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The impact of eco-innovation on environmental performance in different regional settings: new evidence from Chinese cities

Lichao Wu[1] · Lili Wang[2] · Niels J. Philipsen[3,4] · Xinyi Fang[1]

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Abstract

Eco-innovation is crucial for pollutants emissions reduction and environmental improvement. However, little is known on how it functions in relation to different technology capabilities and regulations. Using economic and environmental information collected for 285 Chinese cities in the period of 2005–2017, this paper investigates how eco-innovation functions in different contexts. First, different from the existing literature that has mainly focused on direct eco-innovation, our study shows that indirect eco-innovation—spillovers from other regions—can have an even greater impact than direct eco-innovation. This demonstrates the importance of absorbing eco-innovation spillovers from other regions to reduce the amount of pollutants and strengthen environmental performance, in particular for regions without sufficient local R&D capabilities. Second, this study investigates how different kinds of environmental regulation can function differently in stimulating new eco-innovation, which stresses the importance of differentiated instruments in incentivizing firms to adopt eco-innovation and maximize their contributions to environmental performance. In addition, our study also emphasizes the role that cities' financial development plays in influencing the connection among eco-innovation, different kinds of environmental regulation and environmental performance. An understanding of these mechanisms is critical for the government to improve eco-innovation activities accordingly and make policies that fit specific regional contexts.

Keywords Eco-innovation · Spillovers · Environmental regulation · Environmental performance

✉ Lichao Wu
xmwulichao@163.com

Lili Wang
l.wang@maastrichtuniversity.nl

1 Department of International Economics and Business, Xiamen University, Xiamen 361005, People's Republic of China

2 UNU-MERIT, Maastricht University, 6211 AX Maastricht, The Netherlands

3 METRO, Maastricht University, Bouillonstraat 1-3, 6211 LH Maastricht, The Netherlands

4 RILE, Erasmus University Rotterdam, Burgemeester Oudlaan 50, 3062 PA Rotterdam, The Netherlands

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1 Introduction

Eco-innovation is novel and valuable for achieving resource conservation or environmental improvement, which is essential for green development (Valero-Gil et al., 2023). Literature has shown that innovation capabilities and R&D resources have been crucial factors in improving environmental performance (Zhang et al., 2017). Hence, not surprisingly, the related studies (Santoalha & Boschma, 2021; Zhang et al., 2017) on eco-innovation have been mostly limited to regions/nations that are technologically capable of conducting innovation. However, this involves a question of how technologically less capable regions can reach carbon emissions abatement. After all, despite the unbalanced regional development and unequal innovation capability that has been discussed in related research (Horbach & Rammer, 2018), climate change and environmental degradation are global concerns. Maintaining a sustainable development mode is the grand challenge not only for regions/cities that are capable of developing eco-innovation but also for those that are unable to develop their own green technologies due to capability constraints.

Indirect eco-innovation transferred from other regions/cities may offset the lack of local innovative capabilities. However, the indirect effect of eco-innovation to other regions/cities has so far been hardly explored (Costantini et al., 2013). While the existing research on the influencing elements of the eco-innovation activities is increasing, the regional perspective is under researched (see Filiou et al., 2023 as exceptions). Zhang et al. (2017) assess how regional carbon emissions is influenced by eco-innovation based on provincial-level data of China, and find that different eco-innovation measures help CO_2 emissions reduction effectively. Our paper will further take the technology spillovers effect between regions into consideration. We aim to provide insights on the role that eco-innovation spillovers play in China, where innovation capabilities vary greatly across regions. We examine whether eco-innovation and eco-innovation spillovers can improve environmental performance.

Besides innovation capability, which represents the technology-push side in the Schumpeterian theory, environmental regulation (representing the regulatory push effect) can incentivize firms to undertake a series of innovation-related activities and produce environmentally friendly or resource-saving products (Ren et al., 2018). Nevertheless, the well-known Porter Hypothesis states that not all environmental regulations contribute to innovative development—only the "well-designed" ones can do so (Ambec et al., 2013). The next question would then be: what are "well-designed" environmental regulations? It is noteworthy that environmental regulation of distinct kinds may perform various impacts and even the same regulation may impact innovative activities in different ways (Blind, 2012). To this end, this research is aimed at providing an in-depth analysis of differentiated environmental regulations, in order for government to improve eco-innovation activities, and to make better policies on regional technological development and environmental improvement.

Empirically, this paper analyses the joint effects of environmental regulation of different kinds and regional eco-innovation on environmental performance in 285 cities of China spanning from 2005 to 2017. As one of the most dynamic emerging economies, which develops at a rapid speed, China is facing severe environmental challenges. Being one of the fast-industrializing nations, China's coal power generation and emissions from coal consumption power raised by about 15% and 3%, respectively, in 2022.[1] Under these circumstances, China has put more emphasis on energy conservation and emissions reduction. With China committing to achieve its CO_2 emissions peak in 2030 and then achieve its carbon neutrality in 2060, eco-innovation crucially contributes to the balance between economic growth and emissions abatement. Moreover, China can be considered as an interesting case for studying the eco-innovation effect because of the distinctions between various cities in terms of their economic development.

The contributions of this study are twofold: First, we add a supplement and enrichment to eco-innovation relevant research (Horbach & Rammer, 2018) by exploring the effects of direct as well as indirect eco-innovation on regional environmental performance, focusing on cities in emerging economies. This focus is original as the externality and eco-innovation indirect impact on other regions/cities has so far been hardly explored. Indirect eco-innovation transferred from other regions/cities may exert a critical impact on offsetting the lack of local innovation capabilities. We aim to underline the performance of eco-innovation spillovers to solve climate change and environmental degradation problems in China. Because innovative capabilities vary greatly across regions in China, we further include regions with different levels of financial performance in our analysis. Second, we contribute to the environmental policy debate in development related research (Filiou et al., 2023) by examining how environmental regulation of different types can function differently in Chinese cities, and whether financial restrictions can influence the joint effects of regional eco-innovation and environmental regulation.

2 Hypotheses development

2.1 Direct and indirect effects of eco-innovation

Towards reaching the goal of sustainable development, eco-innovation is attracting more and more attention (Filiou et al., 2023). In exploring the relation between environmental performance and eco-innovation, it is crucial to note that innovation capabilities vary greatly across regions/cities, particularly in emerging economies. The most straightforward instrument to improve environmental performance of one region is considered to be local eco-innovation (Valero-Gil et al., 2023). Hence most of the existing studies mainly focus on technologically strong regions and study the direct effect of eco-innovation in those regions. However, considering also the positive externalities of technological innovation—known as technology spillovers that may occur, it is important to understand whether one region (without sufficient innovation capability) can benefit from eco-innovation generated by other regions.

Technology spillovers can promote the learning effect, internal innovation and information communication between firms. Firms can learn new technologies, management practices and process production upgrading through technology spillovers, which is relate to the identification and use of external technologies into firms' own innovative activities (Aldieri et al., 2021). By making use of these advanced technology flows, firms can enhance their internal innovation capabilities. In addition, technology spillovers contribute to knowledge sharing and information communication in the course of contacts and mutual exchanges between firms. According to a case study in China, the spillover effects in provinces with

[1] https://www.iea.org/reports/co2-emissions-in-2022.

high economic agglomeration are relatively high due to the adequate R&D input and knowledge, close geographic distance and market integration, which help to promote emissions reduction in those regions (Cheng et al., 2017). Other literature examines spillover effects from the industrial or firm-level perspective, and additionally there is some literature studying green technology spillovers specifically. Perino and Requate (2012) propose the technological spillovers green production hypothesis. These positive spillover impacts are related to information communication and education attainment. Wang et al. (2021) attach great significance to green technology spillovers which exert a vital role in encouraging internal innovation, inventing new green products, and improving cleaner-production processes. By using various technologies, firms can learn and absorb advanced knowledge and prepare for further technology production and innovation.

Innovation is space dependent, which is manifested in the spatial flow of knowledge or skills and the cross regional linkage of its effects. However, the dissemination of knowledge and technology is not instantaneous or unlimited, because knowledge diffusion channels are territorialized. Spatial spillover is the process of sharing intellectual results through information interchange across geographical units. The spatial correlation and interaction between regions enable technical progress to have spatial spillover effects. Meanwhile, geographical proximity is often believed to be the fundamental factor facilitating technology spillovers (Horbach & Rammer, 2018). Particularly the spillover effect through spatial proximity could be improved if regions are technologically similar. As a localized public good, knowledge, especially tacit knowledge, has strong regional characteristics. Based on geographical view, two regions are closer, information communication are greater so that more opportunities will arise for knowledge and technology spillovers. The proximity and similarity of regions can effectively promote knowledge spillovers as the intensity of spatial spillover decreases with the increase of distance. Keller's study (2002) on the diffusion effect of technology among OECD member countries shows that the dissemination of technical innovation falls by 50% when the distance between nations increases by 1200 km. As the connections among regions are getting closer, the eco-innovation spillovers may have greater impact on decreasing environmental pollution and improving regional environmental performance.

Our research covers not only eco-innovation direct effect in one city but also the indirect effect across different regions, aiming to provide insights on the role that eco-innovation plays in cities where innovation capabilities are different. Taking both direct and indirect eco-innovation into consideration, here we develop the following two hypotheses:

Hypothesis Ia Eco-innovation can decrease environmental pollution and strengthen environmental performance.

Hypothesis Ib Eco-innovation spillovers can decrease environmental pollution and strengthen environmental performance.

2.2 Environmental regulation

Environmental regulation is considered as one of indispensable instruments to enhance eco-innovation activities as well as firm economic and ecological performance, which is known as the effect of "regulatory push" (Ren et al., 2018). The firms are driven by environmental regulation to distribute a part of their input (e.g. labor, capital) to pollution reduction, providing environmental benefits to society. The Porter Hypothesis argued that the government environmental regulation which is properly designed would bring about a scenario known as "win–win" (Porter & Linde, 1995), that is, firms simultaneously achieve competitiveness and generate green products, challenging the conventional wisdom. Eco-innovation is characterized by the "double externality" which discusses the case that both environmental and technology externalities reduce incentives and bring about suboptimal investments in eco-innovation, providing a reason for environmental regulation (Song et al., 2020). Technological innovation can be hindered by relaxant environmental regulation, while the stringent instruments can effectively stimulate it (Faure & Partain, 2019).

Most firms tend to take environmental concerns into consideration conditional only on the existence of certain environmental regulations (Perino & Requate, 2012). Lacking of government intervention, firms will maximize profits without taking into account external costs of their productive activities on the environment and society, thereby generating negative externalities and hindering environmental sustainability (Faure & Partain, 2019). A broad set of instruments can help induce eco-innovation to overcome these problems and advance the green technologies' production and diffusion (Ren et al., 2018). This can be profitable for firms if they can achieve efficiency gains or can profit from new market opportunities, thereby reshaping their images as environmentally-friendly firms and attracting consumers (Horbach & Rammer, 2018). Environmental regulation at the regional level can also help strengthen a region's capabilities leading to greater green specialization and green technologies diffusion (Santoalha & Boschma, 2021).

Environmental regulations are usually categorized into command-and-control type and market-based type.[2] The former type refers to ambient, performance-based and technology-based standards, etc. (Faure & Partain, 2019). Recent research on eco-innovation highlights the important role of command-and-control environmental regulation in stimulating eco-innovation (Filiou et al., 2023). Different from the former type of environmental regulation, market-based instruments (also called economic instruments) are usually in the form of environmental taxes, various subsidies, tradable permits and refund/deposit systems. Although some research suggests that the former regulation can boost firms' innovation, while market-based instruments have no significant influence (Zhao et al., 2015), while other literature points out that market-based instruments are superior in decreasing pollutants emissions compared to the former ones because of cost-efficiency and insists that market-based instruments serve as more valid ways of addressing pollution in India (Harrison et al., 2015). Yet another group of studies focuses on the interaction between the two distinct environmental regulation, suggesting that we often need a mix of both in order to efficiently internalize environmental externalities (Erp et al., 2019).

We predict that both types of environmental regulation exert a critical part in promoting firms' eco-innovation. Hence, the following hypotheses are developed:

Hypothesis IIa Command-and-control environmental regulation can stimulate the eco-innovation development, and they will jointly improve the environmental performance.

Hypothesis IIb Market-based environmental regulation can stimulate the eco-innovation development, and they will jointly improve the environmental performance.

[2] We do not discuss private forms of regulation here, such as private certification, private standards and self-regulation, as our focus is on public (i.e., government) regulation. For further details see Erp et al. (2019).

2.3 Mediation effect

Innovation is costly and risky, which is lacking near-term revenues and the long-term output is not always achieved. Hence, innovation projects can bring about financial risks and uncertainty for their institutions, because of the high costs related to their commercialization. Eco-innovation is even more challenging as it is technologically complex (Cainelli et al., 2015). Moreover, it is time-consuming and costly in the short run to integrate green ideas into new product production (Dangelico et al., 2013). Since green knowledge has the feature of a public good, coping the first innovators is quite simple without bearing the R&D costs and uncertainty. Eco-innovation can absorb various resources from projects providing more short-term profits. Due to the limited resources that are available to firms, the uncertainty of eco-innovation activities increases the management difficulty.

It is emphasized that eco-innovation can be facilitated by stringent environmental regulation (Filiou et al., 2023). Firms are affected by institutional and stakeholders' pressure towards environmentally friendly behavior that may impact on their eco-innovation performance (Hu et al., 2017). The economic growth rate is fast in emerging economies in general (and China in particular) and has been accompanied by extensive energy use, which has caused environmental degradation. The adoption of energy saving technologies can diminish abatement costs and innovation may become more and more essential in diminishing pollutants emissions. Previous studies, particularly those pertaining to the reduction of energy consumption and environmental improvement, demonstrate that changes in the energy consumption can be influenced by innovation. The high cost of energy will stimulate firms to devote themselves to the green technologies' R&D that can reduce their emissions, which is a virtuous cycle of production (Bose, 2010). Hence, eco-innovation exerts a mediating role between energy consumption and environmental regulation of different types. When environmental regulation becomes stringent, firms are inclined to be more active to develop advanced eco-innovation, and can subsequently achieve reduction of their energy consumption. We hence develop the relevant hypothesis III as below:

Hypothesis III Eco-innovation mediates between environmental regulation and energy consumption.

3 Data and methods

3.1 Data

We employ the green patents granted data from the China National Intellectual Property Administration which offers details about patents (Dang & Motohashi, 2015). City-level economic and environmental data are obtained from the China City Statistical Yearbook, China Environmental Statistical Yearbook and China Energy Statistics Yearbook. The patent application numbers have increased drastically since the turn of the century, annually growing by 31% and reaching 1,426,644 in 2021, in accordance with the World Intellectual Property Organization.

3.2 Variables

3.2.1 Environmental performance

City-level environmental performance is the dependent variable. Energy consumption (*En_cons*) is one of the chief causes bringing about the environmental pollution, which we use as direct measure in mediation effect analysis. We select sulfur dioxide (*Env_sulfur*), smoke (powder) dust emissions (*Env_smok*) and industrial wastewater discharge scaled by GDP (*Env_wate*) as the main indicators to represent environmental performance in that city in the joint effects empirical analysis.

3.2.2 Eco-innovation

Patents can be treated as the most direct indicator to measure the output of innovation. The patent data is widely utilized in the existing innovation-related studies (Barbieri et al., 2023; Liang et al., 2022) and also in specific analysis on eco-innovation (Filiou et al., 2023; Wagner, 2007). Therefore, the green patents granted are selected as the measurement of eco-innovation. Green patents refer to a series of patents for inventions, appearance designs and utility models utilizing various green technologies which contribute to the enhancement of energy efficiency, the decrease of pollution, and the achievement of sustainable development. By researching and developing green technologies and applying for relevant patents, firms can diminish environmental pollution caused by production, sales and use, and improve resource utilization. Meanwhile, they can achieve the purpose of shaping corporate healthy image and attracting consumers.

Following Haščič and Migotto (2015), we employ a patent searching approach provided by the OECD to identify eco-innovation, combining the "IPC Green Inventory" developed by the WIPO.[3] We employ the amount of green patents filed by each city to represent the eco-innovation level in that city, and the aggregated spillovers effect of the green patents to represent the eco-innovation spillovers or indirect eco-innovation. We will explain the calculation of eco-innovation spillovers in the following section.

3.2.3 Environmental regulation

Two sorts of environmental regulation are covered in the study. For command-and-control type, we utilize the employee numbers working in environmental regulation institutes (*Regu_comm*) (Li et al., 2021a; b).[4] We use the sewage discharge income (*Regu_market*)[5] for market-based environmental regulation (Yang et al., 2018).

[3] http://www.wipo.int/classifications/ipc/en/green_inventory/.

[4] We assume here that a larger number of staff members to enforce environmental regulation is a measure of the strictness of such regulation. Although we cannot verify whether the underlying regulation is efficiently designed, we assume that (at the very least) it is effective in the sense of giving incentives firms to reduce environmental harm. See further on efficiency and effectiveness of regulation Erp et al. (2019).

[5] This sewage discharge fees income can be considered as part of the local tax regime and can therefore be considered a market-based instrument.

3.2.4 Control variables

Several factors that might affect city environmental performance are also controlled. The population density (*pop*) is calculated by total population scaled by square kilometer. The GDP per capita (*gdp_pc*) is captured by the city scale to proxy economic development degree. The secondary industrial output value scaled by GDP (*ind_str*) is employed to represent the industrial structure. FDI is an important driving forces for economic development in many developing countries. This paper selects the actual use of FDI scaled by GDP to measure the openness (*fdi_gdp*). We select the amount of college students in 10 thousand population to reflect the education level (*edu*) in that city. Table 1 documents all the relevant variables in this research.

3.3 Methods

3.3.1 Eco-innovation spillovers

To what extent knowledge spillovers occur between different regions depends on their closeness, connectedness or technological congruence (Jacob & Szirmai, 2007; Wang et al., 2017). This study combines both geographical proximity (to capture spatial closeness) and technological similarity (to capture technological congruence) in calculating spillovers from other places. The eco-innovation spillovers[6] can be expressed as follows:

$$Eco\_inn\_s_{it} = \sum_{i \neq j} w_{ij} Eco\_inn\_s_{jt} \tag{1}$$

where spillover weight w_{ij} is calculated as the product of p_{ij} (proximity weight) and s_{ij} (similarity weight). The subscript $_t$ refers to the time period, $_i$ represents a city and $_j$ represents other cities, respectively.

$$w_{ij} = p_{ij} \cdot s_{ij} \tag{2}$$

p_{ij} represents the region i and j standardized spatial weight. Considering the crucial role of knowledge diffusion, most studies on spillovers emphasize the presence of relatively strong distance decay effects when considering spillover effects of innovation between regions (Cabrer-Borras & Serrano-Domingo, 2007; Jaffe et al., 1993). We maintain that spillovers are localized and there won't be spatial spillovers when the distance is beyond a specific value. We follow Wang et al. (2017)'s method and chosen a cut-off value of 1520 km—the distance between the capital city of the most remote Chinese region and its closest capital city. Suppose d_{ij} represents the region i and j geographical distance, the matrix of spatial proximity weight can be illustrated as follows:

$$\begin{array}{ll} p^*_{ij} = 0 & \text{if } i = j \\ p^*_{ij} = 1/d^2_{ij} & \text{if } d_{ij} \leq \text{cutoff} \\ p^*_{ij} = 0 & \text{if } d_{ij} > \text{cutoff} \end{array} \tag{3}$$

[6] Due to the data availability, we rely on provincial-level data of China to calculate the eco-innovation spillovers indicators.

Table 1 List of variables

	Variables	Code	Description
Environmental performance	Sulfur dioxide emissions	*Env_sulfur*	Industrial sulfur dioxide emissions/GDP (logarithmic form)
	Smoke (powder) dust emissions	*Env_smok*	Industrial smoke (powder) dust emissions/GDP (logarithmic form)
	Wastewater discharge	*Env_wate*	Industrial wastewater discharge/GDP (logarithmic form)
	Energy consumption	*En_cons*	Total energy consumption (tons of standard coal)/GDP (logarithmic form)
Eco-innovation	Eco-innovation	*Eco_inn*	The number of city green patents (logarithmic form)
	Eco-innovation spillovers	*Eco_inn_s*	Aggregated spillovers effect of green patents from other regions (logarithmic form)
Environmental regulation	Command-and-control	*Regu_comm*	The number of employees working in environmental regulation institutes (logarithmic form)
	Market-based	*Regu_market*	Sewage discharge fees income/number of enterprises in the city (logarithmic form)
Control variables	Population density	*pop*	Population scaled by square kilometer (logarithmic form)
	Per capita GDP	*gdp_pc*	GDP per capita (logarithmic form)
	Industrial structure	*ind_str*	Output value of secondary industry/GDP
	FDI	*fdi_gdp*	Foreign direct investment in actual use/GDP
	Education level	*edu*	High school students numbers per 10,000 (logarithmic form)

where the distance weight (p^*_{ij}) is the inverse form of region i and region j squared distance.[7] By standardizing this distance weight (i.e., $p_{ij} = p^*_{ij} / \sum p^*_{ij}$) we obtain the proximity weight (p_{ij}).

To capture the technology similarity, we adopt the calculation employed by Jacob and Szirmai (2007). The s_{ij} is as follows:

$$s_{ij} = \sum_n \min\left(X_{in}, X_{jn}\right), \quad n = 1, 2, \ldots, 37 \tag{4}$$

in which, $X_{kn}(k = i, j)$ represents output shares of sectors in specific region k ($k = i, j$). There are 37 sectors. s_{ij} takes value of 1 if the two regions' output structures of sectors are completely same and takes value of 0 if when two regions' output structure are completely different.

3.3.2 Regression models

To explore whether and how environmental performance is affected by eco-innovation and environmental regulation, we use the following baseline empirical model:

$$Env_{it} = \alpha_0 + \alpha_1 Eco\_inn_{it-1} + \alpha_2 Eco\_inn\_s_{it-1} + \gamma Controls_{it-1} + \phi_i + \varphi_t + \varepsilon_{it} \tag{5}$$

where Env_{it} represents the city i environmental performance at time t, Eco_inn_{it-1} and $Eco\_inn\_s_{it-1}$ represent the city i direct eco-innovation and indirect eco-innovation effects at time *t-1*. The coefficients of the regressors α_1 and α_2 respectively represent the influence of direct and indirect eco-innovation on the environmental performance. ε is the error term.

Although eco-innovation and environmental regulation are both deemed as important factors influencing environmental performance, there can be a causal effect between eco-innovation and environmental regulation. That is, more stringent environmental rules can prompt more actions by firms in developing eco-innovation, which further improves environmental performance. Therefore, following the method of Baron and Kenny (1986), the relation among the three variables is captured using the mediation effect model in our study. We use the city energy consumption scaled by GDP to measure energy consumption which partly accounts for the environmental pollution in that city. Therefore, we examine this mechanism using the mediation effect method. We have the following 3-step model:

$$En\_cons_{it} = \beta_0 + \beta_1 Regu_{it-1} + \beta_2 Controls_{it-1} + \phi_i + \varphi_t + \mu_{it} \tag{6}$$

$$Eco\_inn_{it} = \chi_0 + \chi_1 Regu_{it-1} + \chi_2 Controls_{it-1} + \phi_i + \varphi_t + v_{it} \tag{7}$$

$$En\_cons_{it} = \delta_0 + \delta_1 \mathrm{Regu}_{it-1} + \delta_2 Eco\_inn_{it-1} + \delta_3 Controls_{it-1} + \phi_i + \varphi_t + \psi_{it} \tag{8}$$

Regu represents the environmental regulation stringency of city i at time *t-1*, *Controls* represents a set of control variables, $\beta_{1,2}$, $\chi_{1,2}$ and $\delta_{1,2,3}$ are the coefficients that will be estimated by the Equations, ϕ_i and φ_t is city and year fixed effects respectively, μ, v, ψ are error terms. β_1 and χ_1 respectively reflect how the energy consumption and the direct eco-innovation are affected by the environmental regulation stringency; $\delta_{1,2}$ reflect the influence of the environmental regulation stringency and direct eco-innovation on energy consumption,

[7] The distance of the capital cities is used as the measurement of the distance of provinces.

respectively. All the explanatory variables are 1 year lagged. The mediation effect is measured by $\chi_1 \times \delta_2$.

Furthermore, we introduce cross-terms to investigate the joint effects of environmental regulation (*Regu*) and eco-innovation on the environmental performance in that city. We set up the empirical model as below:

$$
\begin{aligned}
Env_{it} = \alpha'_0 + \alpha'_1 \mathrm{Reg}u_{it-1} + \alpha'_2 Eco\_inn_{it-1} + \alpha'_3 Eco\_inn\_s_{it-1} + \alpha'_4 \mathrm{Reg}u_{it-1} \\
\times Eco\_inn_{it-1} + \alpha'_5 \mathrm{Reg}u_{it-1} \times Eco\_inn\_s_{it-1} + \gamma' Controls_{it-1} + \phi_i + \varphi_t + \varepsilon'_{it}
\end{aligned}
\tag{9}
$$

$\alpha'_{1,2,3}$ reflect how the environmental performance is influenced by environmental regulation, direct eco-innovation and indirect eco-innovation, respectively; $\alpha'_{4,5}$ reflect the joint effects of eco-innovation and environmental regulation.

4 Empirical results

4.1 Baseline results

To test Hypothesis I, we use sulfur dioxide emissions (Env_sulfur, industrial-level) and smoke (powder) dust emissions (Env_smok, industrial-level) as proxies of environmental performance in each city. In Table 2, the panel fixed effect regression results (displayed in columns 1 and 2) indicate that eco-innovation and eco-innovation spillovers can significantly reduce industrial smoke (powder) dust emissions as well as industrial sulfur dioxide.

In column (3) and (4), in line with the literature (Li et al., 2021a; b), we employ panel two stages least square (2SLS) and use lag of eco-innovation variables as instrumental variable to deal with the endogeneity problems, e.g. reverse causality. Using the endogenous variable lagged value as the instrument variable is common (Zhao et al., 2018). Firstly, the lag of eco-innovation variable satisfies the correlation assumption. The lag period impact exists in eco-innovation improvement, so eco-innovation in 1-year lag period is highly correlated to the eco-innovation in the current period. Secondly, the lag of eco-innovation meets the exogeneity requirement. Since the past eco-innovation cannot be affected by the emissions of the current period, we utilize the lag of eco-innovation as an instrumental variable in this section. We also test under-identification with the report of the Anderson canon. corr. LM statistic, weak identification with the report of the Cragg-Donald Wald F statistic, and over-identification with the report of the Sargan test statistic. Due to significant LM statistic and Wald F statistic, we respectively reject under-identification and weak-identification. We cannot reject the orthogonality of conditions due to an insignificant Sargan statistic. Panel 2SLS regression results reveal that eco-innovation and its spillovers still significantly and negatively influence the pollutant emissions of the city, which is in line with columns (1) and (2), supporting Hypothesis I.

Economic development (*gdp_pc*) is negatively correlated with the amount of pollution discharge, which indicates that the cities with better economic development have greater advantages in controlling overall pollution discharge and reducing energy consumption. The coefficient of the industrial structure (*ind_str*) shows that if the secondary industry proportion rises, the emissions of urban pollutants increase considerably. That is, environmental performance heavily depends on the improvement of urban industrial structure. The level of openness (*fdi_gdp*) is negatively correlated with the pollutant emissions, which supports the pollution-halo hypothesis.

Table 2 Baseline results

Environmental performance measurement	(1) *Env_sulfur*	(2) *Env_smok*	(3) *Env_sulfur*	(4) *Env_smok*
Eco_inn	−0.026**	−0.053**	−0.111*	−0.746***
	(−2.167)	(−1.962)	(−1.790)	(−4.263)
Eco_inn_s	−0.472***	−0.470***	−0.756***	−1.191***
	(−7.738)	(−7.966)	(−11.631)	(−6.508)
pop	−0.360	−1.035*	−0.155	−0.312
	(−1.184)	(−1.661)	(−0.569)	(−0.931)
gdp_pc	−0.081***	−0.024*	−0.054***	−0.010
	(−4.765)	(−1.846)	(−7.714)	(−0.833)
ind_str	0.004	0.014***	0.004**	0.014***
	(1.000)	(2.800)	(2.000)	(4.667)
fdi_gdp	−0.755	−5.043***	−1.175	−4.611***
	(−0.380)	(−3.249)	(−1.493)	(−3.783)
edu	−0.029	−0.049	−0.064*	−0.029
	(−0.271)	(−0.681)	(−1.778)	(−0.509)
Constant	1.115	4.614	−5.344***	−4.621***
	(0.612)	(1.314)	(−36.108)	−29.433)
Number of observations	3,141	3,417	2,624	2,901
Adjusted R^2	0.61	0.32	0.62	0.36
C-D Wald F statistic			194.118***	40.018***
Anderson LM statistic			334.068***	78.015***
Sargan statistic			0.001	1.422
Methods	Fixed effects		Two-stage least squares	

City and time dummies included. The t values in parentheses.

***, ** and * respectively significance at 1%, 5% and 10%. The same to the tables hereafter

4.2 Joint effects of eco-innovation and environmental regulation

Environmental regulation can be a crucial way to correct environmental externalities (Faure & Partain, 2019). Environmental regulation can increase the sewage discharge cost, motivate firms to innovate or purchase green production technology in the market, thus promoting spillovers of green technology innovation (Perino & Requate, 2012). As displayed in Tables 3 and 4, we introduce the cross-term of eco-innovation and environmental regulation (see Eq. 9) so as to further test their joint effects.

The relevant results of command-and-control type represent that coefficients of direct eco-innovation and indirect eco-innovation (eco-innovation spillovers) are negative at the 1% significant level, and in addition, eco-innovation spillovers display greater impact than eco-innovation in all models. Environmental regulation also exists significant negative correlation with pollutant emissions. The negative coefficients of the cross-terms reveal that the environmental regulation's stringency regarding eco-innovation and its spillovers perform a joint positive effect on the city-level environmental performance, which is consistent with the theoretical analysis in Perino and Requate (2012).

Different from environmental regulation of the former type, market-based instruments usually take the form of tradable permits, environmental taxes, various subsidies

Table 3 Joint effect analysis (command-and-control type)

Environmental performance measurement	(1) *Env_sulfur*	(2) *Env_smok*	(3) *Env_sulfur*	(4) *Env_smok*
Regu_comm	−3.057***	−0.594	−6.516***	−1.632*
	(−3.345)	(−0.428)	(−4.400)	(−1.707)
Eco_inn	−0.198***	−0.338***	−1.160***	−1.266***
	(−2.605)	(−3.714)	(−2.992)	(−5.504)
Eco_inn_s	−0.734***	−0.750***	−1.811***	−1.824***
	(−8.066)	(−6.757)	(−4.704)	(−7.042)
*Regu_comm*Eco_inn*	−0.346***	−0.491***	−1.597***	−0.786***
	(−2.813)	(−3.340)	(−2.920)	(−2.944)
*Regu_comm*Eco_inn_s*	−0.396***	−0.384**	−1.535***	−0.769***
	(−3.474)	(−2.233)	(−3.273)	(−3.329)
Number of observations	2883	3159	2624	2901
Adjusted R^2	0.62	0.31	0.58	0.39
C-D Wald F statistic			10.259***	19.042***
Anderson LM statistic			40.533***	74.348***
Sargan statistic			0.670	1.785
Methods	Fixed effects		Two-stage least squares	

Control variables, as well as city and time dummies included, the same to the tables hereafter

Table 4 Joint effect analysis (market-based type)

Enviromental performance measurement	(1) *Env_sulfur*	(2) *Env_smok*	(3) *Env_sulfur*	(4) *Env_smok*
Regu_market	−0.291	−1.122***	−0.130***	−0.590*
	(−1.323)	(−3.329)	(−2.826)	(−1.657)
Eco_inn	−0.031	−0.164**	−0.207**	−2.233**
	(−0.596)	(−2.563)	(−2.050)	(−2.386)
Eco_inn_s	−0.330***	−0.632***	−0.738***	−2.225***
	(−3.882)	(−5.962)	(−5.811)	(−3.402)
*Regu_market*Eco_inn*	−0.029	−0.082***	−0.053**	−0.825**
	(−1.160)	(−2.563)	(−2.038)	(−2.426)
*Regu_market*Eco_inn_s*	−0.045*	−0.159***	−0.010*	−0.483***
	(−1.667)	(−3.245)	(−1.667)	(−3.401)
Number of observations	3141	3417	2624	2901
Adjusted R^2	0.61	0.37	0.62	0.31
C-D Wald F statistic			47.972***	5.221***
Anderson LM statistic			92.506***	74.348***
Sargan statistic			0.047	2.027
Methods	Fixed effects		Two-stage least squares	

and refund/deposit systems. A considerable body of empirical work (Harrison et al., 2015; Zhao et al., 2015) has revealed mixed evidence on environmental regulation of these two sorts in reducing pollution. We further study the impact of market-based instruments. Table 4 uses sewage discharge fee income (*Regu_market*) as an indicator for market-based environmental regulation.

The regression results of Table 4 shows that both coefficients of eco-innovation and eco-innovation spillovers are significantly negative, which further support Hypothesis I. The spillovers indicators still have greater effects on environmental performance. Environmental regulation also performs a significant negative correlation with city pollutant emissions. The negative coefficients of the cross-term are in line with Table 3.

The results of Tables 3 and 4 are compatible with the conclusions of Cheng et al. (2017). The coefficients of the cross-terms in both tables are significantly negative, which shows that the direct and indirect effects from eco-innovation with environmental regulation stringency exert joint positive impact on environmental performance.

4.3 Mediation effect analysis

The baseline results reveal that eco-innovation significantly enhances the city environmental performance. It can also decrease environmental pollution and enhance environmental performance through an energy conservation effect. The dependent variable is total energy consumption (ton of standard coal) scaled by GDP and the mediator is eco-innovation. To compare the different impact of the two sorts of instruments, *Regu_comm* and *Regu_market* are both used (see Table 5).

In Step I, the coefficients of environmental regulation (*Regu_comm* and *Regu_market*) are significantly negative in the regressions that do not include the mediator (column 1 and 2), which meet the precondition of the mediating effect test. Both environmental regulation coefficients in Step II are significantly positive in column (3) and (4), indicating that environmental regulations exert positive impact on eco-innovation. Both environmental regulation coefficients in Step III (column 5 and 6) are significantly negative, but with a smaller magnitude than in Step I. The mediation effect is 0.5 and 0.06, respectively. We also conduct a bootstrapping test, and the ACEM (Average Causal Mediation Effects) is statistically significant (p value = 0). This indicates that eco-innovation partially mediates between energy consumption and environmental regulation, that is, eco-innovation can be

Table 5 Mediation effect analysis

Dependent variable:	Step I		Step II		Step III	
	(1)	(2)	(3)	(4)	(5)	(6)
	En_cons	*En_cons*	*Eco_inn*	*Eco_inn*	*En_cons*	*En_cons*
Regu_comm	−2.352***		5.945***		−1.810***	
	(−8.340)		(9.260)		(−8.786)	
Regu_market		−0.232***		0.666***		−0.172***
		(−7.483)		(8.649)		(−7.478)
Eco_inn					−0.091***	−0.089***
					(−8.273)	(−8.90)
Number of observations	3183	3441	3183	3441	3183	3441
Adjusted R^2	0.73	0.76	0.54	0.58	0.81	0.79

partially pushed by stringent environmental regulation, which in turn helps reduce energy consumption. Energy consumption will influence the environmental performance.

4.4 Economic development stages—urban financial development perspective

Due to the high risks and asymmetric information, firms' innovation activities often face up to financial constraints, particularly with regard to eco-innovation (Hall et al., 2007). Whether or to what extent firms can develop eco-innovation or purchase eco-innovation from outside depends on their economic capabilities. Financial development can increase firms' financing resources, reduce the financial constraints and advance capabilities in managing risks. Taking this aspect into consideration, we further classify the 285 cities into two financial development groups, based on the equities trading volume per capita. The *High-group* covers cities with the financial development degree greater than (or equal to) the median level of whole cities, and the *Low-group* includes cities with the financial development level lower than the median value. Table 6 reports how environmental performance is influenced by environmental regulation and eco-innovation in different financial development groups.

We conduct the Fisher test, with the results indicating that in comparison with sample group of lower regional financial development, the coefficient of the environmental regulation in the group with higher regional financial development level is greater. We find that, in cities with an above median financial development level, both *Regu_comm* and *Regu_market* exert a significant positive influence on city environmental performance, with *Regu_comm* performing a greater and more significant effect (see col. 1 and 3). This indicates that both types of environmental regulation can significantly diminish pollutants emissions and improve environmental performance in cities above the median financial development level. However, in cities below the median financial development level, *Regu_comm* (command-and-control) can improve environmental performance, while *Regu_market* (market-based) has no significant effect (see col. 2 and 4).

In terms of cross-terms, similar patterns are observed. The cross-terms of environmental regulations with eco-innovation and eco-innovation spillovers are significantly negative in the high financial development subsample (see col. 1 and 3). This means that the eco-innovation development and spillovers work significantly together with both types of environmental regulation in the financially capable cities. However, cross-terms related to *Regu_market* appear to be insignificant in the low financial development subsample (see col. 4). This indicates that (this type of) market-based environmental regulation will not function well in cities with weak financial resources. Actions (including developing new eco-innovation or utilizing eco-innovation spillovers from other regions) will be taken only when confronting stringent environmental regulation of command-and-control type (see *Eco_inn*Regu_comm* and *Eco_inn_s*Regu_comm* in Col. 2). If regulation is less stringent, the role of eco-innovation spillovers may also be limited.

Table 6 also shows that in both High-group and Low-group, market-based environmental regulation exert in general less significant influence than environmental regulation of command-and-control type. This indicates that in China, at least in its current development stage, it is more efficient to introduce command-and-control policies rather than market-based tools. Such policy seems to be effective in advancing the effect of both direct and indirect eco-innovation.

Table 6 Subsample analysis

Dependent variable: *Env_sulfur*	Command-and-control		Market-based	
	High	*Low*	*High*	*Low*
	(1)	(2)	(3)	(4)
Regu_comm	−14.726***	−2.124***		
	(−6.897)	(−2.798)		
Regu_market			−1.981***	−0.188
			(−4.762)	(−1.197)
Eco_inn	−0.548***	−0.457**	−0.071**	0.068
	(−3.028)	(−2.525)	(−2.535)	(0.654)
Eco_inn_s	−1.029***	−1.098***	−0.161	−0.742***
	(−5.359)	(−5.602)	(−1.376)	(−7.420)
*Regu_comm*Eco_inn*	−1.176***	−0.529***		
	(−3.960)	(−2.770)		
*Regu_comm*Eco_inn_s*	−1.567***	−0.497***		
	(−4.990)	(−2.840)		
*Regu_market*Eco_inn*			−0.016*	−0.009
			(1.778)	(−0.45)
*Regu_market*Eco_inn_s*			−0.239***	−0.017
			(4.686)	(−0.85)
Number of observations	685	1743	685	1743
Adjusted R^2	0.66	0.66	0.65	0.65
C-D Wald F statistic	31.299***	23.792***	28.262***	33.263***
Anderson LM statistic	105.128***	90.242***	96.589***	123.263***
Sargan statistic	0.104	0.276	1.102	0.008
Methods	Panel 2SLS			

5 Robustness tests

Considering the price factors' impact on the results, we employ the GDP deflator to deflate the gross output value (2000 as base year) in column (1)–(4) of Table 7. We also use industrial wastewater discharge per unit of GDP (*Env_wate*) as an alternative variable to reflect the environmental performance of a city and investigate the eco-innovation influence in columns (5) and (6). The regression results remain consistent and robust. Indirect eco-innovation seems to have relatively greater and more significant impact than direct eco-innovation.

Table 7 Robustness tests

	(1)	(2)	(3)	(4)	(5)	(6)
	Env_sulfur deflated	*Env_smok deflated*	*Env_sulfur deflated*	*Env_smokdeflated*	*Env_wate*	*Env_wate*
Regu_market			−0.077**	−0.303***	−0.092**	
			(−2.026)	(−2.730)	(−2.044)	
Regu_comm						−3.478***
						(−5.521)
Eco_inn	−0.017*	−0.024*	−0.016*	−0.421**	−0.557**	−0.026**
	(−1.889)	(−1.846)	(−1.778)	(−2.116)	(−2.126)	(−2.000)
Eco_inn_s	−0.160***	−0.100***	−0.197***	−0.462**	−1.102***	−0.673***
	(−7.273)	(−4.762)	(−3.863)	(−2.221)	(−3.412)	(−4.547)
*Regu_market*Eco_inn*			−0.008**	−0.161*	−0.215**	
			(−2.000)	(−1.769)	(−1.720)	
*Regu_market*Eco_inn_s*			−0.005*	−0.117***	−0.123*	
			(−1.667)	(−2.600)	(−1.757)	
*Regu_comm*Eco_inn*						−0.141**
						(−2.169)
*Regu_comm*Eco_inn_s*						−0.122*
						(−1.718)
Number of observations	2895	3409	2619	2895	2908	2908
Adjusted R^2	0.43	0.43	0.54	0.37	0.57	0.61
C-D Wald F statistic	195.987***	39.511***	46.857***	14.610***	15.386***	18.672***
Anderson LM statistic	336.720***	76.933***	90.515***	19.226***	20.773***	72.949***
Sargan statistic	0.033	0.316	0.027	1.503	0.478	3.605
Methods	Panel 2SLS					

6 Conclusions and policy implications

We examine the effect of (direct and indirect) eco-innovation and explore whether stringent environmental regulation can stimulate eco-innovation, which can further improve environmental performance.

Firstly, our results exhibit that both direct eco-innovation and indirect eco-innovation (i.e. eco-innovation spillovers) contribute to the enhancement of environmental performance at city level in China. Eco-innovation can prominently decrease the pollutants emissions, and the effect of eco-innovation spillovers from other regions is even greater than that of direct (local) eco-innovation. This emphasizes that absorbing/utilizing eco-innovation spillovers from other regions provides an efficient means to reduce the amount of pollutants and improves environmental performance, particularly for cities without sufficient local R&D capabilities.

Secondly, our results prove that eco-innovation can be significantly driven by environmental regulation. The reason may be that when there are stringent local environmental rules, the initially passive end-of-pipeline pollution control no longer meets the higher requirements set by the local authorities, and the pollution control expenditure and the cost for purchasing pollution emissions rights are greatly increased. The profit is therefore reduced. In order to satisfy the environmental regulation requirements, to reduce costs and increase profitability (and perhaps also to set up a good corporate image), firms have an incentive to find solutions through eco-innovation.

Thirdly, evidence indicates that environmental regulation which is more stringent is associated with the greater effect of direct and indirect eco-innovation on the city environmental performance. The indirect spillovers effect is greater than eco-innovation itself under the two types of environmental regulation studied here, which reflects that eco-innovation spillovers exert a more crucial part in enhancing the environmental performance. At the aggregated level of all 285 cities covered by our study, both types of environmental regulation have positive impacts, where the command-and-control environmental regulation performs greater effect.

Fourthly, this paper also illustrates the mechanisms of eco-innovation and environmental regulation constrained by different financial development levels. The results show that command-and-control (i.e. *Regu_comm*) combined with market-based (i.e. *Regu_market*) environmental regulation both exert significant positive effects on environmental performance of cities with higher level of financial development. However, in cities where financial development level is low, only command-and-control instrument (not market-based instrument) can help reduce pollutants emissions and improve environmental performance. This calls for differentiated environmental policies in different cities. While market-based tools may not function well in certain cities, environmental regulation of command-and-control type has appeared to serve significantly in improving city environmental performance, at least in all the studied cities in China and for the two specific types of indicators (representing the two types of regulation) studied here.

Facing the severe threats of global warming, most countries have made efforts to reduce carbon footprints. Carbon neutrality, a hot topic all over the world, has become an urgently practiced concept in China. It calls for accelerated efforts to the advancement of green and low-carbon technologies. Both sorts of environmental regulation can exert positive effects on environmental performance, and in our context the effect of *Regu_comm* is greater. The beneficial impacts of the environmental regulation of both types on developing eco-innovation imply that the Chinese government should enact appropriate environment laws and regulations. Eco-innovation has been proved to significantly promote environmental performance, even though the current utilization rate of eco-innovation in China is relatively low. Government drafting stricter environmental regulatory framework can reduce the burden of pollution by introducing more green technologies. Therefore, we suggest that the government can increase the stringency of environmental regulation (if such regulation is designed in an appropriate manner), and actively build relevant policies that promote the development of eco-innovation.

Coordinated efforts by policymakers in distinct departments and at distinct levels in China (central, provincial and municipal governments) is possibly a valid approach to improve the effective utilization of various environmental regulation for combating pollution and climate change. The government should consider a differentiation in the mechanism design, by formulating flexible and well-targeted environmental policies, by further improving the incentive and restraint mechanism of environmental regulation and eco-innovation, and by stimulating market solutions through regulation. After all, great importance should be attached to the prominent position of innovative firms. The Chinese government should support and encourage high-tech industries development, guide firms to put more efforts in increasing their investment and attention to eco-innovation and provide firms actively engaged in eco-innovation activities with financial support along with incentives such as environmental subsidies. Considering that the regional financial development may exert influence on the environmental regulation effect, we recommend the government to continue to encourage eco-innovation activities by rising R&D funding support. For example, policies could aim at strengthening financial credit support for emerging green industries, at guiding social capital towards ecological and environmental projects, and at providing firms with convenient financing channels and tax incentives to increase investment in eco-innovation activities.

Meanwhile, considering the variation across various regions in financial level, industrial development and eco-innovation conditions, the Chinese government should facilitate the communication between cities about eco-innovation, in order to make use of knowledge spillovers that can further improve the environmental quality and promote the green technologies development. In addition, the government could improve the platforms for eco-innovation services such as scientific and technological resource sharing services, thereby providing continuous channels of communication between the government and firms to promote the industrialization of eco-innovation.

Our research is not without limitations. First, the hypothesis investigations are based on one emerging economy, China. While our theoretical insights are broadly applicable to most emerging countries, the econometric results may change depending on the country to which it is applied. The generalizability of empirical analysis requires further study. Second, hypotheses that are tested at the micro-level (e.g., firm-level) can render more solid and detailed evidence on the essential role of eco-innovation spillovers. Furthermore, since the empirical measurement of environmental regulation is a persistent problem in the literature, future research might strengthen and extend the index system to glean more insight into the eco-innovation paradigm. Utilizing data of more recent years so as to test and verify our research hypotheses is one of the future research directions.

Appendix

See Table 8.

Table 8 Correlation coefficients

	Env_sulfur	*Env_smok*	*Env_wate*	*Eco_inn*	*Eco_inn_s*	*Regu_comm*	*Regu_market*	*pop*	*gdp_pc*	*ind_str*	*fdi gdp*
Env_smok	0.748										
Env_wate	0.531	0.402									
Eco_inn	−0.490	−0.508	−0.347								
Eco_inn_s	−0.466	−0.387	−0.274	0.254							
Regu_comm	−0.109	−0.074	−0.077	0.235	0.149						
Regu_market	−0.438	−0.563	−0.100	0.228	0.109	0.012					
pop	−0.247	−0.340	0.007	0.194	0.218	0.214	−0.204				
gdp_pc	−0.438	−0.432	−0.424	0.220	0.147	0.105	−0.085	0.161			
ind_str	0.104	0.017	0.007	0.173	0.211	0.247	0.101	−0.211	0.278		
fdi gdp	−0.208	−0.260	−0.022	0.315	0.264	0.038	−0.184	0.305	0.296	0.134	
edu	−0.258	−0.290	−0.236	0.342	0.206	0.035	−0.134	0.254	0.297	0.135	0.380

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Data availability Environmental performance, command-and-control environmental regulation and other city-level variables data were obtained from https://data.cnki.net/yearBook/single?id=N2022040095. Energy consumption data was obtained from https://data.cnki.net/yearBook/single?id=N2022060061. Market-based environmental regulation data was obtained from https://data.cnki.net/yearBook/single?id=N2022030234;Eco-innovation data was found at https://pss-system.cponline.cnipa.gov.cn/conventionalSearch.

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.

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