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Industrial Agglomeration Patterns and Green Innovation Efficiency under Environmental Regulation: Evidence from China's Yangtze River Delta Urban Agglomeration

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Abstract: This study investigates the impact of industrial agglomeration patterns on green innovation efficiency within the Yangtze River Delta (YRD) urban agglomeration in China. Utilizing panel data from 41 cities spanning 2010 to 2020, the research differentiates between specialized and diversified agglomeration patterns. A super-efficiency SBM-DEA model is employed to evaluate urban green innovation efficiency, incorporating undesirable outputs into the analysis. The findings reveal that specialized agglomeration positively influences green innovation efficiency, particularly in less-developed cities, by lowering production costs and alleviating financing constraints for small and medium-sized enterprises (SMEs) within clusters. In contrast, diversified agglomeration does not significantly improve green innovation efficiency and may even hinder it in non-core and developed cities due to heightened competition and resource inefficiencies. Furthermore, environmental regulation negatively moderates the relationship between both agglomeration patterns and green innovation efficiency. The results emphasize the need to optimize regional industrial structures and promote specialized industrial clusters based on comparative advantages. They also underscore the importance of developing cross-regional coordination mechanisms to enhance the flow of innovation resources and strengthen collaboration among industry, academia, and research institutions. These insights offer valuable guidance for policymakers seeking to refine environmental regulations and industrial policies in urban agglomerations.

Key words: Specialized Agglomeration; Diversified Agglomeration; Green Innovation Efficiency; Environmental Regulations; Urban Agglomeration

1 Introduction

In the context of China’s transition to a “new normal” economic paradigm, green innovation has emerged as a crucial catalyst for high-quality development. Industrial agglomeration, serving as a fundamental determinant of regional innovation capacity, plays a pivotal role in driving regional green innovation (Du & Li, 2021). Notably, government-initiated programs such as low-carbon economic demonstration zones and eco-industrial parks have become predominant forms of low-carbon industrial clusters. Local governments actively shape the spatial distribution and evolution of industrial agglomeration through policy instruments that facilitate the integration of innovative resources within their jurisdictions.

As regions pursue comprehensive green ecological development, optimizing industrial agglomeration through diversification and specialization has become imperative for enhancing regional competitive advantages and green innovation efficiency. Concurrently, regional integration strategies have emerged as key drivers in industrial transformation and the cultivation of new economic growth engines. Urban agglomerations, as essential components of regional integration, increasingly function as primary spatial carriers of development factors (Yi et al., 2020). The Yangtze River Delta (YRD) urban agglomeration, strategically positioned at the intersection of China's "Belt and Road Initiative" and the Yangtze River Economic Belt, represents one of the nation's most innovative and economically dynamic urban clusters. Given its pioneering role in advancing regional integration and implementing national innovation strategies, examining the impact mechanisms of diverse industrial agglomeration models on green innovation development in the YRD urban agglomeration holds substantial practical significance.

Prior research on the relationship between industrial agglomeration and green innovation efficiency provides theoretical underpinnings for this study. Hu et al. (2018) identified a U-shaped relationship between high-tech industrial agglomeration and green economic efficiency, primarily manifested through improvements in green pure technical efficiency. Liu et al. (2020) empirically demonstrated that industrial collaborative agglomeration significantly enhances regional green innovation, with more pronounced effects in eastern regions compared to central and western areas. More recent research by Liu et al. (2023) revealed that coordinated agglomeration of manufacturing and producer services industries contributes to improved green innovation transformation and overall efficiency, though its impact on green innovation R&D efficiency remains insignificant. Song and Li (2023) empirically validated an inverted U-shaped relationship between industrial collaborative agglomeration and industrial green innovation efficiency, currently exhibiting a positive effect.

Despite these valuable insights, existing literature presents varying findings due to methodological differences and diverse research contexts. Several critical gaps persist: First, most studies employ singular indicators to measure industrial agglomeration levels, with limited attention to the differentiated effects of various agglomeration patterns in regional green development. Second, while environmental regulation significantly influences regional green innovation efficiency, few scholars have explored the interplay among industrial agglomeration, environmental regulation, and green innovation efficiency, particularly at the urban agglomeration level (Zhu et al., 2021; Wang & He, 2022; Zheng et al., 2023).

To address these research gaps, this study analyzes panel data from 41 cities in the YRD region spanning 2010-2020, distinguishing between specialization and diversification patterns of industrial agglomeration. We employ a super-efficiency SBM-DEA model with undesirable outputs to measure urban green innovation efficiency and investigate the impact mechanisms of different industrial agglomeration patterns on urban agglomeration green innovation efficiency under environmental regulation through panel data models. This research makes two principal contributions: theoretically, it integrates diverse industrial agglomeration patterns, environmental regulation, and urban green innovation efficiency within a unified analytical framework, enriching industrial agglomeration theory; empirically, it comprehensively examines regional variations in industrial agglomeration distribution, environmental regulation, and factor endowments in the YRD urban agglomeration, providing evidence-based insights for identifying optimal industrial agglomeration patterns that promote regional green innovation development.

2 Research Hypotheses

2.1 Specialized Agglomeration and Urban Green Innovation Efficiency

Specialized agglomeration refers to the concentration of homogeneous industries within a specific region, characterized by advantages in specialized division of labor, cooperation, and homogeneous knowledge spillover (Li & Phillips, 2015). The primary theoretical foundation stems from Marshall's externality theory (Marshall, 1920), which posits that specialized agglomeration generates externalities through shared specialized labor markets, intermediate input markets, and knowledge spillover, promoting innovation efficiency through regional scale effects and networked production systems.

Regarding the impact of specialized agglomeration on regional green innovation efficiency, existing literature provides substantial evidence. Liu et al. (2016) explored the influence of different industrial agglomeration patterns on regional spatial disparities in innovation efficiency at the provincial level, demonstrating that specialized agglomeration effectively enhances regional innovation efficiency and scale efficiency, while diversified agglomeration shows less pronounced effects. Ren et al. (2019)

empirically verified that manufacturing specialization agglomeration significantly promotes the improvement of green total factor productivity. Liu and Yang (2020) indicated that both industrial diversification and specialization agglomeration significantly enhance regional innovation performance, with varying effects across different innovation development stages.

The influence of specialized agglomeration on green innovation efficiency primarily manifests through three mechanisms: scale effects, knowledge spillover, and resource sharing. First, specialized agglomeration leads to structural homogeneity among enterprises, facilitating scale effects within single industries. This homogeneity reduces barriers to green knowledge spillover, enabling firms within the same industry to share infrastructure, human resources, specialized production factors, and industry information. Second, more refined specialized division of labor forms mature networked production systems. The communication and factor mobility within these networks drive the improvement of regional green innovation levels. Geographic proximity among firms in the same industry generates imitation and learning effects, resulting in lower knowledge spillover costs and more efficient knowledge diffusion. Furthermore, specialized agglomeration tends to create market monopoly effects. Green technological innovation becomes a crucial condition for breaking market barriers. To obtain and maintain market monopoly positions, enterprises must continuously increase investment in green technology research and development to secure excess profits and sustain development, thereby effectively promoting the overall improvement of regional green innovation efficiency. Based on these theoretical analyses, we propose the following hypothesis:

H1: Specialized agglomeration has a positive impact on green innovation efficiency in the YRD urban agglomeration.

2.2 Diversified Agglomeration and Urban Green Innovation Efficiency

Diversified agglomeration represents the concentration of different industries within a specific region, forming an open industrial system. However, such diversified “knowledge pools” and “labor pools” may impede deep inter-industry communication and specialized knowledge sharing. Overly dispersed knowledge accumulation might fail to provide sufficient depth of support for innovation development in specific fields, while excessive inter-industry competition may suppress collaborative innovation. For instance, Wei and Hou (2021) demonstrated that while specialized agglomeration promotes regional green development, diversified industrial agglomeration exhibits an inhibitory effect. Similarly, Andersson et al. (2019) indicated that diversified agglomeration shows no significant impact on total factor productivity. Furthermore, Xuan et al. (2024) revealed that within limited urban spaces, diversified agglomeration intensifies competition for production factors and resources, simultaneously increasing production costs and energy consumption, thereby impeding urban green innovation development.

In a diversified agglomeration environment, excessive market openness and high industry differentiation may lead to knowledge fragmentation and uncertainty in innovation direction. On one hand, inter-industry differences may obstruct the effective dissemination of advanced green innovation technologies and management concepts, creating greater barriers to cross-industry technology integration. On the other hand, the diversified agglomeration of upstream and downstream related industries may disperse the innovation resources and attention of the primary industry while increasing coordination and communication costs, resulting in resource waste to some extent. Based on these theoretical analyses, we propose the following hypothesis:

H2: Diversified agglomeration has a negative impact on green innovation efficiency in the YRD urban agglomeration.

2.3 The Moderating Effect of Environmental Regulation

Research indicates that environmental regulation can promote green innovation behavior and enhance green innovation efficiency (Peng et al., 2021; Fan et al., 2021). However, Li et al. (2021) found that when industrial agglomeration promotes green technological innovation, environmental regulation exhibits an inhibitory effect on agglomeration innovation. Firms within the same industry may diverge due to differences in environmental compliance capabilities, weakening inter-firm collaborative development and dissolving existing mutual benefit communities. Stringent environmental standards may force some firms to exit the market, reducing opportunities for technical exchange and cooperation within the industry, thus suppressing the momentum for specialized agglomeration to develop in a green and clean direction.

Regarding diversified industrial agglomeration, Shen et al. (2018) noted that while diversified agglomeration faces lower risks of convergence and solidification, negative externalities emerge as cluster capacity approaches saturation. Environmental regulation may exacerbate the congestion effects that arise at certain stages of diversified agglomeration development. Strict environmental standards could lead to complete withdrawal of certain industries, disrupting existing industrial ecosystems and hindering green innovation development. Under diversified agglomeration, industries with lower correlation levels may see their symbiotic industrial chains disrupted by environmental regulation. Specific pollution control technologies adopted by one firm to meet environmental regulations may be incompatible with other industries' production processes, creating additional cost pressures for all firms along the industrial chain and ultimately suppressing improvements in green innovation efficiency. Based on these analyses, we propose the following hypotheses:

H3a: Environmental regulation negatively moderates the impact of specialized agglomeration on green innovation efficiency.

H3b: Environmental regulation negatively moderates the impact of diversified agglomeration on green innovation efficiency.

3 Research Design

3.1 Model Specification

This study employs panel data from 41 cities in the YRD urban agglomeration. We construct panel data models incorporating both time and regional effects to investigate the impact mechanisms of different agglomeration patterns on green innovation under environmental regulation at the urban agglomeration level.

First, we establish the following model to examine the effects of different industrial agglomeration patterns on green innovation efficiency:

$$\ln \mathrm{GIE}_{\mathrm{it}} = \alpha_1 + \beta_1 \ln RIS_{it} + \gamma_1 \ln P_{it} + \mu_{\mathrm{i}} + \lambda_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (1)$$

$$\ln \mathrm{GIE}_{\mathrm{it}} = \alpha_2 + \beta_2 \ln RID_{it} + \gamma_2 \ln P_{it} + \mu_{\mathrm{i}} + \lambda_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (2)$$

Second, to examine the impact of industrial agglomeration on green innovation efficiency under environmental regulation, we construct Models (3) and (4):

$$\ln \mathrm{GIE}_{\mathrm{it}} = \alpha_3 + \beta_3 \ln RIS_{it} + \eta_1 \ln RIS_{it} \times \ln ER_{it} + \gamma_3 \ln P_{it} + \mu_{\mathrm{i}} + \lambda_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (3)$$

$$\ln \mathrm{GIE}_{\mathrm{it}} = \alpha_4 + \beta_4 \ln RID_{it} + \eta_2 \ln RID_{it} \times \ln ER_{it} + \gamma_4 \ln P_{it} + \mu_{\mathrm{i}} + \lambda_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (4)$$

Where:

- $\mathrm{GIE}_{\mathrm{it}}$ represents the green innovation efficiency of city i in year t
- RIS_{it} denotes the specialized industrial agglomeration index
- RID_{it} represents the diversified industrial agglomeration index
- ER_{it} is the environmental regulation index
- P_{it} is a vector of control variables including: FDI (Foreign Direct Investment), Hum (Human Capital), Fra (Infrastructure Level) and Urb (Urbanization Level)
- μ_{i} captures city fixed effects
- λ_{t} represents time fixed effects
- $\varepsilon_{\mathrm{it}}$ is the random error term

3.2 Variable Definitions and Measurement

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3.2.1 Dependent Variable

Green Innovation Efficiency (GIE): This study employs a super-efficiency SBM-DEA model with undesirable outputs to measure urban green innovation efficiency (Li et al., 2022), we select the following variables:

Input Variables:

- R&D personnel in industrial enterprises above designated size
- Internal R&D expenditure of industrial enterprises above designated size
- Total social electricity consumption

Desirable Output Variables:

- Total number of three types of patent grants
- Sales revenue of new products from industrial enterprises above designated size

Undesirable Output Variables:

- Industrial sulfur dioxide emissions
- Industrial smoke and dust emissions
- Industrial wastewater discharge

3.2.2 Independent Variables

Industrial Agglomeration: We categorize industrial agglomeration into two types:

1. Specialized Agglomeration: Measured using the Krugman Specialization Index
2. Diversified Agglomeration: Measured using the Herfindahl Index

3.2.3 Moderating Variable

Environmental Regulation: Drawing from Zhao (2014) and Zhu et al. (2018), we construct a comprehensive environmental regulation intensity index at the city level using three indicators:

- Industrial sulfur dioxide emissions
- Industrial smoke and dust emissions
- Industrial wastewater discharge

The calculation formula is as follows:

$$P_{ijt} = T_{ijt}/Y_{it}/\frac{1}{n}\sum_{i=1}^{n}\frac{T_{ijt}}{Y_{it}} \tag{5}$$

$$ER_{it} = 3/\sum_{j=1}^{3} P_{ijt} \tag{6}$$

Where:

- n represents the number of cities in the study
- P_{ijt} represents the relative intensity of pollutant type j in city i in year t
- T_{ijt} represents the total emissions of pollutant type j in city i in year t
- Y_{it} represents the total industrial output value of city i in year t
- ER_{it} represents the environmental regulation intensity of city i in year t, where a higher value indicates stricter environmental regulation and better pollution control outcomes

3.2.4 Control Variables

This study selects foreign investment level, human capital level, infrastructure level, and urbanization level as control variables.

Foreign direct investment (FDI) generates spillover effects in knowledge and technology. Domestic enterprises can learn from advanced international knowledge and technology, promoting green innovation efficiency in cities through either technological imitation or innovation based on these foundations (Wang et al., 2014). This variable is measured by the ratio of actual utilized foreign investment to GDP.

Human capital forms the foundation for innovation. In this study, human capital is measured by the number of university students per 100,000 population (Zhang & Xu, 2022).

Well-developed infrastructure reduces transportation costs while attracting human capital, thereby providing support for technological innovation (Zhou et al., 2020). In this study, we measure infrastructure level using road area per capita of permanent residents in each city (Wang & Miao, 2015).

The degree of urbanization is often accompanied by the agglomeration of talent, capital, and industries, which plays a positive role in promoting green innovation efficiency in urban agglomerations. This study measures urbanization using the ratio of urban permanent residents to the total permanent population of the city.

4 Empirical Results and Analysis

4.1 Descriptive Statistics and Correlation Analysis

This study primarily investigates the impact of different industrial agglomeration patterns on urban green innovation efficiency, using a balanced panel dataset from 41 cities in the YRD region. Table 1 presents the descriptive statistics and correlation coefficients for all variables. The mean Variance Inflation Factor (VIF) for all variables is 1.63, with a maximum value of 2.63, which is less than the common threshold of 5.0 and indicates that multicollinearity is not a concern in this study.

Table 1 Descriptive statistics and correlation analysis

Variables	1	2	3	4	5	6	7	8
1.ln*GIE*	-							
2.ln*RIS*	0.243***	-						
3.ln*RID*	-0.287***	-0.187***	-					
4.ln*ER*	0.316***	-0.155***	-0.411***	-				
5.ln*FDI*	-0.032	0.113**	-0.128***	-0.008	-			
6.ln*Hum*	-0.076	-0.121**	-0.462***	0.315***	0.144***	-		
7.ln*Fra*	0.012	-0.046	0.332***	-0.119**	-0.055	-0.284***	-	
8.ln*Urb*	0.040	-0.264***	-0.622***	0.425***	0.066	0.334***	-0.281***	-
Mean	2.071	3.145	0.974	4.858	3.091	6.367	3.043	4.078
Std. Dev.	0.350	0.561	0.120	0.673	0.808	0.530	0.387	0.217
Obs	451	451	451	451	451	451	451	451

(Notes：*** p<0.01, ** p<0.05, * p<0.1)

4.2 Regression Analysis

In Model (1), which includes specialized agglomeration and all control variables, empirical results show that specialized agglomeration has a significant positive impact on green innovation efficiency （$\beta = 0.07$， $p < 0.05$）， confirming Hypothesis H1。Specialized agglomeration enables firms within the same industry to share information technology, labor markets, and intermediate input markets, thereby reducing related intermediate costs and increasing investment in green innovation technology research and development. This improves resource utilization efficiency and facilitates knowledge and technology spillovers within similar specialized industries, demonstrating both MAR and Porter externalities, thus promoting regional green innovation efficiency.

In Model (2), diversified agglomeration shows no significant impact on green innovation efficiency. This finding aligns with several scholars' perspectives, such as Li et al. (2021), who found that diversified agglomeration has an insignificant positive effect on green technology innovation and green product innovation， Similarly, Li (2022) discovered that industrial diversification agglomeration does not significantly promote regional innovation efficiency. When multiple industries cluster in a region, diversified agglomeration fails to fully leverage the advantages of technological complementarity. Instead, it intensifies competition between industries, leading to poor cooperation and potential resource waste within industries, which may hinder the improvement of regional green innovation efficiency. Additionally, industrial barriers exist among different sectors within the YRD urban agglomeration, impeding the efficient flow of various innovation factors. The congestion effects of diversified agglomeration outweigh its economic benefits, ultimately resulting in an insignificant impact on green innovation efficiency in the region.

Regarding control variables, infrastructure development shows a significant positive impact on green innovation efficiency in the YRD urban agglomeration. This may be attributed to improved transportation accessibility, which facilitates the rapid circulation of resources and technology, promotes the diffusion of green innovation technology, and provides new momentum for regional green innovation development. The level of urbanization demonstrates a significant negative effect on green innovation efficiency, suggesting that rapid urbanization has led to environmental pollution, traffic congestion, and ecological degradation, hindering green innovation development in the YRD urban agglomeration.

Table 2 Empirical regression results of industrial agglomeration's impact on green innovation efficiency in the YRD urban agglomeration

	(1)	(2)	(3)	(4)
lnRIS	0.070**		0.041	
	(2.02)		(1.22)	
lnRID		-0.124		-0.190
		(-0.36)		(-0.57)
lnER			0.128***	0.179***
			(3.85)	(5.28)
*lnRIS*lnER*			-0.124***	
			(-4.24)	
lnRID lnER*				-0.804***
				(-3.10)
InFDI	-0.012	-0.011	-0.021	-0.023
	(-0.46)	(-0.40)	(-0.81)	(-0.89)
InHum	0.269*	0.232*	0.320**	0.209
	(1.91)	(1.66)	(2.37)	(1.54)
InFra	0.302***	0.310***	0.251**	0.276**
	(2.79)	(2.79)	(2.42)	(2.56)
InUrb	-1.090***	-1.168***	-0.848**	-1.051***
	(-3.15)	(-3.26)	(-2.53)	(-3.03)
_cons	3.583**	4.441***	2.690	4.126**
	(2.09)	(2.66)	(1.64)	(2.45)
R^2	0.225	0.218	0.297	0.276
N	451	451	451	451

(Notes: t-statistics in parentheses, * p <0.1， ** p<0.05，*** p<0.01)

4.3 The Moderating Effect of Environmental Regulation

Model (3) demonstrates the moderating effect of environmental regulation on the relationship between specialized agglomeration and green innovation efficiency in the YRD urban agglomeration. The results show that the interaction coefficient between environmental regulation and specialized agglomeration is negative and significant at the 1% level, indicating that environmental regulation negatively moderates the relationship between specialized agglomeration and green innovation efficiency. This may be attributed to strict environmental regulations increasing firms' environmental compliance costs, which crowd out resources originally available for innovation and research, weakening firms' ability to utilize the collaborative innovation effects of agglomeration. Additionally, environmental regulations may compel firms to shift their innovation focus toward pollution control and emission reduction rather than breakthrough green technological innovations, thereby reducing the knowledge spillover benefits generated by specialized agglomeration.

Model (4) examines the moderating effect of environmental regulation on the relationship between diversified agglomeration and green innovation efficiency. The findings reveal that the interaction coefficient between environmental regulation and diversified agglomeration is also negative and significant at the 1% level, suggesting that environmental regulation negatively moderates the relationship between diversified agglomeration and green innovation efficiency. As environmental regulations become more stringent, industries must allocate resources to environmental protection, dispersing resources originally available for collaborative innovation and weakening the resource complementarity effects brought by diversified agglomeration. Furthermore, under environmental regulatory pressure, some firms may choose to exit or relocate, disrupting the existing diversified innovation network and reducing the innovation benefits derived from Jacobs externalities.

4.4 Robustness Tests

4.4.1 Alternative Dependent Variable

To assess the robustness of our findings, we begin by conducting sensitivity analyses using an alternative measure of the dependent variable. Specifically, we re-estimate the green innovation efficiency of the YRD urban agglomeration employing a super-efficiency EBM model that accounts for undesirable outputs. We then integrate these new measurements into our regression equations. The results of these robustness checks are presented in Table 3. Regression outcomes from Models (5) to (8) indicate that both the signs and significance levels of the regression coefficients for our key independent variables and their interaction terms remain largely consistent with those of the baseline model. These findings provide further validation of our conclusions regarding the direct impact of industrial agglomeration on urban green innovation efficiency, as well as the moderating effect of environmental regulation.

Table 3 Results of robustness analyses

	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
lnRIS	0.087***		0.069**		0.088***		0.070**	
	(3.06)		(2.46)		(2.97)		(2.42)	
lnRID		0.122		0.082		0.195		0.018
		(0.43)		(0.30)		(0.63)		(0.06)
lnER			0.117***	0.149***			0.118***	0.162***
			(4.22)	(5.25)			(4.07)	(5.37)
*lnRIS*lnER*			-0.070***				-0.071***	
			(-2.86)				(-2.77)	
*lnRID*lnER*				-0.477**				-0.689**
				(-2.20)				(-2.69)
lnFDI	-0.015	-0.012	-0.021	-0.021	-0.013	-0.010	-0.020	-0.022
	(-0.67)	(-0.54)	(-0.98)	(-0.95)	(-0.56)	(-0.42)	(-0.89)	(-0.98)
lnHum	0.089	0.036	0.115	0.021	0.062	-0.004	0.085	0.006
	(0.76)	(0.30)	(1.02)	(0.18)	(0.48)	(-0.03)	(0.68)	(0.05)
lnInfra	0.352***	0.344***	0.370***	0.309***	0.356***	0.341***	0.308***	0.303***
	(3.94)	(3.72)	(3.53)	(3.42)	(3.61)	(3.36)	(3.21)	(3.07)
lnUrb	-0.699**	-0.882***	-0.557**	-0.803***	-0.713**	-0.909***	-0.501	-0.891***
	(-2.44)	(-2.95)	(-1.99)	(-2.77)	(-2.11)	(-2.64)	(-1.50)	(-2.69)
_cons	2.976**	4.214***	2.667*	4.237***	3.128**	4.432***	2.596*	4.636***
	(2.10)	(3.02)	(1.94)	(3.01)	(1.99)	(2.89)	(1.69)	(3.05)
R^2	0.197	0.178	0.256	0.234	0.190	0.170	0.253	0.236
N	451	451	451	451	407	407	407	407

(Notes: t-statistics in parentheses, * p <0.1， ** p<0.05，*** p<0.01)

4.4.2 Sample Size Reduction Analysis

Second, we perform robustness tests by reducing the sample size. Municipalities, provincial capitals, and first-tier cities typically possess stronger research capabilities and more robust economic foundations, attracting talent through favorable policies and abundant high-quality resources. As a result, these cities generally exhibit higher levels of green innovation compared to other cities. To enhance the robustness of our regression results, we exclude cities with relatively high levels of green innovation—such as Shanghai, Nanjing, Hangzhou, and Hefei—and re-estimate our models using this reduced sample. The results are presented in Table 3. Regression outcomes from Models (9) to (12) indicate that the significance levels of all variables remain consistent with those of the original models, even after sample reduction. This further strengthens the reliability and robustness of our findings.

4.4.3 Endogeneity Tests

We acknowledge the potential endogeneity concerns arising from the possibility that regional development levels and superior resource endowments may attract firms, thereby facilitating industrial agglomeration. This could create endogeneity between different patterns of industrial agglomeration and green innovation efficiency. To address this issue, we employ the System Generalized Method of Moments (System GMM) estimation technique. As presented in Table 4, the results show that specialized agglomeration continues to have a significant impact on green innovation efficiency, whereas diversified agglomeration remains insignificant. Furthermore, environmental regulation consistently exhibits negative moderating effects on both types of agglomeration. These findings provide additional support for our core hypotheses.

Table 4 System GMM estimates for endogeneity analysis

	lnGIE	lnGIE	lnGIE	lnGIE
L.lnGIE	0.353***	0.365***	0.255***	0.326***
	(5.46)	（5.41）	(3.37)	（4.90）
lnRIS	0.158**		0.178***	
	(2.08)		（2.66）	
lnRID		-0.510		-0.940**
		（-0.75）		（-2.25）
lnER			0.076*	0.126***
			（1.91）	（2.66）
*lnRIS*lnER*			-0.173**	
			(-2.01)	
*lnRID*lnER*				-0.766**
				(-2.10)
lnFDI	-0.035	-0.007	-0.021	-0.003
	(-1.15)	(-0.22)	(-0.51)	(-0.08)
lnHum	0.034	-0.064	0.005	-0.111*
	(0.57)	(-0.58)	(0.10)	(-1.83)
lnInfra	0.060	0.052	-0.031	0.108
	(0.75)	(0.40)	(-0.45)	(1.11)
lnUrb	0.069	-0.177	0.055	-0.355
	(0.61)	(-1.07)	(0.41)	(-2.68)***
AR(1)	0.000	0.000	0.000	0.000
AR(2)	0.721	0.866	0.533	0.853
Hansen test	1.000	1.000	1.000	1.000
_cons	0.264	2.817*	1.434*	3.204***
	(0.40)	(1.80)	(1.96)	(4.64)
N	410	410	410	410

(Notes: t-statistics in parentheses, * p <0.1， ** p<0.05，*** p<0.01)

4.4.4 Heterogeneity Analysis Based on City Characteristics

To examine whether the impact of industrial agglomeration on green innovation efficiency varies across cities with different characteristics in the YRD urban agglomeration, we conduct a heterogeneity analysis along three dimensions: city status, development level, and innovation capability, following the classification method of

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Kong et al. (2022). For city status, we classify the original 27 cities (before expansion) as core cities and the remaining cities as non-core cities. In terms of development level, cities are grouped into developed and less-developed categories based on the sample mean of GDP per capita. For innovation capability, we use the annual number of patent applications as the indicator.

Table 5 Regression results of specialized agglomeration by city groups

	Core Cities	**Non-core Cities**	**Developed Cities**	**Less-developed Cities**	**High-innovation Cities**	**Low-innovation Cities**
InRIS	0.032	0.078	0.033	0.122**	0.054	0.051
	（0.87）	（1.04）	（0.74）	（2.30）	(0.81)	（1.28）
Controls	Y	Y	Y	Y	Y	Y
Time-fixed	Y	Y	Y	Y	Y	Y
City-fixed	Y	Y	Y	Y	Y	Y
ρ	1.292	17.847***	0.760	7.787***	3.703	8.899***
	（0.67）	（4.08）	（0.23）	（3.16）	(1.10)	（1.28）
R^2	0.561	0.747	0.527	0.710	0.520	0.671
N	297	154	209	242	154	297

(Notes: t-statistics in parentheses, * p <0.1， ** p<0.05， *** p<0.01)

Table 6 Regression results of diversified agglomeration by city groups

	Core Cities	**Non-core Cities**	**Developed Cities**	**Less-developed Cities**	**High-innovation Cities**	**Low-innovation Cities**
InRID	-0.253	-1.942*	-0.873**	0.432	-1.276***	0.476
	（-0.77）	（-1.74）	（-2.38）	（0.58）	(-3.07)	(1.06)
Controls	Y	Y	Y	Y	Y	Y
Time-fixed	Y	Y	Y	Y	Y	Y
City-fixed	Y	Y	Y	Y	Y	Y
ρ	1.360	20.032***	0.215	10.331 ***	2.870	10.050***
	（0.71）	（5.48）	（0.07）	（4.56）	(0.89)	(4.46)
R^2	0.560	0.751	0.541	0.703	0.552	0.670
N	297	154	209	242	154	297

(Notes: t-statistics in parentheses, * p <0.1， ** p<0.05， *** p<0.01)

The results, shown in Tables 5 and 6, reveal several key findings:

Specialized agglomeration significantly boosts green innovation efficiency in less-developed cities. This is because specialized agglomeration helps distribute production costs and risks, alleviates financing constraints for SMEs within clusters, and generates economies of scale, fostering business entry and driving green innovation. For example, less-developed cities like Fuyang and Huaibei are focusing on specialized industries such as biomedicine and metallurgy, which has contributed to both scale expansion and improved green innovation efficiency.

Diversified agglomeration has no significant effect on green innovation efficiency in core cities but significantly inhibits efficiency in non-core cities. This may be due to the ongoing growth and marginal returns in non-core cities, which were later incorporated into the YRD urban agglomeration. These cities lack strong inter-industry linkages and mature networks, limiting the benefits of cross-industry collaboration. Moreover, diversified agglomeration has a negative impact on green innovation efficiency in developed cities and cities with strong innovation capabilities. Despite their economic strength, diversified agglomeration in these cities has led to congestion effects and environmental pollution, which outweigh the benefits of inter-industry labor sharing and technological spillovers. In cities with strong innovation capabilities, diversified agglomeration is negatively correlated with green innovation, likely due to barriers to inter-industry entry, restricted mobility of innovation resources, and inefficient channels for commercialization.

In conclusion, the heterogeneity analysis shows that the effects of industrial agglomeration on green innovation efficiency differ across city types: specialized agglomeration significantly promotes green innovation in less-developed cities, while diversified agglomeration inhibits efficiency in non-core cities, developed cities, and cities with strong innovation capabilities.

5 Conclusions and Policy Recommendation

This study employs a two-way fixed effects model to examine the impact of different industrial agglomeration patterns on green innovation efficiency in the YRD urban agglomeration, while investigating the moderating role of environmental regulation and conducting heterogeneity analysis based on city characteristics. Our empirical analysis yields three key findings: First, specialized agglomeration significantly enhances green innovation efficiency in the YRD urban agglomeration, while diversified agglomeration shows no significant impact. Second, environmental regulation demonstrates negative moderating effects on both specialized and diversified agglomeration's influence on green innovation efficiency. Third, heterogeneity analysis reveals that the effects of both agglomeration patterns vary substantially across cities with different development characteristics.

These findings yield several important policy implications:

First, policymakers should focus on optimizing regional industrial structure and fostering agglomeration advantages through coordinated development strategies. Our empirical evidence suggests that specialized agglomeration currently plays a dominant role in driving green innovation, indicating the importance of cultivating specialized industrial clusters based on regional comparative advantages. Urban agglomerations should establish cross-regional coordination mechanisms to facilitate the flow of innovation resources from core cities to peripheral areas. This could involve creating innovation networks that connect leading firms, research institutions, and emerging enterprises, thereby enhancing knowledge spillovers and technology diffusion across the region. Furthermore, urban agglomerations should strengthen the integration of innovation chains and industrial chains by promoting collaborative platforms between industry, academia, and research institutions, which can accelerate the transformation of environmental technologies into practical applications.

Second, the findings highlight the need for more nuanced environmental governance approaches that balance innovation promotion with environmental protection. Given the observed negative moderating effect of environmental regulation, policymakers should consider implementing adaptive regulatory frameworks that accommodate different stages of industrial development and innovation capabilities. This could include establishing innovation-friendly environmental standards that provide flexibility for R&D activities while maintaining essential environmental safeguards. Additionally, governments should develop comprehensive innovation support systems, including green innovation funds, environmental technology transfer platforms, and shared innovation infrastructure. These support mechanisms should be designed to reduce the innovation costs associated with environmental compliance while encouraging enterprises to pursue more ambitious environmental goals through technological advancement.

This study has several limitations that warrant attention in future research. Due to data availability constraints, our evaluation system for green innovation efficiency remains incomplete. Research on specialized and diversified agglomeration at the city level is relatively scarce, lacking unified measurement methods. This study only considers different agglomeration patterns; future research could explore various types of industrial agglomeration to enrich the depth and breadth of relevant studies. Additionally, examining the temporal dynamics of agglomeration effects on green innovation and conducting comparative analyses across different urban agglomerations would provide valuable insights for policymaking and theoretical development.

Disclosure statement

The authors declared no potential conflicts of interest.

Declarations of interest: None

Data availability

The datasets produced and/or analyzed in the current study can be obtained from the corresponding author upon reasonable request.

Ethical Approval

No ethical approval was sort for this research because we used a secondary panel data

Consent to publish

We, the authors of this manuscript, give our consent for the publication of this manuscript to be published in the Environmental Science and Pollution Research.

Author's contribution

Conception of the presented idea (Su Jialu), development of the theory and performed the computations (Su Jialu and Oswin Aganda Anaba), data collection and analysis (Su Jialu and Zhen Wang), verification of analytical methods (Yuting Zhang and Oswin Aganda Anaba). All authors discussed the results and contributed to the final manuscript.

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