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Can central and local forces promote green innovation of heavily polluting enterprises? evidence from China

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Adequate government environmental supervision is the key to promoting green innovation which is an essential driver of green development. In environmental decentralization, an analysis of the mechanism of the inherent influence of central and local supervision on green innovation may prove to be of practical importance. The paper selects data from heavily polluting enterprises in A-shares in China from 2013 to 2019 using fixed-effects models, moderating effect models, heterogeneity tests, and other research methods for analysis. These results are: 1. Both central and local supervision can significantly facilitate green innovation in heavily polluting enterprises. Local supervision has a weaker promotion effect than central supervision. 2. The two environmental supervision approaches can work synergistically. Central supervision can enhance the effect of local supervision on enterprises' green innovation. 3. An analysis of heterogeneity indicates that the two environmental supervision approaches significantly promote eastern heavy polluters engage into green innovation. However, they do not promote it significantly for non-eastern enterprises. In addition, the same regional heterogeneity exists in the positive moderating effect of central supervision. 4. Further research finds that both types of supervision induce high-quality substantive green innovation. Central supervision can further enhance the impact of local supervision on enterprises' substantive green innovation. The paper provides empirical data references for establishing an environmental supervision path under collaboration by governments at different levels, and offers implications for achieving green innovation and optimizing pollution emission mechanisms in heavy polluters.

KEYWORDS

green innovation, central supervision, local supervision, green development, heavily polluting enterprises

1 Introduction

China's economy has achieved high growth, but environmental problems are becoming increasingly serious. According to the 2022 Environmental Performance Index, China is in 160th place out of 180 countries and regions participating in the global ranking, with a score of 28.4. The government have raised the importance of promoting high-quality economic development and adhering to the green development to an new height. Achieving green development requires green innovation. Unlike general innovation methods, green innovation can reduce environmental pollution and energy consumption while achieving high-quality economic development. However,

green innovation has high externalities (Zhao et al., 2021). The important force behind green innovation is heavy polluters. These enterprises will lose their willingness to continue green innovation when they cannot obtain sufficient economic benefits after bearing high costs (Liang et al., 2022). Therefore, studying how to facilitate green innovation of heavy polluters has become a pressing concern in China. In studies conducted in the past, environmental supervision by the government has shown to be effective in encouraging heavily polluting enterprises to fulfill their environmental protection responsibilities. (Liu et al., 2022; Jiang et al., 2022). Heavy polluters must be actively involved in green innovation to fulfil their environmental protection responsibilities. Enterprises primarily cause pollution, and the government is the primary supervisor. The government's supervision and the enterprises' response are key factors in solving the environmental pollution problem. The pursuit of green development necessarily requires the establishment of a governmental supervision system that contributes to environmental protection. China implements a decentralized supervision system for the environment, divided into central and local supervision. In this regard, the effectiveness of environmental protection supervision will depend on a combination of three factors: central oversight, local oversight, and enterprise oversight. So, will the forces from central and local supervision effectively encourage heavy polluters to adopt green innovation?

Central supervision is an essential component of China's environmental protection supervision system, and significantly impacts enterprises' green innovation behaviour. A sound government environmental supervision system is necessary for China to embark on the green development path. The traditional "foot voting" theory states that the government can efficiently supply public goods through a decentralized system. Given the uneven economic development and varying level of environmental pollution across regions, the use of environmental decentralization of environmental supervision system is in line with the reality. There are, however, questions about the effectiveness of the system. According to the so-called environmental decentralization system, local administrations are in charge of carrying out the central environmental policies established. In the early days, local governments would compromise environmental protection for economic growth, protecting the heavily polluting enterprises in their territories and concealing their pollution emissions. Since the central government did not have comprehensive information on local environmental pollution, it could not effectively supervise (Sun and Feng, 2021). To improve the effectiveness of central supervision, the Chinese Ministry of Ecology and Environment selects and publishes a list of national specially monitored enterprises. Heavily polluting enterprises will be placed on the list when their emissions reach a certain level. The data on their pollution emissions will be monitored and supervised by the governments at different levels. Enterprises that do not comply will face immediate sanctions from the central government. Developing a list of national specially monitored enterprises makes up for the shortcomings of insufficient monitoring by local governments and asymmetric information from the central environmental authorities.

Local supervision can supervise and restrain the environmental pollution behaviour of heavily polluting enterprises and prompt them to fulfil their responsibility for environmental protection. In the early stage, local governments excessively pursued rugged economic growth. They used their power to protect the polluting behaviour of heavily polluting enterprises, paying a costly ecological and environmental price. Currently, China has included environmental protection factors into its evaluation of local officials, and the local have increased environmental protection supervision. Thus, heavily polluting enterprises must make environmental protection and green innovation their strategic goal (Kuai et al., 2019). Moreover, the local can enact environmental laws. They will make environmental regulations that meet local realities and improve the blind spots of relevant national regulations.

The research objectives are as follows: 1. Can central supervision effectively promote green innovation among heavy polluters? Can local supervision be actively empowered by central supervision? 2. Can tighter and better local supervision successfully encourage enterprises to adopt green innovation? What is the inherent mechanism? 3. What is the role assumed by the government in environmental protection? 4. Are there any actual flaws in environmental supervision? 5. Are there any policy implications for achieving an environmental governance path for green innovation in heavy polluters? Thus, This study collects data from 2013 to 2019 for A-share listed firms in Shanghai and Shenzhen, China, in order to examine how central and local supervision affect green innovation. The novelties of this paper lie in three aspects: research perspective, research content, and research method. 1. Research perspective: This paper is not limited to a single perspective of central and local governments or enterprises but constructs a framework for empirical analysis of enterprises' central and local green innovation. It enriches the research on the economic consequences of environmental supervision and the factors influencing green innovation and provides a new research perspective for the multi-entity environmental governance model. 2. Research content: This paper assesses the impact of central and local supervision collaboration and further examines the mechanism of the effect. It provides empirical data facts for improving realistic environmental decentralization structure and building an environmental governance path for collaboration between central and local supervision. This paper further explores the heterogeneity of the mechanisms of the role of central and local supervision on green innovation. Moreover, it analyzes their effects on substantive green innovation. Thus, this paper provides policy recommendations for how the government should respond to different types of heavily polluting enterprises and how to induce high-quality green innovation. 3. Research Method: Previous studies on the environmental supervision patterns of government and enterprises have mainly used qualitative analysis, and some of the quantitative analyses only use a single indicator to measure government supervision. This study measures central and local supervision indicators separately to quantitatively analyze the impact of central and local supervision on green innovation, which helps to understand the relationship between central, local and enterprises more deeply. In addition, this paper uses fixed-effects models and robustness tests for estimation, improving the results' precision.

2 Theoretical background and literature review

2.1 Theoretical background

The influencing factors of green innovation include economic and policy aspects, among which the national policies of energy and environmental supervision can positively impact enterprises' green innovation. The compensation effect theory can explain the relationship between government environmental supervision and green innovation. The compensation effect theory is mainly derived from Porter hypothesis, which suggests that when environmental regulations constrain firms, they will increase their investment in innovation as profit maximizers and promote the green transformation of production. By increasing the production level and improving the firm's overall productivity, the firm will compensate for the negative impact of environmental regulation on its profits by chasing down green compensation (Porter and Linde, 1995). This response helps firms to increase their level of technological innovation. In addition, corporate legitimacy theory suggests that firms will strive to maintain a good image and adopt appropriate ways to manage how they behave to safeguard their legitimacy (Suchman, 1995). It has been shown that enterprises, as the main polluters, will face various environmental supervision in the context of green development. They take the initiative to fulfil their environmental responsibilities and green innovation to maintain legitimacy (Amores-Salvadó et al., 2014).

2.2 Literature review

2.2.1 Government and institutional quality in regulating the environment

Many studies have discussed the impact of government environmental regulation and institutional quality on the environment. Institutional quality includes various perspectives, such as the efficiency of government governance, level of the rule of law, level of marketization, and degree of regulation, reflecting the overall degree of regional social development (Udemba and Tosun, 2022). Good institutional quality guarantees the allocation of resource endowments and policy implementation and enhances the incentive effect of environmental regulation. Institutional quality is critical for improving environmental performance (Udemba, 2021). Several studies have found that institutional quality plays a crucial role in government regulation development, implementation and regulation that can mitigate carbon emissions and improve the environment (Khan et al., 2022; Udemba, 2022). Environmental regulations are laws, regulations, and measures governments enact to protect the environment (Song and Han, 2022). Renewable energy policies are governmental environmental regulations. It has been found that the development of renewable energy is a key way to transform energy and protect the environment, and the formulation of renewable energy policies is essential for using renewable energy (Udemba et al., 2022; Xing et al., 2023). The Chinese government has a decentralized system of environmental regulation. In essence, environmental decentralization is the division of power and responsibility on environmental management among multi-level governments, which reflects the autonomous decision-making power of local governments in local environmental governance. In terms of environmental pollution, scholars have not yet formed a unified view. Some scholars believe that environmental decentralization will hinder local carbon emission reduction and environmental governance (Lin and Xu, 2022). However, Hao et al., 2021 found that environmental decentralization can significantly reduce the air pollution problem. In terms of green development, some scholars believe that environmental decentralization has a positive effect on regional innovation, especially green technological innovation (Feng et al., 2020). Zou et al., 2019 found that different types of environmental decentralization can directly or indirectly promote regional green development, but Wu et al. pointed out that environmental decentralization may lead to "race to the bottom" effect within and between regions, which will hinder the green development (Wu et al., 2020).

2.2.2 The environmental governance effects of government supervision

Academic research on central supervision, local supervision, and green innovation focuses are: 1. The environmental governance effects of central and local supervision; 2. Discussion on the elements that affect green innovation.

Due to the fact that environmental pollution has the property of public goods and externality characteristics, supervising the environmental pollution problem only by the market will result in the market failure (Sun et al., 2021). The government needs to solve the environmental pollution problem through environmental protection supervision as the public interest's defender (Zhang et al., 2021). Therefore, there has been a lot of interest in study on environmental governance and government supervision. The related literature focuses on two aspects of the environmental governance effects of central and local supervision.

Local governments' "race to the bottom" may weaken environmental supervision requirements and contribute to the collapse of central environmental policies (Wu et al., 2020). Increasing central supervision's status can break the deficiencies of the inherent environmental decentralization system (Li and Xu, 2020). With the implementation of various policies regarding central supervision, its environmental governance effects have attracted scholarly inquiry. Pan et al., 2022 found environmental interviewing strategy under central supervision system can give certain deterrent pressure to polluters and significantly effectively mitigate water pollution. Zhang et al., 2018 assessed the implementation central supervision policy's impact. They suggested that central supervision can effectively empower supervision system and lower the amount of pollutants released into enterprises industrial effluent. Yuan et al., 2022 found that a central environmental inspection system reduce the pollutants in the air. Kou and Han found that the pressure exerted by the central government facilitated local supervision of enterprises' sulfur dioxide emissions (Kou and Han, 2021).

The environmental decentralization system gives more supervisory power to local governments (Liu and Yang, 2022). Local government officials may protect the polluting behaviour of local enterprises and lower the standard of public goods supply for the sake of GDP growth and personal promotion, resulting in

environmental degradation (Zhao et al., 2022). By measuring the carbon output in China, Ran et al., 2020 empirically found that local monitoring exacerbates the output. However, as the central government included environmental quality in the assessment criteria for local government officials and continued to strengthen environmental supervision, the environmental governance capacity of local environmental supervision was improved (Chen et al., 2022a). Zhang and Li, 2020 determined that local supervision has a supportive influence on green innovation by using the quantity of supervisors to quantify local supervision. Yuan et al., 2022 examined how the local supervision affects haze pollution. They emphasized the importance of local government supervisory power in environmental governance. Zeng et al., 2022a found a positive effect of local supervision on corporate investment in environmental protection.

2.2.3 The elements that affect green innovation

Green innovation is a creative activity that improves environmental performance and reduces environmental pollution (Wang et al., 2021). In the research on green innovation, an emphasis has been placed on exploring influencing elements. The elements that affect green innovation are as follows: environmental regulation (Peng et al., 2021; Yang et al., 2022), market forces (Qiu et al., 2020; Shao et al., 2022), and intrinsic elements of enterprises (Soewarno et al., 2019). Because environmental regulation aims to solve environmental problems and is intimately tied to green innovation, scholars are keen to study how it affects green innovation. The Porter hypothesis served as the foundation for the early studies: environmental regulation has the potential to stimulate corporate innovation. Green finance (Huang et al., 2022), environmental taxes (Wang and Yu, 2021), and national innovation cities (Zhang et al., 2022) are examples of environmental regulation which can encourage corporate green innovation. Studies opposing this view argue that Enterprises are burdened with costs by environmental regulations, so the regulations harm green innovation (Jin et al., 2019). For example, Chen et al. found that China's carbon emissions trading system squeezes the funds that enterprises spend on green innovation, hence hindering its development (Chen et al., 2021).

By combing through the literature, this paper finds that: 1. A wealth of research findings have emerged around the increasingly severe environmental problems. With the increase in government environmental supervision, numerous academics have investigated how central or local supervision affects pollution reduction and emission reduction. However, There are relatively few studies in the existing literature on how central and local supervision affects green innovation. There is no literature yet that includes central and local regulation and enterprises in the same framework for research. 2. The existing literature lacks in-depth studies on the quality improvement of central and local supervision on green innovation and the mechanism of the effect therein. Studies have paid less attention to the relationship between central and local supervision and ignored the joint role of the both. 3. Most of the existing literature has discussed the factors influencing green innovation. Enterprises facing environmental supervision may differ in different aspects of their environmental performance. Few studies have conducted comparative analyses of green innovation when different types of enterprises face environmental supervision. Few studies have also analyzed the impact of environmental supervision on substantive green innovation. Thus, this research investigates how central and local supervision individually and jointly influences green innovation of heavy polluters in Shanghai and Shenzhen A-shares in China between 2013 and 2019. It is also necessary to examine in detail the mechanism and heterogeneity and the effect of central and local supervision on the quality improvement of green innovation.

3 Theoretical analysis and research hypothesis

3.1 Central supervision and green innovation

This paper explains three aspects that central supervision affects green innovation. 1. The issue of information asymmetry between the government and heavy polluters can be mitigated through central supervision. Compared with the government, the operators of heavily polluting enterprises have more comprehensive and realistic information about pollution emissions and are advantageous among information users (Liu and Bai, 2022). Information asymmetry can lead to adverse selection and moral hazard (Chen et al., 2022b). Heavily polluting enterprises may conceal information to avoid the cost of environmental violations, making it impossible for the government to implement effective environmental supervision instruments (Ding et al., 2022). The government will install automatic pollution source monitoring equipment in the heavily polluting enterprises whose emissions exceed the standard. A list of national specially monitored enterprises includes these enterprises. The central government can have the first information about the heavy polluters' emission through the uninterrupted monitoring of the equipment (Fang et al., 2020). This environmental supervision measure reduces information asymmetry between governments and heavy polluters. The government supervises the actual situation of the heavily polluting enterprises. Thus, these enterprises must make green innovations and improve environmental governance to comply with environmental regulations. 2. Central supervision enables heavily polluting enterprises under pressure from the public. The public's environmental awareness is increasing with the seriousness of the environmental pollution situation. They will actively participate in environmental management activities to obtain a livable living environment (Zeng et al., 2022b). The government will publicize the list of national specially monitored enterprises. These enterprises with low environmental performance can easily attract public scrutiny. The public will demand that the government strengthen the supervision and disciplinary measures against the enterprises through complaints (Liu et al., 2023). In addition, the public will express dissatisfaction with their polluting environmental behaviours through social opinion and other means (Chu et al., 2022). The pressure from the public forces enterprises to maintain their reputation and image, undertake social responsibility and reduce pollution and emissions through green innovation and technological upgrading. 3. Central supervision will act as a deterrent to heavily polluting enterprises that are not under monitoring. National specially monitored enterprises will bear a high environmental cost due to pollution emission violations and be

fined by central supervision or even penalized by production reduction or suspension. These penalties will deter enterprises that are not under monitoring. These enterprises will be aware of the cost of violations due to inadequate environmental management (Zhang et al., 2018). Therefore, this deterrent effect will motivate them to green innovation to avoid the risk of environmental penalties. Accordingly, the hypothesis is suggested.

Hypothesis 1: Central supervision can promote green innovation among heavily polluting enterprises.

3.2 Local supervision and green innovation

Local supervision is a kind of formal environmental regulation. Under formal environmental regulatory constraints, heavily polluting enterprises internalize pollution externalities and incur pollution treatment costs (Wang et al., 2021). China has explicitly proposed to build a green innovation system and developed a series of policies to help enterprises to upgrade their industries to green. This reasonable formal environmental regulation can incentivize enterprises to work on green innovation, which will enhance resource efficiency and productivity (Wu et al., 2022). The expense of pollution mitigation may be offset by the green compensation that businesses gain via green innovation (Yang et al., 2020). In addition, Environmental governance has been evaluated as part of local governments' performance by the central.Thus, local governments have become stricter and stricter in supervising the enterprises in their areas. Strict environmental supervision means that the cost of non-compliance for heavily polluting enterprises increases and exceeds their cost of pollution control (Zhang and Li, 2020). Under the trade-off, enterprises will actively engage in green innovation and pursue green compensation to avoid high violation costs and meet local regulatory requirements. Accordingly, the hypothesis is suggested.

Hypothesis 2: Local supervision motivates heavy polluters to work on green innovation activities.

3.3 Moderating effect of central supervision

The central supervision's moderating effect is explained in three aspects: 1. Central supervision strengthens the importance of local government's environmental protection efforts. Previously, the central government used economic development as the key evaluation metric for local governments (Zhao et al., 2022). In order to achieve political performance, local officials only valued economic growth and neglected environmental protection efforts (You et al., 2019). Facing severe environmental pressure, the central government began to factor on the environment when evaluating local governments (Wen and Lee, 2020). The evaluation of the success of local governments will increasingly depend on emission statistics from central supervision. Thus, the local will improve the efficiency of environmental supervision of heavy polluters. 2. Central supervision signals to local governments that higher-level governments attach importance to environmental protection (Zhang et al., 2018). In turn, subsidies, tax incentives, technology, and other resources to secure green innovation activities for heavy polluters will be provided by local governments. These resources will motivate heavy polluters to actively work on green innovation activities and enhance their environmental sustainability. 3. Local governments dominate environmental decentralization framework, and the central government does not understand the complete picture of local governments' environmental governance efforts (Yang et al., 2021). Through pollution source monitoring equipment, the central government can accurately obtain the emission data of heavy polluters and grasp the local environmental governance (Zhang et al., 2018). This supervisory approach addresses the issue of information asymmetry between central and local, and strengthen local supervision. Accordingly, the following hypothesis is suggested.

Hypothesis 3: Local supervision's effect on heavily polluting enterprises' green innovation is positively moderated by central supervision.

4 Research design

4.1 Sample selection and data sources

Considering the availability of data and the fact that the measurement criteria of PITI have changed since 2013, this paper uses the heavy polluters in Shanghai and Shenzhen A-shares from 2013-2019 as the research sample. This paper selects the heavy polluters according to the List of Industry Classification and Management of Environmental Verification of Listed Companies published by the Ministry of Environmental Protection in 2008. Heavily polluting enterprises are those with high waste emissions and serious environmental pollution, and are identified in thermal power, cement, coal and other 16 industries. For the reliability of the research results, this paper treats the data as follows: 1. Exclude the enterprises marked with ST, *ST, and PT. 2. Exclude the newly listed enterprises after 2013. 3. Exclude the enterprises whose primary business has changed significantly during the study period. 4. Exclude the enterprises with missing severe data. 5. Select the enterprises whose registered places are in the 120 cities in the PITI report. 6. To eliminate the effect of extreme values, the up and down 1% tail reduction was performed for all continuous variables. After data processing, this paper obtained 2583 sample observations from 369 heavily polluting enterprises. The data sources are: 1. The green patent data are from CNRDS. 2. The data on whether or not the heavily polluting enterprises are under national monitoring is from CSMAR. 3. PITI is from the annual report by IPE and NRDC. 4. The other financial data are from CSMAR.

4.2 Variable definition

4.2.1 Green innovation

Green patents can effectively demonstrate enterprises' green innovation (Fu et al., 2023). The amount of green patent applications of an enterprise and its subsidiaries is utilized to indicate green innovation (*GP*) according to the existing study (Yang et al., 2022; Yang et al., 2022; Liu and Dong, 2022). The

TABLE 1 Variable definitions.

Variable type	Variable	Symbol	Meaning
Explained variable	Green innovation	*GP*	The amount of green patent applications of the enterprise and its subsidiaries
Explanatory variable	Central supervision	*CS*	If the enterprise belongs to the national specially monitored enterprise, the variable is 1; otherwise, 0
	Local supervision	*LS*	PITI of the city where the enterprise is registered
Control variable	Enterprise size	*Size*	Natural logarithm of the total assets of the enterprise
	Enterprise age	*Age*	Natural logarithm of the number of years the enterprise has been in existence
	Return on total assets	*Roa*	Net profit/Average total assets
	Debt status	*Debt*	Natural logarithm of total liabilities
	Dual chairman and general manager status	*Dual*	If the chairman and general manager are the same person, the variable is 1; otherwise, it is 0

data on enterprises' green patents were obtained from Chinese Research Data Services (CNRDS) which takes the patents of listed enterprises from the World Intellectual Property Organization (WIPO).Therefore, this paper's green patent application data are accurate and reliable.

4.2.2 Central supervision

The Chinese Ministry of Ecology and Environment regularly selects and publishes a list of specially monitored enterprises. Zhang et al. use this item as a proxy variable for central supervision (*CS*). We refer to this method and measure the central supervision variable by whether the enterprises are part of the national monitoring (Zhang et al., 2018). The *CS* takes the value of 1 if the heavily polluting enterprise is under national monitoring. If the enterprise is not under monitoring, the *CS* takes the value of 0. The National specially monitored enterprises are installed with pollution source monitoring equipment, and the central environmental protection department supervises their pollution emission data. Suppose an enterprise has emission violations. In that case, the central environmental protection department will pressure the local government directly and punish the violating enterprises. If the heavily polluting enterprises are not under national monitoring, they are mainly supervised by the local government. It can be seen that the measure of the *CS* variable chosen in this paper has theoretical and practical bases.

4.2.3 Local supervision

This paper measures the level of local supervision (LS) using the Pollution Information Transparency Index (PITI) in 120 cities made public by the Institute of Public and Environmental Affairs (IPE) and the Natural Resources Defense Council (NRDC). PITI assesses local government participation in environmental supervision from various aspects, such as online monitoring information disclosure, enterprises' emission data and violation record release. Therefore, the PITI is a tool that can effectively reflect the strength of environmental protection supervision conducted by local governments (Tu et al., 2019).

4.2.4 Control variable

Based on existing studies (Li et al., 2020; Liu et al., 2022), enterprise size (*Size*), enterprise age (*Age*), return on total assets (*Roa*), debt status (*Debt*), and dual chairman and general manager status *(Dual*) are utilized as control variables. The specific definitions of the variable used are shown in Table 1.

4.3 Research model construction

The following models are constructed in this paper.

1. To test how central supervision affects green innovation, model (1) is constructed.

$$GP_{i,t} = \alpha + \beta_0 CS_{i,t} + \beta_1 X_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

2. To test how local supervision affects green innovation, model (2) is constructed.

$$GP_{i,t} = \alpha + \beta_0 LS_{i,t} + \beta_1 X_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (2)$$

3. To test the joint influence of central supervision and local supervision on green innovation, model (3) is constructed.

$$GP_{i,t} = \alpha + \beta_0 CS_{i,t} + \beta_1 LS_{i,t} + \beta_2 X_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (3)$$

4. To test the positive moderating effect of central supervision, model (4) is constructed.

$$GP_{i,t} = \alpha + \beta_0 CS_{i,t} + \beta_1 LS_{i,t} + \beta_2 CS_{i,t} \times LS_{i,t} + \beta_3 X_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (4)$$

The meaning of the indicators in the models is as follows: 1. i and t represent the enterprise and year, respectively; 2. α represents the constant term; 3. β is the regression coefficient; 4. *GP* is the explanatory variable, indicating the green innovation; 5. *CS* and *LS* represent the explanatory variables central and local supervision, respectively; 6. *X* represents the control variable; 7. γ and μ represent the enterprise fixed effect and year fixed effect, respectively; 8. ε is the error term.

TABLE 2 Descriptive statistics.

Variable	N	Mean	Sd	Min	P25	P50	P75	Max
GP	2583	1.004	1.260	0	0	0.693	1.792	7.405
CS	2583	0.395	0.489	0	0	0	1.000	1.000
LS	2583	54.355	15.973	15.300	43.100	55.700	67.000	80.800
Size	2583	22.693	1.389	19.889	21.729	22.474	23.634	26.599
Age	2583	2.831	0.341	1.386	2.639	2.890	3.045	3.401
Roa	2583	0.040	0.060	−0.175	0.010	0.034	0.068	0.234
Debt	2583	21.740	1.753	17.885	20.475	21.541	23.024	26.020
Dual	2583	0.185	0.389	0	0	0	0	1.000

TABLE 3 Results of the main regression.

Model	(1)	(2)	(3)	(4)
Variable	*GP*	*GP*	*GP*	*GP*
CS	0.106*** (0.0389)		0.103*** (0.0391)	0.0962** (0.0393)
LS		0.00455* (0.00234)	0.00430* (0.00235)	0.00434* (0.00236)
CS×LS				0.00374* (0.00212)
Size	0.395*** (0.0757)	0.404*** (0.0760)	0.397*** (0.0756)	0.396*** (0.0755)
Age	−0.254 (0.280)	−0.302 (0.280)	−0.263 (0.281)	−0.252 (0.282)
Roa	0.425 (0.292)	0.379 (0.291)	0.421 (0.292)	0.429 (0.292)
Debt	−0.101** (0.0508)	−0.107** (0.0508)	−0.104** (0.0507)	−0.104** (0.0507)
Dual	−0.0714 (0.0500)	−0.0647 (0.0499)	−0.0697 (0.0501)	−0.0757 (0.0501)
Constant	−5.080*** (1.246)	−5.225*** (1.248)	−5.265*** (1.247)	−5.296*** (1.247)
Observations	2,583	2,583	2,583	2,583
R-squared	0.777	0.776	0.777	0.777
Enterprise fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

5 Results and discussions

5.1 Descriptive statistics

Table 2 presents the results of descriptive statistics of the main variables of the sample of heavily polluting enterprises. In total, there are 2583 observations in the sample. The 25% quantile of the green innovation (*GP*) is 0, and the median is 0.693. The result indicates that more than 25% and less than 50% of the enterprises in the sample did not apply for green patents. Thus, there is room for improving green innovation. In addition, the minimum, maximum, and standard deviation of *GP* are 0, 7.405, and 1.260, respectively, indicating disparities in the level of green innovation among enterprises. The remaining variables results are within reasonable limits.

5.2 Analysis of the main regression results

Model (1) in Table 3 displays the regression results of central supervision on green innovation. The coefficient of the central supervision (*CS*) in the model (1) is 0.106, indicating significantly positive at the 1% level. Considering the joint influence of central and local supervision, this paper constructs model (3) after adding the local supervision variable (*LS*) to model (1). In model (3), the coefficient of central supervision (*CS*) is 0.103, indicating significantly positive. The regression results in the model (1) and model (3) indicate that central supervision can improve the green innovation level of heavy polluters. Hypothesis 1 is proved. This result somewhat corroborates the findings (Du et al., 2022). Possible explanations for these results are that: 1. Central environmental authorities alleviate the information asymmetry between central and

TABLE 4 Robustness test.

Model	(1)	(2)	(3)	(4)
Variable	*GP*	*GP*	*GP*	*GP*
CS	0.112*** (0.0390)		0.109*** (0.0392)	0.102*** (0.0394)
LS		0.00444* (0.00235)	0.00416* (0.00236)	0.00420* (0.00236)
CS×LS				0.00354* (0.00211)
Size	0.392*** (0.0758)	0.401*** (0.0761)	0.394*** (0.0757)	0.394*** (0.0755)
Age	−0.273 (0.282)	−0.323 (0.282)	−0.282 (0.283)	−0.272 (0.283)
Roa	0.416 (0.292)	0.368 (0.290)	0.413 (0.292)	0.420 (0.292)
Debt	−0.100** (0.0508)	−0.106** (0.0508)	−0.103** (0.0507)	−0.103** (0.0507)
Dual	−0.0786 (0.0501)	−0.0716 (0.0501)	−0.0769 (0.0502)	−0.0826 (0.0502)
Constant	−4.978*** (1.249)	−5.116*** (1.251)	−5.158*** (1.249)	−5.187*** (1.249)
Observations	2,583	2,583	2,583	2,583
R-squared	0.777	0.776	0.777	0.778
Enterprise fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

heavily polluting enterprises by installing pollution source monitoring equipment. Heavy polluters find it difficult to conceal the actual emission data. Therefore, enterprises must improve their production efficiency and gain revenue through active green innovation. Otherwise, enterprises need to bear the cost of non-compliance. 2. Central supervision makes the situation of heavy polluters more open and transparent. Violating enterprises will be under public pressure. They need to reduce pollution emissions through green innovation through green innovation and alleviate the conflict with the public. 3. The development of the list of national specially monitored enterprises will deter the heavy polluters, and this deterrent motivates them to upgrade their technology and improve their green innovation to avoid environmental violations.

Model (2) in Table 3 shows the coefficient of local supervision (*LS*) is significantly positive. This paper adds the central supervision variable (*CS*) to model (2) and constructs model (3). In model (3), the coefficient of local supervision (*LS*) is still significantly positive. Therefore, local supervision can motivate heavy polluters to work on green innovation, and hypothesis 2 holds. Comparing the magnitude of the absolute value of the coefficient of central supervision (*CS*), this paper also finds the promotion ability of local supervision is weaker than that of central supervision. This result agrees with some of the outcomes (Zhao and Chen, 2022), which show that the power of local supervision contributes to sustainability. The possible explanation is that enterprises will actively engage in green innovation and pursue green compensation to avoid high violation costs and meet local regulatory requirements.

Model (4) of Table 3 reports the moderating effect of central supervision. This paper decentralizes *CS* and *LS* and constructs the interaction term (*CS* × *LS*). The result shows the regression coefficients of the term (*CS* × *LS*) and local supervision (*LS*) are both significantly positive. It indicates that central supervision strengthens the promotion of local supervision on the green innovation. Thus, hypothesis 3 holds. This result is partially the same as the outcomes (Zhang et al., 2018). The possible reasons are: 1. The central government assesses the environmental governance performance of local governments based on the emission data of national specially monitored enterprises. The local will improve the environmental supervision. 2. As the central focuses more on environmental protection, the local will provide guarantees for heavy polluters such as capital, tax incentives, and technical equipment. These guarantees help the green innovation activities of heavy polluters. 3. Central supervision enables the central to understand the level of work of local supervision and makes local governments feel the pressure to strengthen local supervision. In addition, the regression coefficients of central supervision (*CS*) and local supervision (*LS*) are significantly positive, further verifying hypotheses 1 and 2.

5.3 Robustness test

Referring to the method (Cao and Zhang, 2023), this paper performs the robustness tests. The amount of green patent applications (*GP*) of the enterprise, with its subsidiaries and joint ventures, is utilized as a proxy variable for green innovation. Columns (1) and (3) of Table 4 indicate the regression coefficients of central supervision (*CS*) are significantly positive. This result proves hypothesis 1. Columns (2) and (3) indicate that the regression coefficients of local supervision (*LS*) are significantly positive. This result supports hypothesis 2. The coefficients of the term (*CS* × *LS*), as well as local supervision

TABLE 5 Analysis of regional heterogeneity.

Variable	Eastern region sample		Non-eastern region sample	
	GP	*GP*	*GP*	*GP*
	(1)	(2)	(3)	(4)
CS	0.118** (0.0591)	0.0192 (0.0822)	0.0898* (0.0503)	0.0505 (0.0585)
LS	0.00854** (0.00390)	0.00983** (0.00403)	−0.00252 (0.00289)	−0.00227 (0.00287)
CS×LS		0.00889** (0.00443)		−0.00431 (0.00348)
Size	0.603*** (0.118)	0.597*** (0.117)	0.258** (0.101)	0.255** (0.102)
Age	−0.727** (0.364)	−0.700* (0.368)	0.230 (0.447)	0.209 (0.450)
Roa	0.0849 (0.416)	0.0741 (0.413)	1.008** (0.418)	0.979** (0.415)
Debt	−0.164** (0.0686)	−0.156** (0.0681)	−0.0519 (0.0774)	−0.0498 (0.0775)
Dual	−0.170*** (0.0641)	−0.173*** (0.0644)	0.0243 (0.0809)	0.0285 (0.0811)
Constant	−7.537*** (1.912)	−7.713*** (1.925)	−4.457** (1.743)	−4.360** (1.752)
Observations	1,428	1,428	1,155	1,155
R-squared	0.796	0.797	0.744	0.744
Enterprise fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

(*LS*) in column (4), are significantly positive. This result indicates that local supervision's effect on heavy polluters' green innovation is positively moderated by central supervision and demonstrates hypothesis 3. The robustness test results are essentially compatible with the main regression results, indicating the study results' robustness.

6 Further research

6.1 Analysis of regional heterogeneity

Economic development and resource allocation are uneven across China's regions. The governments will adjust the strength of supervision according to the actual economic level of each region. In addition, each region's different resource endowments also affect the green innovation level. Therefore, this paper argues that there is a need to test regional heterogeneity's impact on enterprises' green innovation. The whole sample is separated into two groups, the eastern and non-eastern region, according to the region where the enterprises are registered, and then performs grouped regressions. The results in Table 5 show that: 1. This paper compares the results of the two groups in column (1) and column (3). The regression coefficients of central supervision (*CS*) and local supervision (*LS*) in the eastern region group are significantly positive and more prominent than those in the non-eastern region. This result indicates regional heterogeneity, with a more pronounced promotion effect in the eastern region. 2. This paper compares the results in columns (2) and (4). The interaction term ($CS \times LS$) and local supervision (*LS*) regression coefficients are both significantly positive in the eastern region sample and negative and insignificant in the non-eastern region sample. This result suggests the positive moderating effect of central supervision is more pronounced in the eastern region. The possible explanations for the above results are: 1. The economy is more prosperous in the eastern region of China. The government will have more effort in environmental management work, environmental protection supervision will be more strict, and the penalty for violation of enterprises will be more substantial. The non-eastern regions of China have a more backward economy and will rely more on heavily polluting enterprises. The government will focus its efforts on the economy rather than the environment, and therefore government environmental supervision will be weaker. 2. Compared with the non-eastern region, the eastern region has superior resources, such as talents, technology, and transportation. These excellent resource conditions can support heavily polluting enterprises to make green innovations.

6.2 Analysis of the quality of green innovation

According to the quality of innovation, there are two types of innovation: substantive and strategic (Jiang and Bai, 2022). Substantive innovations are of great difficulty and can achieve technological progress. Strategic innovations are of low difficulty. Enterprises often respond to government environmental supervision through strategic innovations. Whether central and local supervision can enhance the quality of green innovation needs further research. Generally speaking, the quality of green invention patents is high, and the technical content of utility patents is low. Therefore, this paper refers to the approach (Liu and Dong,

TABLE 6 Analysis of the quality of green innovation.

Variable	*GIP*		*GUP*	
	(1)	(2)	(3)	(4)
CS	0.0715** (0.0331)	0.0619* (0.0333)	0.0728** (0.0351)	0.0701** (0.0353)
LS	0.00501** (0.00203)	0.00507** (0.00202)	0.000351 (0.00198)	0.000370 (0.00198)
CS×LS		0.00547*** (0.00181)		0.00157 (0.00192)
Size	0.389*** (0.0668)	0.389*** (0.0665)	0.180*** (0.0600)	0.180*** (0.0600)
Age	−0.310 (0.222)	−0.295 (0.221)	−0.230 (0.237)	−0.226 (0.237)
Roa	0.547** (0.239)	0.558** (0.240)	−0.00282 (0.249)	0.000456 (0.249)
Debt	−0.129*** (0.0434)	−0.129*** (0.0434)	−0.0139 (0.0397)	−0.0139 (0.0397)
Dual	0.0268 (0.0424)	0.0181 (0.0426)	−0.120*** (0.0428)	−0.122*** (0.0428)
Constant	−4.772*** (1.024)	−4.817*** (1.021)	−2.516** (1.062)	−2.529** (1.064)
Observations	2,583	2,583	2,583	2,583
R-squared	0.775	0.776	0.737	0.738
Enterprise fixed Effects	Yes	Yes	Yes	Yes
Year fixed Effects	Yes	Yes	Yes	Yes

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

2022) to measure substantive innovation (*GIP*) and strategic innovation (*GUP*) by the number of applications for green invention patents and utility patents, respectively.

Column (1) of Table 6 shows that the coefficient of central supervision (*CS*) on substantive green innovation (*GIP*) is 0.0715, which is significantly positive, indicating that central supervision can enhance the quality of green innovation. Column (1) shows that the regression coefficient of *LS* on *GIP* is significantly positive. However, its regression coefficient on strategic green innovation (*GUP*) in column (3) is insignificant. The result indicates that local supervision significantly enhances the substantive innovation of heavily polluting enterprises but not the low-quality strategic innovation. After adding the interaction term (*CS* × *LS*) to the model, column (2) shows that the coefficients of both the interaction term and local supervision on substantive innovation are significantly positive. However, neither of their regression coefficients on strategic innovation in column (4) is significant. This result suggests that central supervision plays a positive moderating role in the effect of local supervision on enterprises' substantive innovation but not on strategic innovation.

The above results align with some of the outcomes (Zhang and Huang, 2022). The possible reasons are: 1. Substantive innovation is a high-quality innovation (Liu et al., 2022). Facing collaborative supervision by the central and local governments, heavy polluters need to work on green innovation to upgrade their emission technologies and circumvent the costs of environmental violations. In addition, heavily polluting enterprises need to make their green compensation benefits from green innovation need to exceed the cost of pollution treatment. Substantial innovation can help enterprises achieve breakthroughs in green innovation technology. Only through this high-quality green innovation approach can enterprises meet environmental protection requirements while gaining more compensation benefits and achieving increased financial profits. 2. Environmental supervision makes the emission information of heavy polluters more open and enables the central to effectively grasp local environmental governance. The low-quality strategic green innovation can not help enterprises reduce pollution emissions. Due to the environmental performance assessment and the pressure of central supervision, local governments will increase their supervision, making heavily polluting enterprises carry out substantial green innovations instead of strategic ones.

7 Research conclusions and policy implications

7.1 Research conclusion

The general background of green development will empower the technology upgrade and green transformation of heavy polluters. Central and local governments thoroughly perform the function of environmental supervision, which is vital to motivate green innovation of heavy polluters Thus, this paper selects data from A-shares in China from 2013 to 2019 and examines how central and local supervision affects green innovation of heavy polluters The research conclusions are that: 1. Central supervision can motivate heavy polluters to work on green innovation. Possible explanations are: 1) Central supervision alleviate the information asymmetry between central and heavy polluters. 2) Central supervision will expose enterprises' polluting behaviour and prompt public participation in environmental governance. Enterprises, pressured by environmental legitimacy, will defend their image and engage in green innovation to improve their environmental performance. 3) The high cost of non-compliance has a

deterrent effect on enterprises. 2. Local supervision also has a promoting effect on enterprises. The effect of local supervision is weaker than that of central supervision. The possible explanation is that enterprises will pursue green compensation to avoid high violation costs and meet local regulatory requirements. 3. Central and local supervision can work together, and local supervision's effect on heavily polluting enterprises' green innovation is positively moderated by central supervision. Central supervision will make the local feel the pressure of environmental management and also can alleviate the problem of information asymmetry between the central and local. Under central supervision, local governments will provide guarantees for heavy polluters such as capital, tax incentives, and technical equipment. These guarantees help the green innovation activities of heavy polluters. 4. There is regional heterogeneity in the environmental governance effects of central and local supervision. Specifically, the two types of supervision can motivate eastern enterprises to work on green innovation. However, they have no positive impact on non-Eastern enterprises. In addition, the positive moderating impact of central supervision exhibits the same regional heterogeneity. Due to the difference in economic levels between China's eastern and non-eastern regions, the government has more strict environmental supervision in the east. The eastern region has superior resources and can better help enterprises with their green transformation. 5. Both types of supervision can empower high-quality green innovation, i.e., substantial green innovation, among heavy polluters. Moreover, central supervision can strengthen the impact of local supervision on enterprises' substantive green innovation. Substantial innovation can help enterprises obtain more green compensation and achieve the real green transformation. Therefore, local governments tend to prompt heavy polluters to engage in substantive green innovation rather than strategic innovation.

7.2 Policy implications

Based on the findings, this paper proposes the policy implications: 1. Environmental supervision should be an active responsibility of the central government. The central should establish a more open and complete system for supervising pollution emission information, to fully grasp the pollution situation of heavy polluters and alleviate the information mismatch issue. The central government should also develop an environmental disclosure system to accompany the supervisory system so that the emission situation of heavily polluting enterprises can receive more attention and supervision at the social level. 2. The state should optimize the environmental decentralization system so that central and local supervision cooperation can play the best role. The central should be more stringent in monitoring the environmental protection work of the local, which in turn will lead to the efficient implementation of local supervision. In the meantime, the central government should establish a more scientific approach to environmental performance assessment and increase its weighting, thus giving local governments more incentive to carry out environmental supervision. 3. The government need establish environmental regulations that take into account the unique circumstances of each location. The government need facilitate the transformation of industrial structure in non-eastern regions and optimize the status of over-reliance on heavily polluting enterprises for economic development.The government also needs to provide more resource support, such as talent, technology, and capital, for enterprises in non-eastern regions. 4. The local need strengthen environmental protection. On the one hand, the local should improve the quality and strength of supervision so that enterprises must engage in green innovation to avoid the high cost of violations. On the other hand, local governments should provide a favourable climate for heavy polluters to work on substantial green innovation and support them with government subsidies, tax incentives, and lenient financing conditions. 5. Heavy polluters should change their production concept, strictly comply with the environmental supervision system in their production process, and control the emission of pollutants at the source. Heavy polluters should take responsibility for environmental protection, actively disclose information on pollution emissions and accept central and local supervision. Heavy polluters should comply with regulations, accept rectification and regulations, and bear the violation cost in case of exceeding emission standards. 6. Heavy polluters should allocate funds reasonably and prepare enough funds for conducting green innovation. At the same time, heavy polluters can respond to the government's call to obtain funds such as green subsidies and tax incentives. In addition, heavy polluters should also maintain their image, cater to the needs of the market, produce green products, and obtain more green revenue while reducing pollution and emission reduction. 7. The public needs to actively participate in environmental management, establish the concept of environmental protection, and form the awareness of green living and supervision of heavy polluters. The public can use appropriate supervision channels to reflect environmental violations to the government.

7.3 Research limitations and future perspectives

The research limitations are as follows: 1. The published Pollution Information Transparency Index (PITI) is until 2019. This paper only studies data from 2013 to 2019 but needs a longer sample period to study the environmental governance effects of current central and local supervision. 2. This paper only studies listed enterprises due to data availability. Non-listed enterprises in heavily polluting industries also pollute the environment. Thus, the future research perspectives are as follows: 1. Change the measurement of local supervision. 2. Extend the research sample period. 3. Include non-listed enterprises in the research sample.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GY: Conceptualization, methodology, data collection, data curation, writing original draft and editing. JJZ: Validation,

writing—review, funding acquisition. JZZ: Methodology, data curation, editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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