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ORIGINAL RESEARCH

The impact of the degree of coupling coordination between green finance and environmental regulations on firms' innovation performance: evidence from China

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Abstract
Integrating the resource-based view and institution-based view theories, this paper examines the impact of the degree of coupling coordination between green finance and environmental regulations on firms' innovation performance. Using a sample of 1698 listed firms in China from 2008 to 2017, we find that the degree of coupling coordination between the regional green finance development level and environmental regulations is positively related to firms' innovation performance. Further, the results show that the degree of state ownership and government governance efficiency strengthen this positive relationship. We deepen our understanding of how environmental institutions coordinate to affect firms' innovation performance by combining the resource- and institution-based view theories.

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1 Introduction

The growing recognition of the need to address environmental issues has led to a surge in interest in green finance and environmental regulations (Bartram et al., 2022; Dang et al., 2022; Flammer, 2021; Irfan et al., 2022; Xiao & Shen, 2022). Green finance is a rapidly expanding area of finance that aims to promote sustainable economic growth by providing capital for eco-friendly projects (Irfan et al., 2022; Zhang et al., 2019; Zhou et al., 2022). In comparison, environmental regulations are government policies aimed at mitigating the negative influence of economic activities on the natural environments (Brown et al., 2022; He et al., 2020; Xu & Kim, 2022). Under the dual influences of green finance and environmental regulations firms operating in the industries with high environmental impact face growing pressures to innovate and adopt sustainable practices to remain competitive and legitimate (Brown et al., 2022; Kim et al., 2022). In this study, we investigate the effects of the degree of coupling coordination between green finance and environmental regulations on firm innovation performance.

Earlier research has indicated that firm innovation performance is influenced by the factors such as financial resources, technological capabilities, and the regulatory environment (Blanco & Wehrhei, 2017; Li et al., 2020a, 2020b; Koh & Lee, 2022). However, there has been a lack of focus on the impact of the potential synergy effects between green finance and environmental regulations. A few studies have noted that environmental regulations may strengthen the impact of green finance on firm innovation activities (Chevallier et al., 2021; Zhao & Xin, 2021). Similarly, green finance is found to amplify the effect of environmental regulations by directing capital investment to technological innovation projects (Guo et al., 2019; Xu & Li, 2020). Nevertheless, this moderation effect may not be sufficient to explain the synergistic effects of the two. Therefore, new perspectives and methods are needed to advance the relevant research (Dong et al., 2021; Wang & Tan, 2020). To fill the research gap, we examine the synergistic effects of green finance and environmental regulations by analysing the degree of coupling coordination of the two forces. Compared with the moderation mechanism, the coupling coordination mechanism more accurately captures the mutual dependence and constraints between the two (Jiang et al., 2021; Yu et al., 2021). Specifically, we explore how the degree of coupling coordination between green finance and environmental regulations affects a firm's ability to innovate and adopt sustainable practices.

In addition, we consider the moderating role that the government plays in this relationship. From an internal perspective, we focus on a firm's degree of state ownership. Government participation may exert increased institutional pressure on the firm (Boisot & Child, 1996; Jiao et al., 2015). When state ownership is high, the government can influence a firm's decision-making by appointing top executives and allocating precious assets (Li et al., 2020a, 2020b). A high degree of state ownership signifies that a firm may need to ensure that its decision-making aligns with the objectives set by the government and respond more actively to the dual forces of green finance and environmental regulations for the sake of synergistic effects than it has in the past (Choi et al., 2011; Liu et al., 2021a, 2021b). From an external perspective, we consider the moderating effect of the governance efficiency of the government. The higher the governance efficiency, the lower the transaction costs for enterprises in the market (Nguyen,

2019) and the more efficient the implementation process of environmental regulations (Ren et al., 2022). In summary, this study takes into account the degree of state ownership and the governance efficiency of the government as the key moderating factors.

Empirically China was chosen as the research context. As one of the largest emerging economies in the world, China is strongly motivated to pursue sustainable development. In addition, the Chinese government has a significant influence on the market, which means that its environmental regulations and financial policies may have a more obvious impact than in other countries on industrial innovation. Thus, we chose a sample of listed firms in the Chinese mainland to test our hypotheses.

This study contributes to the literature in four aspects. First, we extend and enrich the application of the resource-based view (RBV) and institution-based view (IBV) to firm innovation research by revealing the coupling coordination mechanism between green finance and environmental regulations, which impacts firm innovation. Second, we deepen the understanding of the complex roles of the government in influencing this mechanism. Third, we contribute to the research method by measuring the degree of coupling coordination between green finance and environmental regulations using a novel approach. Fourth, this study provides practical implications for policymakers, firms, and investors interested in sustainable economic growth.

The remainder of the paper is structured as follows. Section 2 develops the theoretical framework and hypotheses. Section 3 elaborates on the research method. Section 4 reports the empirical analysis. Section 5 discusses the results. Section 6 provides the conclusions, implications, and limitations of the study.

2 Theory and hypothesis development

2.1 Hypothesizing the impact of the degree of coupling coordination between green finance and environmental regulations

RBV and IBV are instrumental in examining the relationships among green finance, environmental regulations, and firm innovation performance. RBV and IBV are interconnected in the sense that institutional forces influence resource-based factors and vice versa (Wang et al., 2012). The integration of these theories is particularly pertinent in emerging markets where businesses largely function in a hybrid state between market transactions and hierarchy. (Powell, 1990; Wang et al., 2012).

RBV posits that a firm's resources and capabilities are major drivers of its competitiveness in the market. Green finance refers to financing activities and investments with a positive environmental impact which supports sustainable social development (G20 Green Finance Study Group, 2016; Kumar et al., 2022). Green finance equips firms with financial resources for developing sustainable technologies and practices which may result in a competitive advantage (Wang & Wang, 2021; Yang et al., 2021). In addition to financial resources, green finance can provide access to other resources and capabilities necessary for innovation, such as frontier information and talents (Cui et al., 2022).

According to IBV, a firm's behaviours are influenced by the institutional environment in which it operates (North, 1990, 1991; Peng et al., 2008). Both green finance and environmental regulations can affect a firm's capabilities and willingness to innovate and develop more sustainable practices (Chang & Sam, 2015; Sun et al., 2020). Put differently, green finance

may act as a catalyst for developing a firm's organisational capabilities related to sustainability (Bhutta et al., 2022; Yan et al., 2021). As a new measure of environmental governance in financing, green finance restricts the financial resource supply of firms with high pollution and energy consumption by raising interest rates, tightening supervision, and increasing production costs, and meanwhile promotes investment in innovation for clean technologies (Liu et al., 2015). A firm that receives green finance may need to improve its environmental management systems, policies, and practices, which leads to the development of new capabilities related to sustainable practices and technologies thereby driving innovation, particularly for firms in green industries (Zhang, 2021).

Different from the facilitating role that green finance normally plays in firms' innovation process, environmental regulations may bring opportunities for and pressures on firms and affect resource commitment, which influences the effectiveness of technological innovation performance (Cai et al., 2015; Sheng et al., 2012). Thus, when facing the constraints of environmental regulations, firms may have to improve their production processes via innovation (Fabrizi et al., 2018; Jiang et al., 2020) to (more than) offset the losses resulting from increased production costs (Jaffe & Palmer, 1997; Porter, 1992). However, environmental regulations may also force firms to internalise environmental costs by allocating financial resources to prevent and reduce polluting emissions (Chen et al., 2022; Huang et al., 2021). In so doing, environmental regulations may reduce the financial support for a firm's technological innovation activities and restrict the production potential thereby causing a loss of profits and competitiveness (Wagner, 2007).

Given the double-edged effects of environmental regulations discussed above, green finance may have a synergistic effect with environmental regulations that offsets the negative impact of environmental regulations on firm innovation. The degree of coupling coordination between green finance and environmental regulations refers to the extent of coordination through which these two mechanisms interact with and complement each other in promoting sustainable development.

When the degree of coupling coordination between green finance and environmental regulations is high, these two mechanisms may enact an institutional environment which encourages firms to innovate for highly sustainable practices. Environmental regulations incentivise firms to adopt sustainable practices by rewarding firms in compliance (Pan et al., 2017; Song et al., 2020; Veugelers, 2012; Zhao & Xin, 2021). In response to such regulations, investment organisations may provide firms with funds via green finance channels for green or clear energy innovation projects that are consistent with the specific environmental regulations (An et al., 2020; Benlemlih et al., 2022; Cui et al., 2020; Xing et al., 2021).

Conversely, when the degree of coupling coordination between green finance and environmental regulations is low, these two mechanisms may work in isolation or even against each other, leading to a less favourable environment for firm innovation. Hence, the following hypothesis:

Hypothesis 1 The degree of coupling coordination between green finance and environmental regulations is positively related to a firm's innovation performance.

2.2 Hypothesizing the moderating effect of state ownership

IBV proposes that firms are impacted by regulative, normative and cognitive institutions (Scott, 1995). As 'rules of the game', these institutions play a vital role in a firm's behaviours and performance (North, 1990, 1991; Peng et al., 2008). Accordingly, the government exerts

both formal authority and informal influence over how firms allocate resources for innovation (Li et al., 2020a, 2020b). The government can influence state-owned firms' innovation activities through ownership arrangements.

Firms with high state ownership are under institutional pressures to respond to environmental regulations (Boisot & Child, 1996; Jiao et al., 2015). As a result, these firms could be more likely than firms with low state ownership to invest in innovation initiatives aligned with the government's environmental policy goals. This alignment can lead to a higher likelihood of success (Chen et al., 2012). Furthermore, the degree of state ownership can influence a firm's external reputation and stakeholder perceptions (Gao et al., 2019). State-owned firms are often seen as having a greater social responsibility to the public and the environment than private firms (Li & Belal, 2018). As a result, state-owned firms may face greater pressures to engage in green innovation initiatives and have a higher incentive to demonstrate their commitment to sustainability than private firms.

In addition, state-owned firms normally have advantages in obtaining resources that support green innovation initiatives. For example, they may have easier access to green finance to fund the research and development (R&D) for new green technologies and innovation than private firms (Liu et al., 2021a, 2021b). Additionally, compared with private firms, state-owned firms may be given the priority to access public infrastructure and resources, such as research facilities and laboratories, to facilitate green innovation efforts and performance (Choi et al., 2011; Musacchio & Lazzarini, 2014; Zhou et al., 2016). Hence, the following hypothesis is put forth:

Hypothesis 2 The degree of a firm's state ownership is positively related to the relationship between the degree of coupling coordination between green finance and environmental regulations and firm innovation performance.

2.3 Hypothesizing the moderating effect of government governance efficiency

Governance efficiency of government refers to the quality and effectiveness of government policies, institutions, and regulations (Chen et al., 2011; Deng et al., 2020). Efficient governance may provide firms with clear guidance for environmental compliance and facilitate innovation through supporting policies and programs. Specifically, the innovation cost caused by information asymmetry can be reduced by government interventions such as increasing the supply of public resources and optimising institutions (Li et al., 2020a, 2020b; Wright et al., 2005). Conversely, excessive administrative intervention on the part of the government may increase firms' costs and operational risks (Habib & Zurawicki, 2002).

When governance efficiency is high, the degree of coupling coordination between green finance and environmental regulations may positively affect firm innovation performance. For example, efficient governance may provide firms with access to funding, technical support, and research and development resources to develop innovative solutions that meet environmental and green finance standards (Joo, 2018; Nguyen, 2019). Furthermore, efficient governance may create a level playing field for firms, reducing the cost of compliance and encouraging firms to innovate.

On the contrary, when governance efficiency is low, the effects of the coupling coordination mechanism may be weakened. Inefficient governance may result in the inconsistent enforcement of regulations, creating uncertainty that increases innovation costs (Ren et al., 2022). Additionally, inefficient governance may create bureaucratic obstacles that hinder

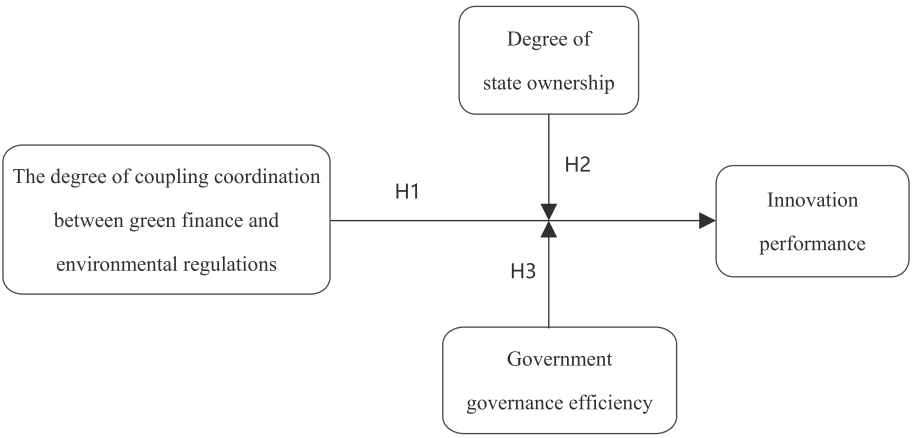

Fig. 1 The theoretical framework

firms' ability to comply with environmental regulations and green finance policies thereby reducing their motivation for innovation. Therefore, the following hypothesis is proposed:

Hypothesis 3 Government governance efficiency is positively related to the relationship between the degree of coupling coordination between green finance and environmental regulations and firm innovation performance. To summarize the three hypotheses, we present the theoretical framework in Fig. 1.

3 Research methodology

3.1 Sample and data source

The study population consisted of 1698 Chinese firms listed on the A share lists of the Shanghai or Shenzhen Stock Exchanges. Firms in the financial industry were excluded. To reduce the influence of variable outliers on the empirical results, the data with obvious outliers were curtailed by 99% and 1%. The final sample size was 6183, excluding missing data and obvious anomalies.

We chose the observation period spanning from 2008 to 2017 by considering the country's economic development trend and government strategies. Since 2008, the Chinese government has paid particular attention to sustainability and green economic development by publishing a series of environmental regulations (He et al., 2020; Ren et al., 2022; Zhou et al., 2022). In 2018, the Chinese government adjusted the standard of reporting related to green finance and environmental regulations and some of the data have not been published since 2018. To maintain the consistency of the data, we believe that the period from 2008 to 2017 is most suitable for our study.

The data for this study were collected from several databases. First, we obtained firm-level data from the CSMAR database, a high-quality database developed by GTA, a Hong Kong-based professional firm. This database is widely used and provides rich and reliable information on publicly listed Chinese firms (Guo et al., 2020). The data on green finance and environmental regulations were retrieved from the China Statistical Yearbook, China Urban

Statistical Yearbook, and China Environmental Statistical Yearbook, published by China's National Bureau of Statistics. We measured governance efficiency of government with an indicator of the marketisation index in the China's Provincial Marketisation Index Report (2018), which was developed by China's National Economic Research Institute (NERI). The NERI index, reflecting the extent of economic market freedom and the governance efficiency of the government at the provincial level, has been widely used in the literature (Ren et al., 2022; Zeng et al., 2021).

3.2 Variables and measurements

Dependent variables *Innovation performance* is measured by the number of granted invention patents (Bendig et al., 2020; Lin et al., 2020; Song et al., 2015). In addition, to improve the model's validity, we calculated *innovation performance* using the logarithmic form of the number of granted invention patents to convert discrete data to continuous data. Innovation performance generally has a time-lagged effect, so we set this variable as lagged by one year (Wang & Hagedoorn, 2014).

Independent variables Our main independent variable measures *the degree of coupling coordination between green finance and environmental regulations* (*GF&ER*).

Green finance is measured by the ratio of urban green investment, namely, environment management expenditure, to the region's gross domestic product (Zhang & Zhang, 2019). This measurement has been widely used previous studies of green finance (Wang & Wang, 2021; Xu & Li, 2020; Yu et al., 2021).

Environmental regulations is measured by the rate of city dust removal and emissions of other hazardous substances (Allevi et al., 2018; Ren et al., 2020). The value of *environmental regulations* indicates that the greater the removal efficiency rate, the stronger the environmental regulations.

The degree of coupling coordination between green finance and environmental regulations. Coupling usually refers to interdependent interactions of two or more systems (Dong et al., 2021). Although the initial calculation method of the degree of coupling originates from physics, it has been widely used to study coupling relationships among multiple systems in economics (Yin & Xu, 2022). We followed previous studies to calculate the degree of coupling (Dong et al., 2021; Zhang et al., 2021). The initial coupling model is as follows:

$$C = 2 \times \left[\frac{GF \times ER}{(GF + ER)^2} \right]^{1/2} \tag{1}$$

C ∈ [0,1] is the degree of coupling between green finance (*GF*) and environmental regulations (*ER*). The closer the value of *C* to one, the stronger the interaction between *GF* and *ER*; The closer the value of *C* to zero, the weaker the interaction between *GF* and *ER*. However, the initial model only calculates the interactive coupling between *GF* and *ER*. It does not profile the coordination level of the two variables (Yin & Xu, 2022). To calculate the degree of coupling coordination, we generated an improved model as follows:

$$T = \alpha \cdot GF + \beta \cdot ER \tag{2}$$

$$D = (C \times T)^{1/2} \tag{3}$$

D represents the degree of coupling coordination between *GF* and *ER* (Zhang et al., 2021). α and β represent the contributions of the subsystems of *GF* and *ER* to the comprehensive system, respectively. In the model, α and β are assigned a weight of 0.5 (Zhang et al., 2021).

Moderation variables The *degree of state ownership* was measured by the proportion of state ownership equity in a firm (Jiao et al., 2015; Liu et al., 2021a, 2021b; Nguyen, 2019).

Government governance efficiency was controlled and measured by the government—market relationship index as a sub-index of the marketisation degree (Ren et al., 2022; Zeng et al., 2021). This variable considers the following five aspects: the resources allocated by the market, the tax burden on farmers, the intervention of governments in firms, firms' non-tax burden, and the size of the government (Chen et al., 2015).

Control variables The control variables included *Firm size*, *Operating capacity*, *Government support*, *Debt level*, *R&D intensity, Regional R&D investment*, and *Regional financial development level. Firm size* is measured by the number of employees (Blanco & Wehrhei, 2017; Nguyen, 2019). Large firms are believed to have sufficient human and capital resources to invest in innovation and improve innovation performance compared to small companies (Peters, 2009). *Operating capacity* is measured by a firm's operating profit (Yi et al., 2021). Therefore, a firm's operating income is a good reflection of its operations (Yi et al., 2021). *Debt level* is controlled and measured by the firm's asset–liability ratio (Hou et al., 2019). *Government support* is measured by government subsidies to firms (Li et al., 2020a, 2020b). Finally, *R&D intensity* is controlled and measured by the ratio of R&D expenditure to revenue (Elia et al., 2020; Xie & Li, 2013).

We also controlled two regional-level variables: *Regional R&D investment* and *Regional financial development level*. *Regional R&D investment* is controlled and measured by the logarithm of R&D investment in the firm's province (Chatterjee et al., 2020; Peters, 2009), because firms can reduce their R&D resource investment level by using external R&D resources efficiently when other conditions are unchanged (Li et al., 2016; Martinez-Sanchez et al., 2020). Regional *financial development level* is controlled and measured by the loan-to-deposit ratio of the province in which the firm is located (Hou et al., 2019). Table 1 presents the details of the measurements and data sources of the variables.

3.3 Models

We used multiple regression models to analyse the data by following previous research (Benkraiem & Zopounidis, 2021; Jiao et al., 2015; Liu et al., 2021a, 2021b; Shao et al., 2020; Zhang, 2021; Zhang et al., 2022). Model 1 tested Hypothesis 1, Model 2 tested Hypothesis 2, and Model 3 tested Hypothesis 3. The models are as follows:

$$\text{Model 1}: Innovation_{i,t+1} = \alpha_0 + \alpha_1 GF\&ER_{i,t} + \beta_i \sum controls_{i,t} + \mu_i + \eta_j + \gamma_t + \varepsilon_{i,j,t} \tag{4}$$

$$\text{Model 2}: Innovation_{i,t+1} = \alpha_0 + \alpha_1 GF\&ER_{i,t} + \alpha_2 Stateownership_{i,t} + \alpha_3 GF\&ER_{i,t} \times Stateownership_{i,t} + \beta_i \sum controls_{i,t} + \mu_i + \eta_j + \gamma_t + \varepsilon_{i,j,t} \tag{5}$$

$$\text{Model 3}: Innovation_{i,t+1} = \alpha_0 + \alpha_1 GF\&ER_{i,t} + \alpha_2 Governanceefficiency_{i,t} + \alpha_3 GF\&ER_{i,t} \times Governanceefficiency_{i,t} + \beta_i \sum controls_{i,t} + \mu_i + \eta_j + \gamma_t + \varepsilon_{i,j,t} \tag{6}$$

Where *i* represents the firm, *j* represents the city, and *t* represents the time.

Table 1 Variable measurements and data sources

	Variable	Measurement	Data source
(1)	Innovation performance	The logarithm of the number of patents granted of the firm ($t + 1$)	CSMAR
(2)	GF&ER	Green finance is measured as the ratio of urban green investment in the province in which the firm is located; environmental regulations is calculated as the dust removal rate of the city in which the firm is located	China Statistical Yearbook, China Urban Statistical Yearbook; China Environmental Statistical Yearbook
(3)	Degree of state ownership	The proportion of state ownership equity of the firm	CSMAR
(4)	Governance efficiency	The score of the relationship between the government and the market	Report of Market Index by Provinces in China (2018)
(5)	Firm size	The logarithm of the number of firm employees	CSMAR
(6)	Operating capacity	The logarithm of the firm's operating profit	CSMAR
(7)	Regional R&D investment	The logarithm of R&D investment in the province in which the firm is located	CSMAR
(8)	Government support	The logarithm of government subsidies to the firm	CSMAR
(9)	Debt level	The ratio of debt to total assets of the firm	CSMAR
(10)	Regional financial development level	The loan-to-deposit ratio of the province in which the firm is located	CSMAR
(11)	R&D intensity	The ratio of R&D expenditure to the firm's revenues	CSMAR

4 Results

Table 2 reports the descriptive statistics and the Pearson correlations, and shows that all of the results are within an acceptable range. There is no high correlation among the independent variables. The results show that the mean of the innovation performance is 1.967, and the standard deviation is 1.125. This indicates that firm innovation performance varies greatly during the sample observation period. The mean of the degree of coupling coordination between green finance and environmental regulations is 0.465, and the standard deviation is 0.155, indicating that the value is moderate.

Table 3 reports the regression results. Hypothesis 1 is supported. The results show that the degree of coupling coordination between green finance and environmental regulations (*GF&ER*) is positively related to the firm innovation performance ($\beta = 0.525$, $P < 0.05$), indicating that good coupling coordination between green finance and environmental regulations can promote firm innovation performance.

Table 2 Matrix of correlations and descriptive statistics of the dependent, explicative, and control variables

	Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1)	Innovation performance	1.000										
(2)	GF&ER	0.066***	1.000									
(3)	Degree of state ownership	0.028**	0.134***	1.000								
(4)	Governance efficiency	− 0.009	− 0.092***	− 0.009	1.000							
(5)	Firm size	0.355***	− 0.001	0.169***	− 0.124***	1.000						
(6)	Operating capacity	0.276***	0.080***	0.117***	− 0.074***	0.624***	1.000					
(7)	Regional R&D investment	0.054***	− 0.393***	− 0.243***	0.382***	− 0.092***	− 0.006	1.000				
(8)	Government support	0.155***	0.072***	0.042***	0.016	0.198***	0.177***	− 0.033***	1.000			
(9)	Debt level	0.183***	0.020	0.155***	− 0.068***	0.490***	0.179***	− 0.116***	0.111***	1.000		
(10)	Regional financial development level	0.022*	0.186***	0.039***	− 0.062***	0.015	− 0.007	− 0.095***	0.001	0.019	1.000	
(11)	R&D intensity	0.094***	0.059***	− 0.127***	− 0.052***	− 0.247***	− 0.178***	0.207***	0.018	− 0.336***	0.008	1.000
	Observations	6,180	6,180	6,180	6,180	6,180	6,180	6,180	6,180	6,180	6,180	6,180
	Mean	1.967	0.465	0.049	8.408	7.694	18.689	15.318	12.566	0.373	1.466	0.041
	Std. dev	1.125	0.155	0.138	1.488	1.228	1.502	1.100	5.381	0.197	0.714	0.044
	Min	0.693	0.000	0.000	3.487	2.833	11.226	9.817	0.000	0.008	0.130	0.000
	Max	8.582	0.984	0.863	12.059	13.223	25.986	16.741	23.551	1.843	13.382	0.485

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$

Table 3 Results of multiple regression models with fixed effects

Innovation (grant)	(1)	(2)	(3)
GF&ER	0.525**	0.471*	− 0.861
	(0.256)	(0.257)	(0.758)
Degree of state ownership		− 0.677**	
		(0.334)	
Governance efficiency			− 0.097**
			(0.041)
GF&ER × Degree of state ownership		1.179**	
		(0.586)	
GF&ER × Governance efficiency			0.164**
			(0.080)
Firm size	0.136***	0.141***	0.137***
	(0.046)	(0.047)	(0.046)
Operating capacity	0.038**	0.039**	0.038**
	(0.016)	(0.016)	(0.016)
Regional R&D investment	0.277*	0.258*	0.216
	(0.154)	(0.153)	(0.161)
Government support	0.003*	0.003*	0.003*
	(0.002)	(0.002)	(0.002)
Debt level	− 0.009	− 0.017	− 0.004
	(0.143)	(0.144)	(0.142)
Regional financial development level	0.000	− 0.000	0.004
	(0.016)	(0.016)	(0.017)
R&D intensity	0.932*	0.937*	0.939*
	(0.507)	(0.506)	(0.506)
Constant	− 4.312*	− 4.049*	− 2.577
	(2.370)	(2.352)	(2.599)
City fixed	Yes	Yes	Yes
Firm fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	5,738	5,738	5,738
R− squared	0.757	0.757	0.757

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$
Robust standard errors clustered to the firm level are in parentheses

Hypothesis 2 is supported. The interaction term of the *degree of state ownership* has a significant positive impact on firm innovation ($\beta = 1.179$, $P < 0.05$), indicating that the degree of state ownership strengthens the positive effects of the coupling coordination mechanism on a firm innovation performance.

Hypothesis 3 is also supported. The interaction term of *governance efficiency* has a significant positive impact on firm innovation ($\beta = 0.164$, $P < 0.05$), indicating that governance

efficiency strengthens the positive effects of the coupling coordination mechanism on firm innovation performance.

Further, the coefficients of *Firm size* ($\beta = 0.136$, $P < 0.01$), *Operating capacity* ($\beta = 0.038$, $P < 0.05$), *Regional R&D investment* ($\beta = 0.277$, $P < 0.1$), *Government support* ($\beta = 0.003$, $P < 0.1$), and *R&D intensity* ($\beta = 0.932$, $P < 0.1$) are also significantly positively related to firm innovation performance. However, there is no evidence of relationships between debt level, financial development, and firms innovation performance.

4.1 Robustness check and additional tests

4.1.1 Robustness check

A series of tests were conducted to check the sensitivity of the multiple regression results. First, we adopted the number of patent applications to substitute for the invention patents in the dependent variable. As shown in Table 4, the results remain consistent with the original measurements.

In addition, we substituted the index of environmental regulations with several other proxies. Table 5 presents the results. In models (1)–(3), we substituted the value of the soot removal rate with the emissions per unit output value of soot. In models (4)–(6), we substituted the value of the soot removal rate with the emissions per unit output value of wastewater. Finally, in models (7)–(9), we substituted the value of the soot removal rate with the emissions per unit output value of sulphur dioxide. As shown in Table 5, the results are mainly consistent with the original measurement.

4.1.2 Additional test: A difference-in-differences (DID) analysis

A DID analysis was conducted to verify the original multiple regression analysis. As multiple regressions may suffer from sample selection bias, we adopted a quasi-natural experiment method using a DID analysis. DID analysis can eliminate the effects of unobserved non-time-varying factors and mitigate coefficient deviations due to missing variables (Agrell et al., 2020). We tested whether the differences in firm innovation performance were affected by external policies such as green finance and environmental regulations (Lin et al., 2019; Ren et al., 2020).

We chose 2011 as the dummy variable for policy impact. The reason for our choice was that in 2011, China's government published a series of influential national environmental policies, such as *Work Plan of Energy Conservation* and *Emission Reduction Guidance on Strengthening of Environmental Protection and the Guidance of Green Credit* for the *Twelfth Five-year Strategy*. The publication of these policies indicated significant changes in China's environmental regulations and green finance policies.

We further classified firms into pollution and non-pollution groups by comparing their polluting emissions with the environmental regulations index. If the magnitude of a firm's emissions was larger than the index, it was classified into the pollution group (Liu et al., 2021a, 2021b).

The process of the difference-in-differences model is as follows:

$$\text{Model 4}: Innovation_{i,t+1} = \alpha_0 + \alpha_1 Treated_i \times Policy_t + \alpha_2 Treated_i + \alpha_3 Policy_t + \beta_i \sum controls_{i,t} + \varepsilon_{i,t} \quad (7)$$

Model 4 examines the effects of external policy on firm innovation performance.

Table 4 Robustness test of alternative dependent variables

Innovation (application)	(1)	(2)	(3)
GF&ER	0.441*	0.377	− 1.467**
	(0.268)	(0.271)	(0.745)
Degree of state ownership		− 0.817**	
		(0.371)	
Governance efficiency			− 0.143***
			(0.042)
GF&ER × Degree of state ownership		1.428**	
		(0.636)	
GF&ER × Governance efficiency			0.225***
			(0.082)
Firm size	0.132***	0.138***	0.133***
	(0.046)	(0.046)	(0.046)
Operating capacity	0.046***	0.046***	0.046***
	(0.016)	(0.015)	(0.016)
Regional R&D investment	0.091	0.068	0.005
	(0.159)	(0.158)	(0.163)
Government support	0.003	0.003	0.003
	(0.002)	(0.002)	(0.002)
Debt level	0.050	0.040	0.055
	(0.147)	(0.148)	(0.146)
Regional financial development level	− 0.007	− 0.008	− 0.002
	(0.014)	(0.014)	(0.014)
R&D intensity	1.279**	1.285**	1.283**
	(0.542)	(0.543)	(0.543)
Constant	− 0.846	− 0.524	1.667
	(2.420)	(2.405)	(2.605)
City fixed	Yes	Yes	Yes
Firm fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	5,738	5,738	5,738
R− squared	0.795	0.795	0.796

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$
Robust standard errors clustered at the firm level are in parentheses

Table 6 displays the results of the DID analysis, which show that the interaction term of policy and pollution group (*Treated* × *Policy*) is positively related to innovation performance ($\beta = 0.074$, $P < 0.1$; $\beta = 0.075$, $P < 0.1$). This result indicates that environmental governance policies positively impact firm innovation performance, supporting the original results of the multiple regression analysis.

Table 5 Robustness test of alternative, independent variables

Innovation (grant)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GF&ER(3)	0.337	0.276	− 1.170	0.437*	0.367	− 0.921	0.427	0.370	− 0.788
	(0.251)	(0.256)	(0.754)	(0.244)	(0.248)	(0.773)	(0.264)	(0.263)	(0.744)
Degree of state ownership		− 0.551*			− 0.596*			− 0.468	
		(0.324)			(0.304)			(0.335)	
Governance efficiency			− 0.103**			− 0.092**			− 0.088**
			(0.040)			(0.041)			(0.039)
GF&ER × Degree of state ownership		0.943*			1.064**			0.801	
		(0.567)			(0.543)			(0.595)	
GF&ER × Governance efficiency			0.180**			0.158*			0.148*
			(0.080)			(0.081)			(0.078)
Firm size	0.136***	0.141***	0.138***	0.142***	0.147***	0.143***	0.137***	0.141***	0.138***
	(0.046)	(0.047)	(0.046)	(0.046)	(0.047)	(0.046)	(0.046)	(0.047)	(0.046)
Operating capacity	0.038**	0.039**	0.038**	0.038**	0.038**	0.038**	0.038**	0.039**	0.038**
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Regional R&D investment	0.285*	0.273*	0.225	0.284*	0.264*	0.224	0.284*	0.274*	0.226
	(0.155)	(0.154)	(0.160)	(0.154)	(0.154)	(0.161)	(0.155)	(0.155)	(0.161)
Government support	0.003*	0.004*	0.003*	0.003*	0.003*	0.003*	0.004*	0.004*	0.003*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Debt level	− 0.008	− 0.015	− 0.005	− 0.010	− 0.017	− 0.006	− 0.008	− 0.015	− 0.006
	(0.143)	(0.144)	(0.142)	(0.143)	(0.144)	(0.142)	(0.143)	(0.144)	(0.142)
Regional financial development level	0.003	0.003	0.008	0.001	0.002	0.006	0.002	0.002	0.005
	(0.016)	(0.016)	(0.017)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.017)

Table 5 (continued)

Innovation (grant)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
R&D intensity	0.947*	0.953*	0.952*	0.923*	0.929*	0.925*	0.942*	0.946*	0.942*
	(0.508)	(0.508)	(0.507)	(0.509)	(0.508)	(0.509)	(0.507)	(0.507)	(0.506)
Constant	− 4.354*	− 4.189*	− 2.595	− 4.418*	− 4.118*	− 2.727	− 4.391*	− 4.240*	− 2.772
	(2.386)	(2.372)	(2.581)	(2.362)	(2.351)	(2.595)	(2.377)	(2.371)	(2.577)
City fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5,738	5,738	5,738	5,725	5,725	5,725	5,738	5,738	5,738
R-squared	0.757	0.757	0.757	0.757	0.757	0.757	0.757	0.757	0.757

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$

Robust standard errors clustered to the firm level are in parentheses

Table 6 Results of the quasi-natural experiment

Innovation	*Model 4 (grant)*	*Model 4 (application)*
Treated × Policy	0.074*	0.075*
	(0.044)	(0.044)
Firm size	0.142***	0.140***
	(0.045)	(0.045)
Operating capacity	0.038**	0.046***
	(0.016)	(0.015)
Regional R&D investment	0.308**	0.122
	(0.155)	(0.159)
Government support	0.004*	0.003
	(0.002)	(0.002)
Debt level	− 0.008	0.043
	(0.141)	(0.144)
Regional financial development level	0.009	− 0.000
	(0.016)	(0.014)
R&D intensity	0.932*	1.278**
	(0.506)	(0.537)
Constant	− 4.645**	− 1.322
	(2.223)	(2.254)
City fixed	Yes	Yes
Firm fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	6,164	6,164
R-squared	0.106	0.142

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$

Robust standard errors clustered to the firm level are in parentheses

A common trend test and a placebo test were further conducted to test the robustness of the DID analysis. The results show that both tests are passed (see Appendix 1 for the results of the two tests).

5 Discussion

The contribution of this study lies in its identification of the synergistic effect between green finance and environmental regulations and how it impacts firm innovation performance. Our overarching argument is that the two forces of green finance and environmental regulations work in a coupling coordination way to affect firm innovation performance. This finding echoes those of several other studies. For example, green financial policies were found to facilitate firm innovation performance (Liu et al., 2021a, 2021b), and green regulations and other environmental policies improve firm innovation performance by supporting environmental agencies (Ren et al., 2020; Shao et al., 2020).

We further confirm that state ownership and government governance efficiency play positive roles as moderators. Unlike the studies that have concluded that state ownership usually plays a negative role in firm innovation process due to agency issues (Bai et al., 2009; Sun

et al., 2020), our findings support the argument that state-owned enterprises are more motivated than private firms to engage in innovation activities under green finance policies and government regulations thereby showing enhanced innovation performance (Lin et al., 2021; Yi et al., 2021). Regarding the moderating effects of government governance efficiency, our findings support the argument of Jiao et al. (2015) that government governance efficiency significantly impacts firm innovation.

The results of the control variables also echo the results of other studies. Our finding that firm size and operating profit are positively related to firm innovation performance is consistent with Peters (2009), Chatterjee et al. (2020), and Yi et al. (2021). Government support is also positively related to innovation performance in this study, consistent with other findings in this area (Huang et al. 2015; Elia et al., 2020; Yi et al., 2021). Our study finds that firm R&D intensity and regional R&D investment are positively related to firm innovation performance, similar to most other research findings in this area (Elia et al., 2020; Xie & Li, 2013; Yi et al., 2021). However, we do not find evidence supporting the correlation between the regional financial development level and firm innovation performance, perhaps due to differences in firms' access to capital between developed and developing countries. Unlike firms in developed economies, firms in developing countries have almost no spatial differences in their access to capital (Lee & Luca, 2019).

6 Conclusion, implications, and limitations

This study investigated the impacts of the degree of coupling coordination between green finance and environmental regulations on firm innovation performance during the 2008–2017 period. Based on an investigation of a sample of 1,698 publicly listed firms in China, we confirm the synergistic effects of the two forces and their coupling impacts on firm innovation performance. The results suggest that different environmental systems need to be coupled and coordinated well to facilitate firm innovation performance. Therefore, government decision-makers should pay attention to the consistency of environmental policies. For example, governments and financial regulatory authorities may need to collaborate to set consistent reward and punishment policies for green finance and environmental regulations.

The moderating effect analysis indicates that state ownership and government governance efficiency strengthen the mechanism mentioned above. These results suggest. that governments may need to be careful about the extent to which they interfere in the market. The degree of a firm's state ownership is positively related to the effect of the degree of coupling coordination between green finance and environmental regulations on its innovation performance. However, this result may also signify that private firms are in a weak position compared with SOEs, which have easier access to strategic resources for innovation. Therefore, governments should also improve green credit access for private firms, particularly small and medium-sized firms.

Although our research contributes to the knowledge of the synergistic effects among different environmental institutions on firm innovation performance, it does have limitations, suggesting potential directions for future research. First, due to the relative uniqueness of the Chinese context, the conclusions of our study may not apply to other empirical settings. Future research could extend our research context to other countries, particularly other emerging countries. Second, our research was based on a sample of publicly listed firms. Thus, our conclusions may not apply to private firms, especially small and medium-sized enterprises (SMEs), which are more sensitive and responsive to external institutions than

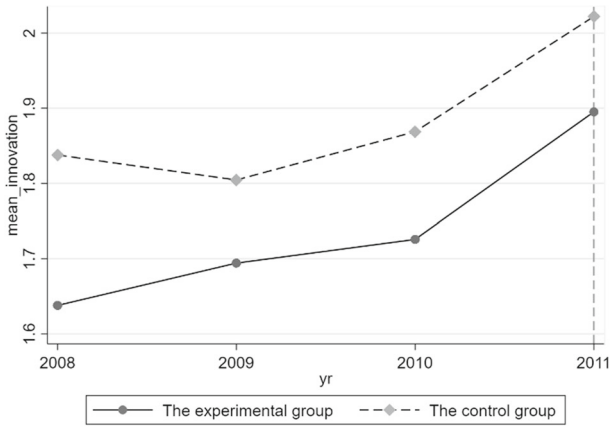

Fig. 2 Common trend chart

larger enterprises. More research is warranted to see if and to what extent our results are generalizable.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Appendix 1

Common trend test for the DID analysis

Figure 2 shows that the innovation performance of both the experiment and control groups follows a similar trend before Chinese government publishing a series of influential national environmental policies, indicating that the quasi-natural experiment passes the common trend test.

Placebo test for the DID analysis

To test whether the baseline regression results are affected by omitted variables, random factors, and other factors, we conducted a placebo test of a random sampling. We randomly

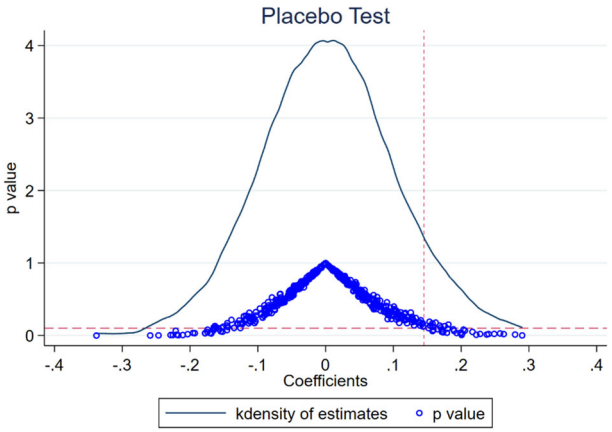

Fig. 3 Kernel density diagram of coefficients and corresponding P values

selected 600 firms from the sample pool to form a fictitious experimental group and examined the reliability of the results using the coefficients of the dummy variable of fictitious policies.

The results of the placebo test are consistent with the original DID analysis. To strengthen the effects of the placebo test, the process was repeated 500 times. Figure 3 presents the distribution of the coefficients of the fictitious policy variables. The figure shows the results of the verification on whether the impact of the policy effect of environmental regulations and green finance on firms' innovation vitality was interfered with by unobserved factors. As shown in Fig. 3, the coefficients of the independent variables are basically distributed near the value of zero after random processing, which signifies that there are no significant factors omitted in the baseline model. This means that the results of the regression mainly reflect the effects of regional environmental regulations and green finance policies.

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