low-carbon economy. Fintech refers to the organic integration of a technology innovation chain and a financial capital chain through innovative financial technology

investment models, guiding various types of financial institutions and capital, innovating financial products, and improving service quality, thereby promoting the development of innovation and entrepreneurship [7]. Therefore, this study focuses on whether fintech can help economies to achieve the dual goals of being green and low-carbon. Especially for developing countries like China, not only do they face high financing demands in the field of green and low-carbon development, but they have also achieved significant results in exploring fintech development to promote economic innovation and development [8].

Environmental pollution and its externality characteristics are the most typical topics in environmental economics [9]. The existing literature has also formed two internalization paths for the externality of environmental pollution, including Pigou's tax path and Coase's property right path. Whether it is the marketization mechanism of the property rights path or the regulatory mechanism of the tax path, these studies aimed at improving resource allocation efficiency from a static perspective, putting enormous transformation pressure on regional economic and industrial development [10]. The Porter hypothesis maintains that regulatory pressure promotes innovation and competitiveness through enhancing dynamic competitiveness [11]. Nevertheless, regional transformation investment and innovation activities require financial support, especially in developing countries, where an imperfect financial system restricts their green and low-carbon development. This financing dilemma leads to the delay of regional transformation investment, and also makes regions pay more attention to short-term goals and ignore long-term goals [12], which leads to a conflict between these short-term and long-term environmental goals and an inconsistency in emission reduction behaviors.

Numerous studies have examined the role and mechanism of financial factors in regional sustainable development, forming a research field of empowering regional green and low-carbon transformation through the financial sector [13,14]. Some studies have evaluated the effect of financial development on green and low-carbon development from the dimensions of scale, structure, and efficiency [15]. Although financial development provides financing support for innovation activities, the innovation effect also differs in terms of the type of clean technology innovation and green technology innovation [16]. Therefore, practitioners and researchers hope to guide regional green technology innovation and low-carbon development through the design of green financial products [17]. Some environmental regulation policies also force enterprises to carry out green innovation activities with the incentive or constraint mechanism of green finance [18,19]. As green innovation is the direct mechanism of regional green and low-carbon development caused by finance, the realization of finance-driven innovation effect is also a research hotspot in this field [5]. Fintech, which aims to leverage corporate innovation through finance, not only directly affects regional innovation, but may also be an important driver of green innovation [20]. Existing studies have focused on the innovation effect of fintech [21,22], but there are relatively few discussions on whether fintech can drive regions to achieve the dual goals of short-term pollution control and long-term carbon emission reduction.

With the realistic background of China's innovation driven by fintech, this study uses the panel data of prefecture-level cities in China to investigate the role of fintech in driving regional green transformation and low-carbon development and the role of innovation factors in the nexus. Specifically, this study examines the impact of fintech on SO_2 emissions, solid waste emissions, carbon emissions, and their collaborative reduction indexes. It is concluded that fintech can take into account the short-term goal of pollution control and the long-term goal of CO_2 emission reduction, so as to reduce pollution emissions and carbon emissions in a coordinated way. In addition, this study demonstrates the critical importance of innovation factors for the emission reduction effect of fintech, and the unimpeded innovation realization mechanism is the key to ensuring that fintech drives regional green and low-carbon development.

This study aims to contribute to the existing literature in terms of the following aspects. Firstly, based on the perspective of innovations in financial technology, this study explores the empowerment mechanism of finance to drive regional improvement in sustainable

dynamic competitiveness. Secondly, this study investigates the collaborative reduction in pollution discharges and carbon emissions. Some studies have begun to focus on the synergistic reduction path of pollution emissions and carbon emissions [23,24], and related research needs to be further expanded. Hence, this study examines the collaborative index of the decline process of pollution discharges and carbon emissions. Thirdly, this study takes innovation as a key factor linking finance and green and low-carbon development, thus providing clear logic and rich evidence for clarifying the relationship between them. Fourthly, the findings of this study provide important policy references for developing countries, as well as for China.

The rest of this article is structured as follows. Section 2 is the background of the development of fintech in China and a theoretical analysis of the financial technology affecting green and low-carbon development. Section 3 is the description of the research materials, econometric models, and related variables. Section 4 aims to present the empirical results of the role of fintech in pollution discharges, carbon emissions, and collaborative emission reduction. Section 5 further discusses the role of innovation factors, and the final part presents the conclusions and implications.

2. Background and Theoretical Analysis

2.1. Background of the Development of Fintech in China

Fintech is the use of emerging information technology and digital technology to reshape the financial service model and improve the efficiency of financial services, aimed at supporting the development of innovation and entrepreneurship [25]. The development of fintech in China is divided into three stages. The first stage is the period from 1993 to 2013, which was mainly the information process of financial enterprises, which greatly improved business efficiency. The second stage is the period from 2013 to 2018, when financial enterprises built online platforms to transform their traditional channels, and technology drove innovation in the supply of financial products. The third stage is after 2018, the deep integration of technology and finance, which greatly promotes the supply capacity of financial products for the real economy.

In recent years, the application of financial technology innovation in China's financial industry has been deepening, and financial technology has gradually evolved from the embedding of creative products to their integration into various fields and the linking of financial service supply and demand. Financial technology enables traditional financial enterprises and technology-based financial enterprises to jointly enhance their ability to serve the real economy. On the one hand, traditional financial institutions actively apply information technology and digital technology, accelerate the digital transformation of their financial service supply, and innovate financial products and businesses, so as to enhance their competitiveness with technology-based financial enterprises. On the other hand, emerging technology financial enterprises are also constantly improving their standardization of business, actively seeking cooperation and sharing with traditional financial institutions, and improving their ability to serve the economy and society.

In fact, China started a pilot policy on the integration of technology and finance in 2011, aiming to promote the regional innovation and high-quality development of fintech services. In 2016, China launched a second batch of pilot policies. These pilot policies have greatly promoted the development of financial technology and are also an important measure for China to enhance the ability of financial services to serve the real economy in the era of the digital economy [26]. China's financial technology has been applied to various fields of financial activities and it is also an important driving force for China's regional economic innovation, development, and industrial upgrading.

2.2. Theoretical Analysis and Research Hypotheses

The problems of pollution and carbon emissions are essentially the excessive use of environmental resources, which is caused by the external characteristics of the development and utilization of environmental resources. As part of the cost of pollution and carbon

emissions is borne by society, the optimal level of pollution and carbon emissions in the private sector is higher than the optimal level in society. Nevertheless, both the private sector and the public have realized that environmental pollution harms social welfare, and a series of environmental regulations and carbon regulation policies have been designed and implemented, thus forcing regional green transformation and low-carbon development. In practice, under the constraints of pollution control and carbon emission reduction targets, regional transformation investment or innovation activities are the key to achieving green and low-carbon development, all of which rely on the financing support of the financial system.

Fintech aims to help regions to achieve innovative development through the effective use of fiscal science, technology spending, and financial resources. In a region pursuing green and low-carbon transformation, green innovation is an important innovation method for micro-entities, which also needs financial support from the public sector and financial institutions [27]. It is precisely because of its characteristics that fintech can effectively help regions to ease the financing constraints of green and low-carbon development. For developing countries especially, the effect of fintech on enabling green and low-carbon development may be greater. It can not only solve the short-term financing problems of green projects, but also effectively promote long-term low-carbon transition projects. Therefore, fintech can help regions to reduce their pollution and carbon emissions. Hence, the following hypothesis is proposed, which need to be tested.

Hypothesis 1. *In certain conditions, fintech can significantly reduce regional pollutant discharges and carbon emissions, which is conducive to green and low-carbon development.*

The environmental challenges caused by human factors in natural systems mainly include regional pollution and global pollution, with sulfur dioxide and solid waste pollution being regional pollutants, and carbon emissions being global pollution. The sources of these two types of pollution are also different, with regional pollution mainly coming from industrial production processes, while carbon emissions mainly come from energy use [28]. In many areas, the emission reduction control for these two types of pollutants is phased, which leads to a certain time inconsistency and target conflict in the process of emission reduction. Fintech aims to leverage regional economic innovation and development and industrial transformation and upgrading through financial leverage, which can greatly ease the financing pressure of transformation industries and enterprises, so as to promote them to balance short-term environmental goals and long-term environmental goals. Therefore, with the support of fintech, regions can promote the collaborative realization of pollution control and carbon emission reduction. Hence, the following hypothesis is proposed.

Hypothesis 2. *Fintech can significantly promote the coordination between pollution control and carbon reduction.*

The green and low-carbon development of regional economies led by fintech depends on government financial support and regional innovation [29]. Fiscal science and technology expenditure are the premise for the government to guide the sound development of financial technology. Under the influence of fiscal science and technology expenditure, the green and low-carbon goals of the government and the public are also reflected in financial technology [30,31]. In addition, regional innovation directly determines the ability of fintech to leverage the high-quality development of a regional economy. Hence, this study maintains that fiscal technology expenditure and regional innovation can regulate the role of fintech.

Hypothesis 3. *Fiscal technology expenditure and regional innovation have significant moderating effects on the impact of financial technology on pollution and carbon emissions.*

3. Research Materials and Econometric Methods

3.1. Sample and Data Source

In recent years, China has made remarkable achievements in the coordinated promotion of pollution control and carbon emission reduction, while there are also great differences in the realization path for the collaborative reduction in pollution and carbon emissions between different regions. Therefore, this study selects the panel data of prefecture-level cities in China for an empirical analysis, including fintech, economy, society, environment, and other aspects. A prefecture-level city is a typical differentiated regional unit of China's economic and social development and its governance. The research period is from 2003 to 2021, and 2021 is the latest data available. This period is also a period of the rapid development of fintech in China.

The data are mainly from the regional economic database of the Development Research Center of the State Council Information Network and the statistical yearbooks of various provinces in China. The degree of fintech development in the prefecture-level cities is based on the number of searches for relevant keywords in Baidu News in China. By searching the relevant important news reports, this study extracts 48 keywords related to fintech and constructs a technological financial index based on the occurrence times of these keywords. The patent and innovation data come from China's China National Intellectual Property Administration. The carbon emissions for the prefecture-level cities are calculated based on the data of their economic activities and energy consumption, including the carbon emissions from transportation and construction, industrial production activities, agriculture, forestry and land-use changes, waste disposal activities, and purchased energy.

3.2. Econometric Models

In order to control the other economic and social factors that affect pollution control and carbon emissions, we refer to study of Guo et al. (2023) [32] and use a two-way fixed-effect panel model to investigate the synergistic emission reduction effect caused by the development of fintech.

$$\ln SO_2(\ln Waster, \ln Carbon)_{it} = \alpha + \beta_1 Fintech_{it} + \mathbf{Z}_{it}\boldsymbol{\gamma} + \mu_{city} + \lambda_{year} + \varepsilon_{it}, \quad (1)$$

where the city and year are represented by the subscripts i and t. The left side of the equation is pollution control and carbon emissions, including sulfur dioxide emissions ($\ln SO_2$), solid waste emissions (lnWaster), and carbon emissions (lnCarbon), respectively. The core explanatory variable is the development of fintech. If its coefficient is significantly less than zero, it is considered that fintech can reduce pollution emissions or carbon emissions. If the coefficients of fintech are significantly negative, regardless of the dependent variables, this indicates that fintech has the synergistic effect of pollution control and carbon emission reduction. The control variables ($\mathbf{Z}$) are a series of variables, including per capita GDP, population density, human capital, urbanization, and so on, which are the influencing factors of pollution and carbon emissions. The time invariant urban characteristics and macro trend characteristics are measured by the fixed effects of μ_{city} and λ_{year}, while ε_{it} represents the random disturbance term.

Compared to the existing research on the nexus of fintech and sustainability [27], this study integrates environmental issues and climate challenges into a unified framework and considers them as object variables. Hence, the coordination index of pollution control and carbon emission reduction is calculated and included in the panel regression model as a dependent variable. The econometric model for investigating the relationship between fintech and the coordination index is as follows.

$$Collabora1(Collabora2)_{it} = \alpha + \beta_1 Fintech_{it} + \mathbf{Z}_{it}\boldsymbol{\gamma} + \mu_{city} + \lambda_{year} + \varepsilon_{it}, \quad (2)$$

where the dependent variable is Collabora1 or Collabora2, and the former is a collaborative indicator of sulfur dioxide control and carbon emission reduction, while the latter is a collaborative indicator of sulfur dioxide control, solid waste control, and carbon emis-

sion reduction. The definitions of the other variables and symbols are consistent with Formula (1). If the coefficient of fintech is significantly positive, this indicates that fintech significantly promotes the collaborative reduction in pollution and carbon emissions.

In order to investigate the moderating effect of the innovation factors on the pollution control and carbon reduction of fintech, this study also includes science and technology financial expenditure and regional innovation index as moderator variables in the panel regression model.

$$\ln SO_2(\ln Waster, \ln Carbon)_{it} = \alpha + \beta_1 Fintech_{it} + \beta_2 Fintech_{it} \times Moderator_{it} + \mathbf{Z}_{it}\boldsymbol{\gamma} + \mu_{city} + \lambda_{year} + \varepsilon_{it}, \quad (3)$$

where $Moderator_{it}$ indicates the fiscal expenditure on science and technology (Fiscal_Tech) or a regional innovation indicator (lnInnovation).

3.3. Variable Definition and Description

Table 1 lists the definitions of the main variables involved in the empirical study of fintech affecting pollution and carbon emissions. The core explanatory variable is the development of fintech (Fintech), which is a variable calculated based on the keyword statistics from the financial development news of Baidu in China. The larger the value, the higher the level of fintech development. Fintech in this study mainly refers to the application of emerging digital technologies by banking and financial institutions, while existing studies have used the digital finance inclusion index provided by Peking University, which focuses on the scope and depth of digital finance applications [27].

Table 1. Definitions of main variables.

Types	Variables	Mean
Dependent Variables	$lnSO_2$	The logarithm of per capita sulfur dioxide emissions
	lnCarbon	The logarithm of per capita carbon dioxide emissions
	lnWaster	The logarithm of per capita fixed waste emissions
	Collabora1	Collaborative index between sulfur dioxide control and carbon emission reduction
	Collabora2	Collaborative index of three kinds of pollutant emissions
Explanatory Variables	Fintech	The number of searches for relevant keywords in Baidu News
	lnRGDP	Logarithm of per capita gross domestic product
	Population	The ratio of registered residence population to land area
	Human	The logarithm of the average salary of urban workers
	UR	The ratio of urban permanent population and registered residence population
	ER	Comprehensive indicators of waste treatment rate and solid waste treatment rate
	Struct	The proportion of the third industry
	Public	The proportion of fiscal expenditure to GDP
	lnFDI	The logarithm of the number of foreign enterprises
Innovation factors	Fiscal_Tech	The logarithm of technological fiscal expenditure
	lnInnovation	The logarithm of regional innovation index
	lnGreenPat	The logarithm of the number of green patent applications

The main dependent variables involved in this study are sulfur dioxide emissions ($lnSO_2$), solid waste emissions (lnWaster), carbon emissions (lnCarbon), and their collaborative indicators. These three emission indicators have all been calculated at the per capita level and logarithmized. Collabora1 is a collaborative indicator of sulfur dioxide

control and carbon emission reduction, while Collabora2 is a collaborative indicator of sulfur dioxide control, solid waste control, and carbon emission reduction.

The collaborative indicator of pollution control and carbon reduction is calculated in three steps. The first step is to standardize the range of variables. The second step is to perform reciprocal processing on the standardized variables, so that the variables reflect the process of pollution control and carbon reduction. The third step is to use the method of Teng et al. (2023) [33] to calculate the collaborative indicators of pollution control and carbon reduction.

Formula (4) shows the calculation method for standardizing the range of variables.

$$\overline{X_{it}} = (X_{it} - X_{min})/(X_{max} - X_{min}) \quad (4)$$

where $\overline{X_{it}}$ is the standardized variable. This study deals with standardized sulfur dioxide emissions and carbon emissions separately, and obtains two variables of $\overline{lnSO_{2it}}$ and $\overline{lnCarbon_{it}}$.

Finally, the second and third steps are integrated together to obtain the following calculation formula for the collaborative indicators.

$$Collabora1_{it} = \left(\frac{4}{\overline{lnSO_{2it}} \times \overline{lnCarbon_{it}}}\right)/\left(\frac{1}{\overline{lnSO_{2it}}} + \frac{1}{\overline{lnCarbon_{it}}}\right)^2, \quad (5)$$

where Collabora1 is the collaborative indicator of sulfur dioxide control and carbon emission reduction.

There are eight control variables, including the per capita gross domestic product (lnRGDP), population density (Population), human capital (Human), urbanization (UR), environmental regulation (ER), industrial structure (Struct), public finance (Public), and foreign direct investment (lnFDI). Population density (Population) is the ratio of registered residence population to land area. Human capital (Human) is defined as the logarithm of the average wage, which is the return of workers, and the difference mainly comes from the difference in human capital. The urbanization rate (UR) is measured by the ratio of urban permanent population and registered residence population. Environmental regulation (ER) is measured based on the waste treatment rate and solid waste treatment rate, and the higher the value, the higher the degree of environmental regulation. The industrial structure (Struct) is the proportion of the third industry, while public finance (Public) is the proportion of fiscal expenditure to gross domestic product. Foreign direct investment (lnFDI) is used for the logarithm of foreign enterprises, and it may generate knowledge spillover effects or lead to pollution chain lock-in, causing complex impacts on pollution emissions.

Innovation factors are a crucial mechanism for fintech to affect pollution and carbon emissions. This study uses science and technology financial expenditure (Fiscal_Tech) and regional innovation indicator (lnInnovation) as the moderating factors and green innovation (lnGreenPat) as the mediating mechanism.

3.4. Descriptive Statistics

Table 2 presents the results of the descriptive statistics for the defined variables. This study has interpolated missing values, which avoids a decrease in the number of regression samples caused by the absence of individual variables. Except for green innovation, the number of observed values for all the variables is the same. In addition, this study tests whether there are outliers in the related variables, and also considers the variability of these related variables, so as to describe the econometric relationship between the variables. The last column shows the coefficient of correlation between the sulfur dioxide emissions and the other variables. This indicates that technology finance is negatively correlated with sulfur dioxide emissions, indicating that technology finance may be able to reduce pollution emissions. In addition, there is a certain positive correlation between carbon emissions, solid waste emissions, and sulfur dioxide pollution emissions, indicating that

synergistic effects may indeed exist. Some regions have missing values for the indicators of green innovation, which may be due to the absence of green patents in these regions or the lack of matching to corresponding regions in the green patent database. Hence, this study does not treat the values of these regions as zero.

Table 2. Descriptive statistics of variables.

Types	Variables	Obs	Mean	Std. Dev.	Min	Max	Corr. Coeff.
Dependent Variables	lnSO_2	4938	4.2893	1.3105	0.0000	7.9817	1.0000
	lnCarbon	4938	2.0927	0.7237	0.0256	5.3715	0.1339
	lnWaster	4938	3.7309	1.1998	0.0057	9.3828	0.7890
	Collabora1	4938	0.9194	0.1078	0.0000	1.0000	−0.0564
	Collabora2	4938	0.8874	0.1305	0.0000	1.0000	0.1105
Explanatory Variables	Fintech	4938	2.1337	1.7761	0.0000	6.9717	−0.4644
	lnRGDP	4938	10.2442	0.8262	2.5802	12.5793	−0.0507
	Population	4938	0.1326	0.0406	0.0296	0.6348	0.0259
	Human	4938	10.4606	0.6840	2.2834	13.8664	−0.3062
	UR	4938	0.4903	0.1649	0.1117	0.9904	0.0388
	ER	4938	1.4097	2.9908	0.0000	100.0000	0.0508
	Struct	4938	38.8606	9.7707	8.5800	98.4884	−0.3661
	Public	4938	0.1862	1.3298	0.0162	93.3969	0.0019
	lnFDI	4938	3.4184	1.5815	0.0000	8.6496	−0.0540
Innovation factors	Fiscal_Tech	4938	9.2707	1.8197	−2.0402	14.6779	−0.2806
	lnInnovation	4938	1.0769	1.1019	0.0000	6.3143	−0.3323
	lnGreenPat	4311	3.7745	1.8774	0.0000	9.6153	−0.2964

Figure 1 shows the correlation coefficients of the variables of interest in this study using graphical methods, including the dependent variables, core explanatory variables, and innovation factors. The correlation coefficient between the two collaborative indexes is as high as 0.84, indicating that the difference is insignificant, whether measured using two or three variables. The high correlation between fintech and the innovation factors indicates that these variables are closely interrelated. In the empirical analysis, this study will focus on examining the role of these innovation factors. The correlation between fintech and pollution emission and the collaborative index is not consistent, and this study will further investigate and analyze it using rigorous econometric methods.

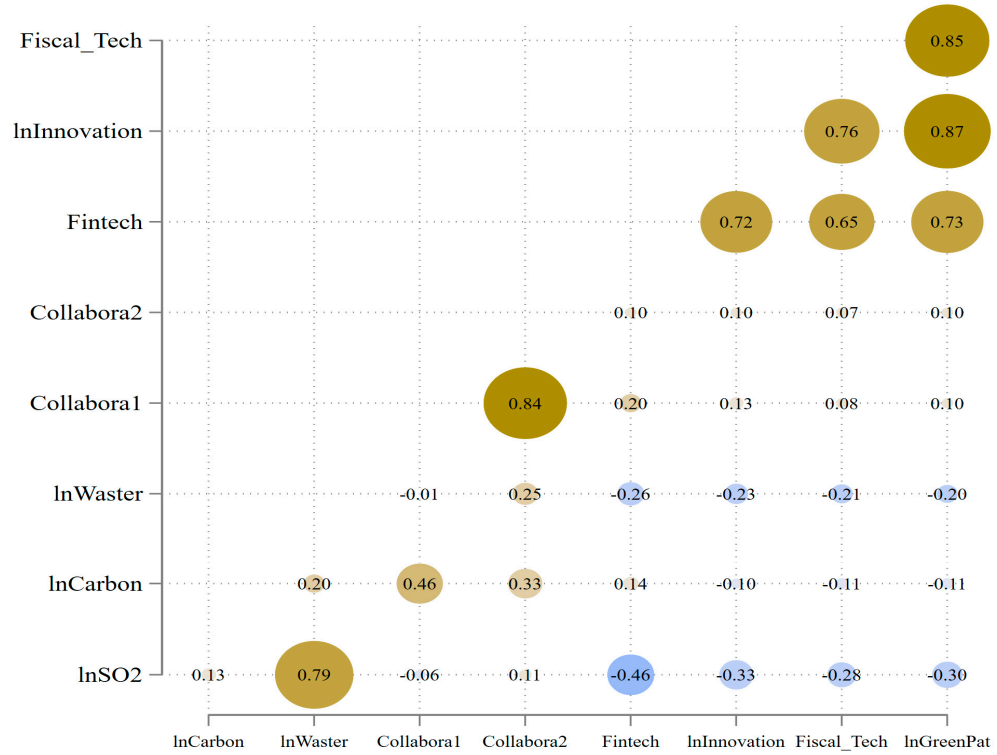

Figure 1. Correlation coefficients of key variables. Notes: The larger the circular bubble in the figure, the stronger the correlation coefficient, and different colors represent the classification of the correlation coefficient.

4. Estimated Results and Analysis

This section reveals the causal relationship between fintech, pollution emissions, carbon emissions, and their collaborative index through graphical descriptions, panel regression models, and DID methods. Specifically, this section is divided into four parts for analysis to demonstrate whether fintech can synergistically reduce pollution and carbon emissions.

4.1. Linear Fitting of the Nexus of Fintech and Pollution and Carbon Emissions

Figure 2 shows the scatter plot and linear relationship between fintech and sulfur dioxide emissions and carbon dioxide emissions. The left figure of Figure 2 shows a negative correlation between fintech and sulfur dioxide emissions, indicating that sulfur dioxide emissions decrease with the development of fintech. However, the right figure in Figure 2 shows a positive correlation between fintech and carbon emissions. The development of fintech may lead to an expansion of economic activities, leading to an increase in pollution and carbon emissions. Before the research sample, China mainly focused on controlling pollution emissions, while the target constraints on the reduction in total carbon emissions were relatively low, which may demonstrate a positive relationship between fintech and carbon emissions. The results in Figure 2 pose a challenge to the viewpoint that fintech leads to the collaborative reduction in pollution and carbon emissions. Nevertheless, the positive correlation between fintech and carbon emissions is likely due to economic development and other factors.

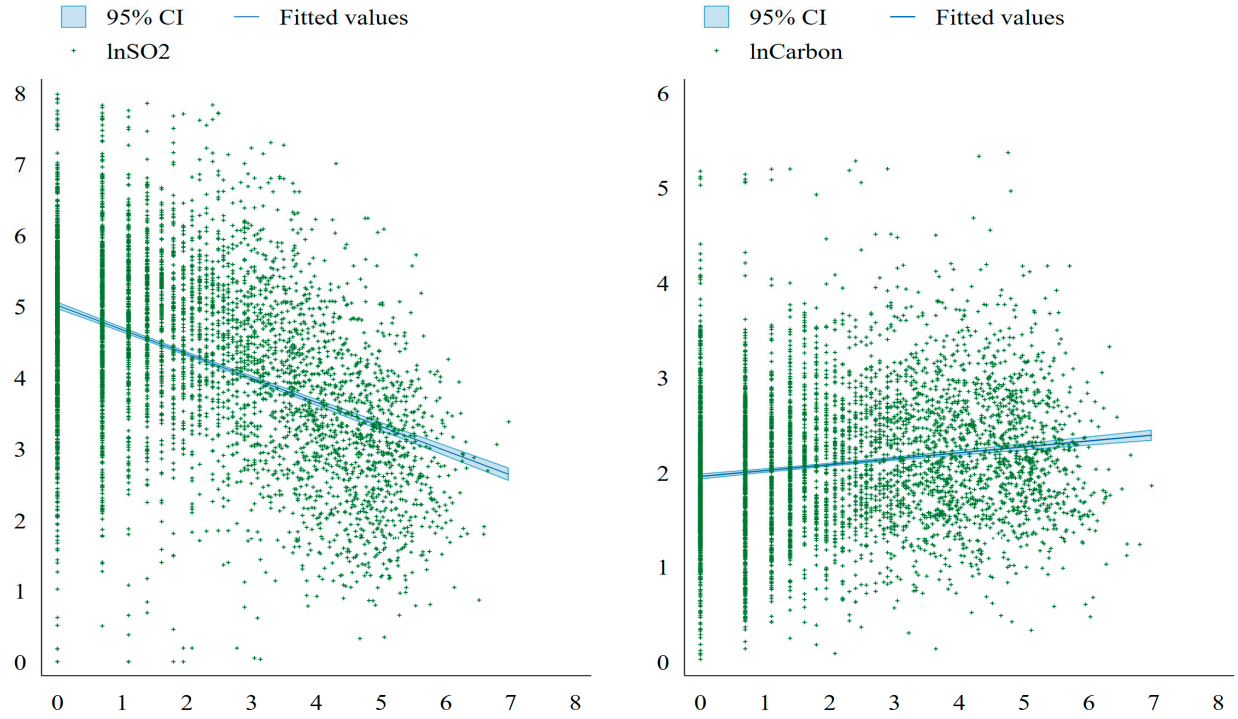

Figure 2. Linear fitting the nexus of fintech and pollution and carbon emissions.

4.2. Empirical Analysis of Fintech Affecting Pollution and Carbon Emissions

Due to the positive correlation between carbon emissions and technology finance, it is necessary to control for factors such as economic development and urban fixed effects to reveal the causal relationship between technology finance, pollution emissions, and carbon emissions. Table 3 shows the regression results of fintech affecting pollution emissions and carbon emissions. The dependent variables of columns (1) to (6) are sulfur dioxide emissions ($lnSO_2$), solid waste emissions (lnWaster), and carbon emissions (lnCarbon), respectively. All the columns control for urban fixed effects and year fixed effects, while columns (1), (3), and (5) do not control for the economic variables that are significantly affected by the development of fintech.

As shown in Table 3, fintech has a significant emission reduction effect on sulfur dioxide emissions, solid waste emissions, and carbon emissions. When the dependent variable is pollutant emissions, from columns (1) to (4), the emission reduction effects of fintech are significantly less than zero at the 1% statistical level, demonstrating the positive role of fintech in controlling pollution emissions. When the dependent variable is carbon dioxide emissions, fintech also exhibits a significant reduction effect at the 10% level. After controlling for fixed effects and urban characteristics, the impact of technology finance on carbon dioxide emissions is negatively significant, indicating that the correlation description is influenced by other factors. Based on the results in Table 3, it can be concluded that fintech has significantly achieved multiple goals of pollution control and carbon reduction, indicating the establishment of a collaborative reduction in pollution and carbon emissions caused by fintech. Some relevant studies have also supported the findings of this study. Awais et al. (2023) [34] demonstrated that fintech has explored new paths for sustainable resource utilization and high-quality economic development, while Tao et al. (2022) [35] maintained that fintech has helped to form a low-carbon development path for the economy and society.

Table 3. Results of fintech affecting pollution and carbon emissions.

Variables	$lnSO_2$		lnWaster		lnCarbon	
	(1)	(2)	(3)	(4)	(5)	(6)
Fintech	−0.0842 ***	−0.0824 ***	−0.0227 ***	−0.0246 ***	−0.0445 *	−0.0425 *
	(0.0213)	(0.0215)	(0.0052)	(0.0051)	(0.0243)	(0.0245)
lnRGDP	0.2303 **	0.2620 **	0.0561 **	0.0953 ***	0.0739	0.0556
	(0.0926)	(0.1028)	(0.0224)	(0.0288)	(0.0713)	(0.0947)
Population	0.6685	0.7655	2.0799 ***	2.0282 ***	2.0140 ***	2.0919 ***
	(0.7864)	(0.7918)	(0.3150)	(0.3124)	(0.7559)	(0.7531)
UR	−0.2274	−0.2738	−0.0219	−0.0356	0.0132	0.0121
	(0.2603)	(0.2589)	(0.0595)	(0.0572)	(0.2756)	(0.2773)
ER	0.0022	0.0023	−0.0010 *	−0.0011 *	−0.0038	−0.0038
	(0.0033)	(0.0033)	(0.0006)	(0.0006)	(0.0040)	(0.0040)
Human		0.0659		0.0052		0.0573
		(0.0415)		(0.0122)		(0.0566)
Struct		−0.0022		0.0034 **		−0.004
		(0.0030)		(0.0015)		(0.0033)
Public		0.0217 ***		0.0067 ***		−0.0005
		(0.0077)		(0.0022)		(0.0068)
lnFDI		0.0488		−0.0074		−0.0214
		(0.0569)		(0.0129)		(0.0684)
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
R^2_Adjusted	0.6637	0.665	0.6132	0.6203	0.3727	0.3731
Observations	4938	4938	4938	4938	4938	4938

Notes: The standard error in parentheses is the robustness estimator, and different asterisks correspond to significance, *** (1%), ** (5%), and * (10%).

4.3. Empirical Analysis of Fintech Affecting the Collaborative Reduction Indexes

In order to further verify the collaborative reduction effect of pollution and carbon emissions caused by fintech, this study also includes the collaborative index in the model and uses it as the dependent variable according to Formula (2). Table 4 shows the regression results of fintech affecting the collaborative reduction indexes of pollution and carbon emissions. The dependent variable in columns (1) to (4) is the collaborative index between sulfur dioxide control and carbon emissions (Collabora1), while in the other columns, it is the collaborative index between sulfur dioxide control, solid waste pollution control, and carbon emissions (Collabora2). The differences in these columns are also reflected in whether the control variables and year fixed effect are controlled.

As shown in Table 4, there is sufficient evidence for the synergistic effect of fintech on promoting pollution emission control and carbon emission reduction. In columns (1) to (4), the variable of fintech consistently has a significant effect greater than zero, indicating that fintech can lead to a collaborative reduction in pollution emissions and carbon emissions. In columns (5) to (6), the control of solid waste emissions is also included in the calculation of the synergy index, and the variable of fintech consistently promotes improvement in the collaborative index at the 5% level. Although there are different paths for controlling pollutant emissions and reducing carbon emissions, there are also collaborative paths. Fintech can achieve the synergistic effect of reducing pollution and carbon emissions by empowering industries with low-carbon development and green transformation. Previous studies have shown that innovation in financial technology leads to the development of green finance [8], which can better support low-carbon development and green transformation.

Table 4. Results of fintech affecting the collaborative reduction indexes.

Variables	Collabora1				Collabora2	
	(1)	(2)	(3)	(4)	(5)	(6)
Fintech	0.0087 ***	0.0082 ***	0.0068 ***	0.0080 ***	0.0062 **	0.0062 **
	(0.0016)	(0.0021)	(0.0019)	(0.0020)	(0.0030)	(0.0029)
lnRGDP	0.0131 ***	−0.0047	0.0165 **	−0.0022	−0.0127	−0.0154
	(0.0038)	(0.0071)	(0.0079)	(0.0106)	(0.0102)	(0.0137)
Population	0.1627 **	0.2624 ***	0.1670 **	0.2544 ***	0.3140 ***	0.3098 ***
	(0.0756)	(0.0780)	(0.0767)	(0.0773)	(0.1046)	(0.1044)
UR	0.0566 **	0.0452 *	0.0507 **	0.0464 *	0.0567 *	0.0594 *
	(0.0250)	(0.0260)	(0.0254)	(0.0259)	(0.0323)	(0.0324)
ER	0.0001	0.0001	0.0001	0.0001	−0.0002	−0.0002
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0004)	(0.0004)
Human			0.0006	−0.0092		−0.0096
			(0.0077)	(0.0066)		(0.0087)
Struct			0.0004	0.0002		0.0001
			(0.0004)	(0.0005)		(0.0005)
Public			0.0013 **	−0.0001		−0.001
			(0.0006)	(0.0008)		(0.0010)
lnFDI			−0.0030	−0.0016		0.0018
			(0.0059)	(0.0066)		(0.0079)
City FE	Y	Y	Y	Y	Y	Y
Year FE	N	Y	N	Y	N	Y
R^2_Adjusted	0.1533	0.1753	0.1543	0.1757	0.0889	0.0889
Observations	4938	4938	4938	4938	4938	4938

Notes: The standard error in parentheses is the robustness estimator, and different asterisks correspond to significance, *** (1%), ** (5%), and * (10%).

4.4. Robustness Results Using the Policy of Integrating Technology and Finance

In 2011, China launched its first batch of pilot policies on the integration of technology and finance, selecting 16 regions such as Shanghai, Shenzhen, and the Jiangsu Province as pilot areas for exploring the ability of technology to enhance the high-quality development of financial services in the real economy. At least 350 policy documents on fintech have been issued in these pilot areas, with a particular focus on financing support for innovation and entrepreneurship. Based on the positive results achieved in the integration of technology and finance, China launched its second batch of pilot policies to promote the integration of technology and finance in nine cities in 2016, including cities such as Zhengzhou, Xiamen, Ningbo, Jinan, Nanchang, Guiyang, Yinchuan, Baotou, and Shenyang.

This study uses a quasi-natural experiment for the integration of technology and finance and adopts the DID method to investigate the causal effect of fintech on reducing pollution and carbon. Table 5 shows the results of the intervention effect of these fintech policies on the collaborative reduction in pollution and carbon emissions. It can be found in Table 5 that policy intervention in fintech significantly reduces sulfur dioxide emissions and carbon emissions, and has a positive effect on the synergistic index of pollution control and carbon reduction. In columns (1) to (4), technology finance shows significant emission reduction effects, while column (5) shows the synergistic effect of technology finance on enhancing pollution reduction and carbon reduction. Although the coefficient of technology finance in column (6) is insignificant, it is still positive and does not contradict the main findings of this study. Therefore, this study maintains that Hypothesis 1 and Hypothesis 2 are valid. These findings are in line with the development of fintech in China. China actively utilizes digital information technology to improve the quality of its financial

services for the real economy, especially through fintech, to guide economic innovation and green transformation, which has had a significant positive effect on pollution control and carbon reduction.

Table 5. Results of the intervention effect of fintech policies.

Variables	$lnSO_2$		lnCarbon		Collabora1	
	(1)	(2)	(3)	(4)	(5)	(6)
Fintech	−0.2803 ***	−0.2877 ***	−0.0744 ***	−0.0891 ***	0.0182 *	0.0123
	(0.0906)	(0.0783)	(0.0211)	(0.0231)	(0.0107)	(0.0107)
lnRGDP	−0.0248	0.2556 **	0.1852 ***	0.0933 ***	0.0220 ***	−0.0016
	(0.1257)	(0.1022)	(0.0227)	(0.0290)	(0.0083)	(0.0107)
Population	−2.0227	0.8216	1.9492 ***	2.0479 ***	0.1844 **	0.2629 ***
	(1.3141)	(0.8168)	(0.3048)	(0.3226)	(0.0760)	(0.0781)
UR	−0.3840 ***	0.0548	0.0622 **	0.0017	0.0061	−0.0089
	(0.1377)	(0.0399)	(0.0248)	(0.0118)	(0.0089)	(0.0065)
ER	−1.4567 ***	−0.3152	0.0275	−0.0478	0.0657 ***	0.0510 *
	(0.3002)	(0.2610)	(0.0538)	(0.0582)	(0.0250)	(0.0265)
Human	0.0068	0.0025	−0.0016 **	−0.0010 *	−0.0001	0.0001
	(0.0044)	(0.0032)	(0.0007)	(0.0006)	(0.0003)	(0.0003)
Struct	−0.0400 ***	−0.0024	0.0050 ***	0.0033 **	0.0007 **	0.0002
	(0.0062)	(0.0030)	(0.0009)	(0.0015)	(0.0004)	(0.0005)
Public	0.0062	0.0211 ***	0.0130 ***	0.0065 ***	0.0017 ***	0.0000
	(0.0092)	(0.0076)	(0.0020)	(0.0022)	(0.0006)	(0.0008)
lnFDI	0.4257 ***	0.0519	−0.0214 *	−0.0065	−0.0075	−0.002
	(0.0583)	(0.0570)	(0.0111)	(0.0132)	(0.0056)	(0.0066)
City FE	Y	Y	Y	Y	Y	Y
Year FE	N	Y	N	Y	N	Y
R^2_Adjusted	0.4653	0.6655	0.6062	0.6217	0.1505	0.1726
Observations	4938	4938	4938	4938	4938	4938

Notes: The standard error in parentheses is the robustness estimator, and different asterisks correspond to significance, *** (1%), ** (5%), and * (10%).

5. Discussion on the Role of Innovation Factors

Innovative development is the direct goal of fintech development, and it is also a crucial factor for the role of fintech in the green and low-carbon development of the economy and society [36]. Therefore, this section further examines the moderating effect and mediating effect of innovation factors. On the one hand, this study considers the moderating effect of scientific and technological fiscal expenditure (Fiscal_Tech) and regional innovation (lnInnovation). On the other hand, this study examines the mediating effect of green innovation (lnGreenPat).

5.1. Empirical Analysis of the Moderating Effect of Innovation Factors

The public fiscal expenditure in the field of science and technology is an important source of leverage for fintech development in China, and regional innovation development is the direct channel for fintech to effectively drive high-quality economic development. Therefore, this study selects public fiscal expenditure and the regional innovation index as the boundary conditions for the role of fintech in pollution control and emission reduction, respectively. Table 6 shows the estimated results of the moderating effect model.

Table 6. Results of the moderating effect of Fiscal_Tech and lnInnovation.

Variables	$lnSO_2$		lnCarbon		Collabora1	
	(1)	(2)	(3)	(4)	(5)	(6)
Fintech	0.1782 *** (0.0621)	−0.0241 (0.0224)	0.1024 *** (0.0130)	0.0024 (0.0042)	−0.0245 *** (0.0072)	−0.0002 (0.0023)
Fintech × Fiscal_Tech	−0.0251 *** (0.0061)		−0.0122 *** (0.0013)		0.0031 *** (0.0007)	
Fintech × lnInnovation		−0.0286 *** (0.0069)		−0.0132 *** (0.0015)		0.0040 *** (0.0009)
Controls	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
R^2_Adjusted	0.6709	0.6710	0.6486	0.6464	0.19300	0.1984
Observations	4938	4938	4938	4938	4938	4938

Notes: The standard error in parentheses is the robustness estimator, and asterisks correspond to significance, *** (1%).

It can be found in Table 6 that the fiscal expenditure on science and technology and regional innovation have significant moderating effects on pollution control and carbon reduction, ultimately leading to synergistic effects. The interaction terms between fintech and fiscal technology expenditure in columns (1) and (3) have a significant emission reduction effect, and the interaction terms between fintech and regional innovation in columns (2) and (4) are also significantly negative. In addition, columns (5) and (6) demonstrate the significant moderating effect of the innovation factors on the impact of fintech on the synergy index. Specifically, the better the innovation factors, the stronger the synergistic effect for reducing the emissions of fintech. Hence, Hypothesis 3 is established. Public technology expenditure can guide the development of financial institutions, regional innovation is closely related to financial development [37], and the moderating effect of Hypothesis 3 is in line with the expectations of relevant theories.

When the dependent variable is pollution emissions, the coefficients of some of the fintech listed in Table 6 are positive, indicating that the marginal impact of fintech on pollution emissions is positive when the innovation factor is low. Therefore, the innovation factor is the boundary effect of fintech on reducing pollution emissions and carbon emissions, and the emission reduction effect of fintech under different boundary conditions is worth paying attention to. Figure 3 shows the boundary effects of fintech under the boundary conditions of fiscal technology expenditure, while Figure 4 shows the marginal effects of fintech under the boundary conditions of regional innovation.

Figure 3 shows that, with an increase in fiscal technology expenditure, the marginal effect of fintech changes from positive to negative. When fiscal technology expenditure is low, relevant financial institutions may lack guidance and tend to support non-clean technological progress and economic activity expansion, leading to the development of financial technology promoting increased pollution and carbon emissions. On the contrary, when fiscal technology expenditure is high, the green and low-carbon development goals of the government and the public are also included in the constraints of fintech development. Relevant financial institutions and capital mainly support clean technology progress and low-carbon innovation activities, thereby achieving a synergistic effect of pollution control and carbon reduction.

The bottom part of Figure 3 shows the kernel density map of the variable of fiscal technology expenditure during the sample period. This reveals that Fiscal_ Tech is mainly distributed within the range of the positive marginal effects of fintech. It indicates that fiscal technology expenditure coexists with fintech, thereby jointly promoting the low-carbon

and green development of the economy and society. It is also consistent with the fourth section, where the average marginal effect of fintech is significantly positive.

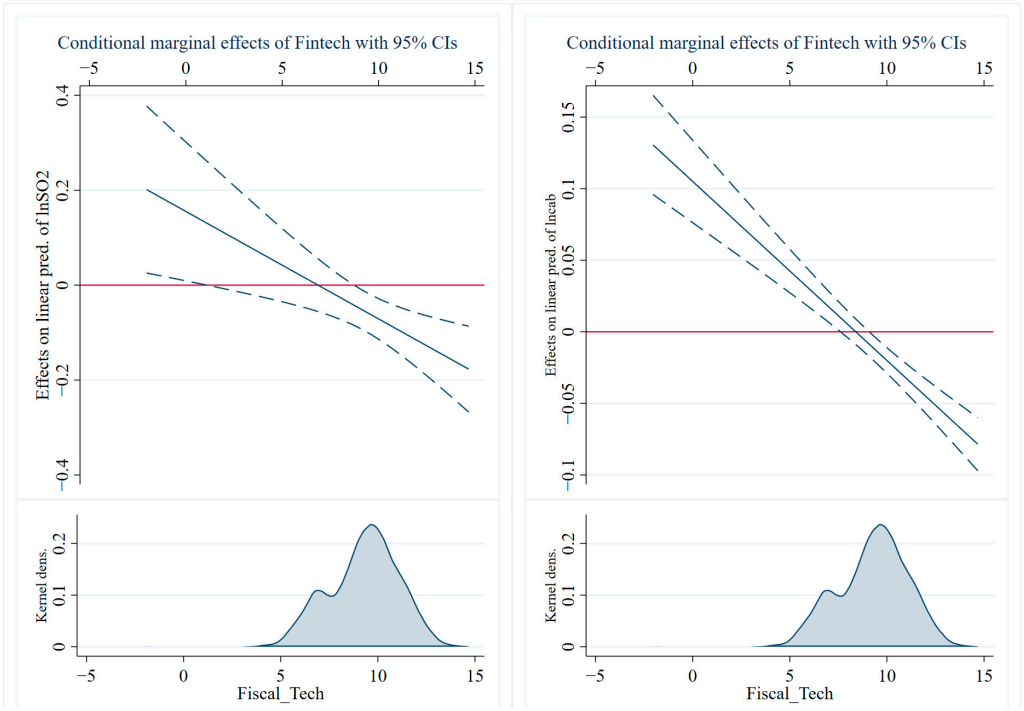

Figure 3. Marginal effects of Fintech under the condition of Fiscal_Tech. Notes: The dashed line represents the confidence interval estimate at the 95% level. The shadow area represents the distribution of the variable.

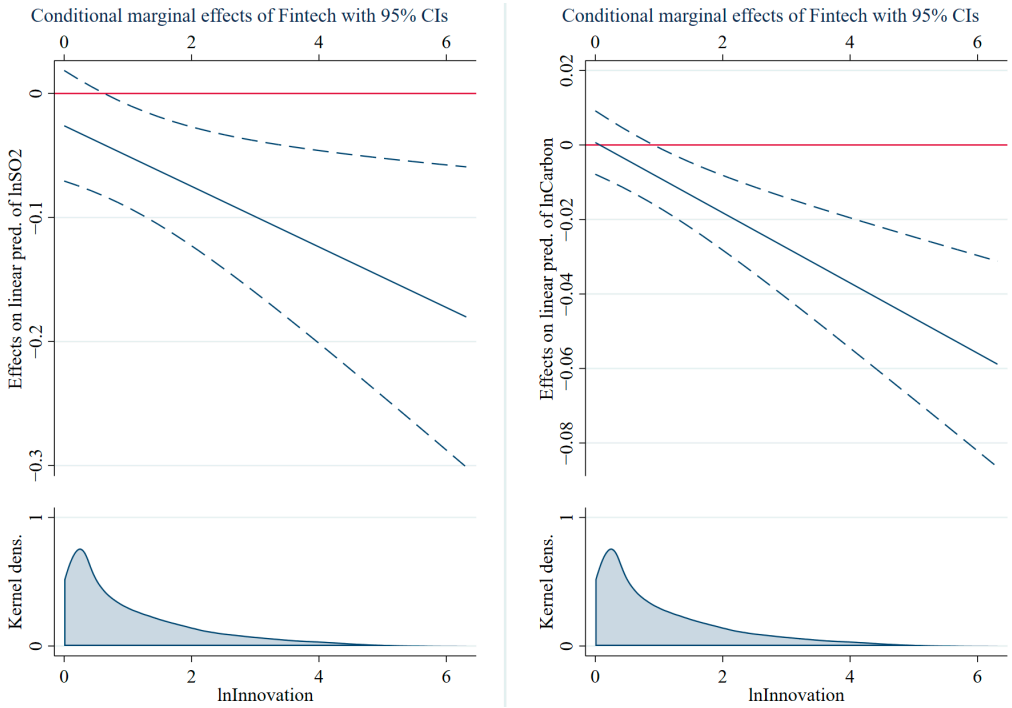

Figure 4. Marginal effects of Fintech under the condition of lnInnovation. Notes: The dashed line represents the confidence interval estimate at the 95% level. The shadow area represents the distribution of the variable.

Figure 4 shows that the marginal effect of fintech gradually decreases with an increase in the regional innovation index. In addition, the marginal effects of fintech have always been negative and gradually become significant from insignificant. The findings in Figure 4 indicate that fintech has significant potential for reducing sulfur dioxide emissions and carbon dioxide emissions, but this potential depends on the improvement in regional innovation. The direct implementation mechanism of fintech's role in high-quality economic development is to promote regional innovation and development, so the pollution reduction and carbon reduction effects it causes remain within the boundary conditions of this direct mechanism. The bottom part of Figure 4 shows the kernel density map of the variable of regional innovation during the sample period. Overall, the regional innovation index mainly tends to be around 0, which makes fintech's actual effect on reducing pollution and carbon emissions relatively low. In order to further unleash fintech's green and low-carbon effects, it is necessary to unblock fintech's mechanism for driving regional innovation.

5.2. Empirical Analysis of the Mediating Effect of Innovation Factors

Green innovation is an important mechanism for realizing the synergy between pollution control and carbon emission reduction, and it is likely to play a mediating effect between fintech and pollution emissions. Table 7 shows the mediating effect of green innovation on the nexus of fintech and these emission indexes. The dependent variable of column (7) is Collabora1, while the dependent variable of column (8) is Collabora2. The results in Table 7 generally support the mediating effect of green innovation, but the effect of reducing sulfur dioxide emissions is insignificant. Columns (1) and (2) indicate that fintech significantly promotes green innovation at the 1% level. Columns (3) to (6) show that green innovation has a significant reduction effect on carbon emissions, while it has an insignificant impact on sulfur dioxide emissions. In addition, although the coefficient of lnGreenPat in column (7) is insignificant, columns (7) and (8) generally support the mediating effect of green innovation. Therefore, the key to guiding regional sustainable development models through financial policies is to activate the vitality of green innovation [16,38].

Table 7. Results of the mediating effect of green innovation.

Variables	lnGreenPat		$lnSO_2$		lnCarbon		Collabora	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fintech	0.0731 ***	0.0721 ***	−0.0705 ***	−0.0682 ***	−0.0221 ***	−0.0242 ***	0.0065 ***	0.0037
	(0.0253)	(0.0251)	(0.0226)	(0.0230)	(0.0051)	(0.0050)	(0.0021)	(0.0031)
lnGreenPat			0.0112	0.0045	−0.0226 ***	−0.0241 ***	0.0028	0.0084 **
			(0.0342)	(0.0350)	(0.0063)	(0.0061)	(0.0025)	(0.0033)
Controls	N	Y	N	Y	N	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
R^2_Adjusted	0.8815	0.8838	0.6642	0.6653	0.6288	0.6378	0.182	0.0937
Observations	4311	4311	4311	4311	4311	4311	4311	4311

Notes: The standard error in parentheses is the robustness estimator, and different asterisks correspond to significance, *** (1%), and ** (5%).

6. Conclusions and Enlightenments

Green and low-carbon development is a necessary path for pursuing sustainable development, and there is a common challenge of financing support for promoting green development and low-carbon transformation. This study took fintech as the research perspective to examine the synergistic mechanism between pollution control and carbon emission reduction. Through panel data from prefecture-level cities in China, this study examined the relationship between fintech and pollution control, carbon emission reduction, and their coordinated promotion. The main conclusions are as follows.

The correlation analysis showed that fintech was negatively correlated with sulfur dioxide emissions, while fintech was positively correlated with carbon emissions. However, empirical evidence from the panel regression model showed the positive role of fintech in regional pollution control and carbon emission reduction. Fintech not only significantly reduced the emissions of pollutants and carbon dioxide, but also significantly promoted the coordination between pollution control and carbon emission reduction. This research also took the pilot policy of combining technology and finance as a quasi-natural experiment and used the DID design method to determine the causal impact of fintech on the collaborative reduction in pollution and carbon emissions. These findings support the economic and social benefits achieved by China in promoting fintech development. The findings theoretically contribute to the collaborative implementation path of environmental issues and climate challenges, advocating for the use of financial technology development to activate the driving force of enterprises to respond to environmental and climate sustainability. In addition, innovation factors were important mechanisms for fintech to achieve pollution control and carbon reduction. Specifically, fiscal expenditure on science and technology and regional innovation had significant moderating effects on pollution control and carbon reduction, while green innovation had a significant mediating effect.

This study has a positive significance for clarifying the theoretical relationship between finance, innovation, and green and low-carbon development, and also has enlightening value for developing countries to formulate and optimize their financial and environmental regulations and innovation policies. Developing countries should pay attention to the financing needs of green, low-carbon, and innovative development, and leverage the innovative momentum of green and low-carbon transformation with financial financing support. Specifically, this study proposes the following recommendations. Firstly, developing countries need to fully utilize the empowering role of technology finance to promote the development of green finance and lead to the green and low-carbon development of their industries. Secondly, developing countries need to strengthen the role of fiscal technology expenditure in guiding financial institutions and various types of capital, so that they can flow more towards clean technology and low-carbon industries. Thirdly, developing countries need to strengthen the role of innovation in leading green and low-carbon development, promoting green technology innovation through enhancing innovation capabilities, and leading to comprehensive green economic and social development. Finally, developing countries should optimize their environmental policies and form a coordinated path for pollution control and carbon reduction, thereby improving the efficiency of these environmental policies and achieving environmental and climate goals at reasonable economic costs.

This study provides some expandable research directions. How fintech can promote green financial development and improve the financing efficiency of sustainable projects needs to be examined, for example, and how to solve the adverse selection and moral hazard in financing sustainable development projects. This study explored the collaborative path between pollution reduction and carbon emissions reduction, which provides insights for the study of green and low-carbon development. Environmental issues are related to climate challenges, but in reality, they are heterogeneous. The formulation of public policies needs to consider a synergistic path to achieve green and low-carbon transformation at reasonable economic costs [24].

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