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Research article

Unveiling the green path: How urban openness reduces pollution and paves the way to sustainability

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ABSTRACT

This study investigates the relationship between openness and pollutant emission intensity across 286 Chinese cities from 1990 to 2019, aiming to evaluate the potential environmental benefits of open economy strategies. The findings indicate that enhanced urban openness significantly lowers pollutant emission intensity. To ensure the robustness of our findings, we make an innovative attempt to employ high-speed rail connection and motorway density as instrumental variables to address potential endogeneity issues, corroborating the reliability of the results through various robustness tests. Moreover, we also find the heterogeneous effects of urban openness on pollution emissions, highlighting the moderating influences of trade complexity, urbanization level, and environmental regulatory intensity. Lastly, the study elucidates the mechanisms through which urban openness diminishes pollution emissions, namely fostering green innovation capacity and enhancing public environmental awareness. This research makes theoretical contributions on understanding the nexus between open economies and environmental protection while offering practical insights to inform governmental environmental policy formulation.

1. Introduction

Since China's accession to the World Trade Organization (WTO) in 2001, foreign trade has experienced rapid growth, leading to continuous improvement in the openness of Chinese cities. Over the past decade, data indicates a substantial increase in China's total import and export volume of goods, rising from 24.4 trillion yuan (~$3.6 trillion) in 2012 to 39.1 trillion yuan in 2021 (NBS, 2022). China's market share in the global market has significantly improved as a result of this rapid expansion. In 2013, it surpassed the United States for the first time, becoming the world's largest country in terms of global trade in goods. In 2021, China maintains its position as the largest global trader in goods, boasting a market share of 13.5% (NBS, 2022).

At the same time, as the economy progresses, there is a growing emphasis on achieving sustainable and harmonious economic and environmental development. China has implemented a series of effective policies and measures, striving to reach the peak of carbon dioxide emissions by 2030 and ultimately achieving carbon neutrality by 2060 (Cao et al., 2021; Khan et al., 2022). The role of trade in emissions reduction cannot be overlooked and has the potential to make significant contributions to global efforts in combating climate change. Although trade can contribute to environmental pollution, it can also serve as a catalyst for positive change by facilitating the transition towards cleaner technologies, promoting sustainable practices, and fostering international collaborations on mitigating global climate change.

Studies on the relationship between urban openness and environmental pollution have garnered increasing interest. Copeland and Taylor (1994) proposed the "*pollution paradise*" hypothesis, utilizing a trade model involving two representative countries—one from the north and the other from the south. They argued that enterprises with higher pollution intensity are more likely to establish themselves in countries or regions with lower pollution costs. However, other studies suggest that trade openness reduces pollutant emissions through technological and

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structural effects (Rafiq et al., 2016; Tiba and Frikha, 2018). While these studies have focused primarily on the national level, it is crucial to examine the impact of openness on pollution at the sub-nation level such as at the city or urban level. Although urban centers account for only 2% of the total land area of the Earth, they contribute to 70% of energy-related greenhouse gas (GHG) emissions (Bellucci et al., 2012). Hence, it is particularly necessary to investigate the influence of openness on air pollution at the prefecture level of major pollution contributors such as China. Studying the impact of trade openness on pollution intensity is more valuable than solely focusing on pollution that fail to take into account the connection between economic activities and pollution. Pollution intensity, however, considers this connection, highlighting efficient resource use that minimizes environmental harm while sustaining economic growth. This paper aims to investigate the influence of openness in China's prefecture-level cities on pollutant emissions.

Using 286 cities in China from 1990 to 2019 as the research setting, we show that enhancement in urban openness leads to a decrease in the emission intensity of urban pollutants. To address potential endogeneity issues, we employed the accessibility of overseas markets and highway density as instrumental variables. The results from the instrumental variable (IV) approach reaffirm the key findings. Moreover, the impact of urban openness on pollutant emission intensity holds true against a battery of robustness checks.

The effect of urban openness on pollutant emissions reduction exhibits heterogeneity across different city attributes. The results reveal that the impact of trade openness on reducing pollution emissions is more pronounced in cities characterized by less trade complexity, lower levels of urbanization and economic development, and stricter environmental regulation. We further explore the mechanisms through which urban openness helps reduce pollutant emission intensity. The results demonstrate that improvements in urban openness helps enhance local green innovation capacity and raise environmental awareness, leading to less pollutant emissions.

This paper contributes to the existing literature in the following aspects. Firstly, the exploration of novel perspectives and mechanisms addresses existing gaps in the literature. This study introduces green innovation capacity and environmental awareness as mediating variables, systematically unveiling their pivotal role in bridging urban openness and pollutant emission intensity for the first time. This discovery not only extends the research frontier on the relationship between urban development and the environment but also establishes a new theoretical framework and points towards future research directions. Secondly, methodological innovation is employed to tackle the issue of endogeneity. This paper introduces overseas market accessibility and road density as instrumental variables for measuring trade openness. This innovative approach not only effectively addresses endogeneity concerns, thereby enhancing the accuracy and reliability of the research findings, but also offers new methodologies for addressing similar challenges in future studies. Thirdly, the study provides deeper practical guidance and policy implications. Beyond theoretical insights, it offers specific recommendations on how to enhance environmental governance in an open economy through empirical analysis. This contribution aims to foster a virtuous cycle between economic growth and environmental preservation, offering robust support for achieving high-quality economic development goals.

The remainder of this study is structured as follows. *Section 2* reviews the existing literature and develop research hypotheses. *Section 3* introduces the methodology and data, and *Section 4* presents the results. *Section 5* concludes the paper and provides policy recommendations.

2. Literature review and hypotheses

2.1. Trade openness and environment

Although existing studies have been investigating the relationship between trade openness and the environment since the 1990s, a definitive consensus remains elusive. Some studies argue that there is a negative correlation between trade openness and the environment. Grossman and Krueger (1991) contend that one of the environmental effects of international trade is the scale effect, whereby a trade-related increase in external demand leads to an expansion of exports. The scale of local production increases, leading to excessive consumption of domestic resources and increased pollution emissions from production and transportation (Streets et al., 2006; H. Wang et al., 2017). In addition, foreign trade, by reinforcing comparative advantage and specialized division of labor, may cause polluting industries to relocate to regions with lower government environmental regulations, leading to changes in the industrial structure of the area, which in turn will affect local pollution emission levels (Li et al., 2015; Wiedmann and Lenzen, 2018).

In recent years, there has been a growing scholarly emphasis on the potential beneficial impacts of trade openness on environmental quality, a trend extensively documented in various studies. The seminal research by Grossman and Krueger (1991), along with subsequent investigations by scholars such as Copeland and Taylor (2001) and Frankel and Rose (2005), underscore the significance of international trade in enabling developing countries to access advanced environmental technologies. Specifically, through the adoption of cleaner production methods and participation in international R&D networks, firms in these nations have notably bolstered their environmental management capabilities and operational efficiencies. This has effectively contributed to curtailing emissions, as evidenced by studies (Noailly and Ryfisch, 2015; Wang and Wang, 2018). Moreover, trade openness stimulates market competition, acting as a potent catalyst for technological innovation among firms (Tang, 2006). To enhance product competitiveness and streamline cost structures, companies have escalated their investments in research and development (R&D), with particular emphasis on integrating environmentally sustainable technologies (Yalabik and Fairchild, 2011; Qiu et al., 2020). This evolution not only enhances the environmental efficiency of production processes but also significantly diminishes pollutant emissions. These findings underscore the positive role of trade openness in advancing environmental protection efforts.

Furthermore, trade openness facilitates optimal global resource allocation and induces structural transformation in industries. As international markets increasingly demand green and environmentally friendly products, enterprises actively respond to market signals by adjusting their production strategies and augmenting the proportion of eco-friendly products, thereby propelling the entire industry towards a green and sustainable direction (Can et al., 2021; Paramati et al., 2022). For pollution-intensive industries, despite short-term industrial relocation due to environmental regulatory disparities (Li et al., 2021a,b), long-term prospects indicate that such relocations indirectly promote the optimization and upgrading of industrial structures in the originating regions, alongside enhancements in environmental standards (Fu et al., 2021). With ongoing industrial upgrading and the continual refinement of environmental regulations, overall pollution emissions have been effectively controlled and exhibit a sustained downward trend (Yu and Wang, 2021; Li et al., 2021a,b).

According to China's official statistics, the total value of China's imports and exports has been increasing yearly, reaching US$6 trillion in 2022, which is 13 times more than that in2000.[1] Air quality has also been gradually improving in recent years, with the concentration of $PM_{2.5}$ in cities declining compared to the preceding year. Hence, while the impact of trade openness on environmental pollution is multifaceted, existing literature and empirical evidence provide proof that, under appropriate policy guidance and market mechanisms, trade openness can facilitate reductions in pollutant emissions intensity through technological and structural effects. Thus, we propose the following hypothesis.

[1] National Bureau of Statistics (NBS). http://www.stats.gov.cn/.

H1. Increased trade openness in cities leads to a reduction in local pollutant emission intensity.

2.2. The mediating effect of green innovation

Trade openness often fosters heightened levels of innovation (Grossman and Helpman, 1990). Several literatures have found that innovative firms in developed countries can earn substantial profits from international trade to cover their innovation costs and spill over their innovations to developing countries through international trade, where developing countries do not pay additional initial R&D costs to learn and absorb technological knowledge from developed countries. This virtuous circle process can promote technological innovation in developed and developing countries (Spulber, 2008). This spillover effect is becoming increasingly important as global value chains become more integrated (Fritsch and Görg, 2015). In recent years, the focus of research has shifted from traditional technological innovation to green technological innovation (Song and Yu, 2018; Q. Wang et al., 2019). Green technological innovation can not only reduce pollution emissions through advanced production processes and technologies, but also improve the efficiency of end-of-pipe treatment, while using high technology to reduce excessive energy consumption and utilization, which in turn reduces environmental pollution from energy consumption (Schiederig et al., 2012).

Boosting green innovation helps curb polluting emissions and enhance environmental quality. Wurlod and Noailly (2018) made a measurement based on sectoral data for 17 OECD countries and found that green innovation promoted a decrease in energy intensity in most sectors. Shan et al. (2021) conducted an empirical test based on the STIRPAT model using data from Turkey from 1990 to 2018, and found that green technology innovation reduced CO_2 emissions. Yang et al. (2021) used the Water Ecological Civilization City Pilot (WECCP) policy as a quasi-natural experiment, conducted an empirical test using the Difference-in-Difference method (DID) with a sample of 283 cities in China from 2010 to 2018, and found that the policy can significantly improve regional green innovation capacity and further reduce regional pollutant emissions. The process of trade openness requires manufacturers to ensure that the products they produced could meet international environmental standards, which can promote green innovation. Therefore, we propose the following hypothesis.

H2. Trade openness fosters green innovation and contributes to further pollutant emission intensity reductions.

2.3. The mediating effect of environmental awareness

When examining the influence of trade openness on the intensity of pollution emissions, environmental awareness emerges as a crucial factor with multifaceted impacts. Firstly, from the perspective of international competitive pressures, with the reduction of trade barriers and deepening global economic integration, governments worldwide are compelled to prioritize environmental conservation in order to maintain competitiveness in international markets and attract foreign investment (Kahn et al., 2015). This external pressure prompts governments to enhance environmental awareness and incorporate environmental protection as a crucial component of national development strategies. Secondly, the widespread adoption of international environmental standards and regulations provides a significant impetus for governments to elevate their environmental consciousness. Participation in international trade necessitates adherence to these standards and regulations, thereby requiring governments to intensify their focus on and management of environmental issues (Ma and Wang, 2021). By aligning with international norms, governments can assimilate advanced environmental concepts and technologies, continuously improving their own environmental awareness and management capabilities. Furthermore, according to the Environmental Kuznets Curve (EKC) theory, as economic growth facilitated by trade openness progresses, governments tend to prioritize environmental protection issues once they achieve a certain level of economic development (Gill et al., 2018). This is because as economies develop, there is an increasing demand from the public for higher quality of life, which includes a stronger emphasis on a healthy ecological environment. Governments respond proactively to meet public demands and expectations by strengthening environmental protection efforts and enhancing environmental awareness.

With heightened governmental awareness of environmental issues, there is a pronounced shift towards prioritizing environmental protection in policy formulation and implementation. Governments are poised to introduce more stringent environmental regulations and standards, bolster penalties for illegal emissions, and encourage enterprises to undertake upgrades in environmental technologies (Pan et al., 2019; Zhou et al., 2021). Concurrently, there will be increased governmental investments in environmental infrastructure and support for the research and application of environmental technologies, aimed at enhancing environmental carrying capacity and reducing pollutant emissions intensity (Feng et al., 2022). Furthermore, the heightened environmental awareness within governments is expected to catalyze public interest and participation in environmental conservation. The public will play a more active role in monitoring corporate and governmental environmental practices, thereby driving both sectors towards more effective environmental measures. This supervisory and motivational role is anticipated to further enhance the implementation effectiveness of environmental policies, thereby lowering pollutant emissions (Jiang et al., 2020).

Thus, trade openness enhances governmental environmental awareness through mechanisms such as international competitive pressures, the proliferation of international environmental standards and regulations, and the dynamics of the EKC. This heightened awareness translates into reduced pollution emissions intensity through policy formulation and implementation, increased environmental investment, and enhanced public engagement and oversight. In light of this, we propose the following hypothesis.

H3. Trade openness enhances the government's environmental awareness and subsequently contributes to further reductions in pollutant emission intensity.

3. Method

3.1. Model setting

To investigate the impact of the urban openness on the pollutant emission intensity, we establish a regression model as follows:

$$PEI_{it} = \alpha + \beta Openness_{it} + \varphi Control_{it} + \mu_t + \gamma_i + \varepsilon_{i,t} \quad (1)$$

The dependent variable PEI_{it} represents the pollutant emission intensity (*PEI*) in city i at year t. $Openness_{it}$ indicates the openness level of the city. $Control_{it}$ represents control variables that may affect the pollutant emission intensity. Specifically, we control for Per capita GDP (*Pgdp*), Population density (*Pop*), Industrial structure (*Stru*), Research and development intensity (*R&D*), Technological level (*Tec*), Transportation (*Trans*), Environmental regulations (*Regu*), Green governance capacity (*Green*). Section 3.3 details these variables selection. μ_t and γ_i are year and city fixed effects, respectively. The coefficient of $Openness_{it}$ is β, which represents the impact of the $Openness_{it}$ on the pollutant emission intensity in the city level.

3.2. Data source

We selected 286 cities in China from 1990 to 2019 as research samples. City-level economic and environmental data, such as gross domestic product, population, foreign direct investment, and environmental pollutant emissions, are all from *China City Statistical Yearbook*.

Night lighting data are all from the National Oceanic and Atmospheric Administration (NOAA). China-US exchange rate data are from CEIC database. Some of the trade data are derived from China Customs Import and Export Statistics Database, Chinese Research Data Services (CNRDS) and United Nations Comtrade database.

3.3. Variables selection

Dependent variable. Pollutant emission intensity (*PEI*), specifically measured as SO_2 emissions per unit of industrial value added, was chosen as the central dependent variable for this study. This metric serves as a critical indicator for evaluating the environmental impacts stemming from regional economic activities. PEI effectively quantifies the volume of pollutants discharged per unit of economic output, playing a vital role in assessing environmental performance and the management capabilities for environmental protection. SO_2, a significant contributor to air pollution, serves as a primary focus due to its direct implications for regional air quality, public health, and overall well-being. It is extensively utilized in the evaluation of air quality and the effectiveness of pollution control measures. Thus, utilizing sulfur dioxide emissions as a specific measure of PEI enables a precise depiction and assessment of pollution levels attributable to urban industrial operations.

Explanatory variable. Our study focuses on urban openness (*Openness*) as the explanatory variable, quantified by the proportion of total import and export trade to GDP. *Openness* serves as a crucial metric for gauging a city's integration into the global economy, delineating both the breadth and depth of its engagement in international economic and trade collaborations. Total import and export trade, serving as a comprehensive and straightforward indicator, directly reflects the extent to which a city embraces external economic interactions. It effectively captures the city's proactive engagement with the global market and underscores the outward-facing nature of its economic activities. Introducing total import and export trade as a core explanatory variable enables a direct and robust exploration of how the city's trade openness influences pollutant emission intensity.

Control variables. Per capita GDP (*Pgdp*): Per capita GDP serves as an indicator for assessing the level of economic development in a city. A higher per capita GDP typically signifies an elevated standard of living and a more advanced economic structure, often accompanied by heightened environmental awareness and investments in environmental protection (Mani and Wheeler, 1998). Population density (*Pop*): Population density refers to the number of individuals residing within a given area. Cities with high population densities usually exhibit a greater concentration of economic and social activities, which can result in increased pollutant emissions (Satterthwaite, 1997). Industrial structure (*Stru*): The industrial structure of a city pertains to the relative composition of different industries within its economy. Various industries have distinct environmental impacts, with heavy industries often generating higher levels of pollutants (Friedl and Getzner, 2003). The proportion of the secondary industry in GDP is used as a variable to control for industrial structure. Research and development intensity (*R&D*): R&D intensity denotes the level of investment dedicated to scientific research and technological innovation within a city. Higher R&D intensity is typically associated with technological advancements and the development of environmentally friendly technologies, which contribute to the reduction of pollutant emissions (Bao et al., 2011). The internal expenditure on city R&D is used as a means to control for this factor. Technological level (*Tec*): Technological level refers to the adoption of advanced production and environmental management technologies within a city. A higher technological level often corresponds to more sophisticated pollution control equipment and environmental management practices, leading to reduced pollutant emissions (Brock and Taylor, 2005). The city's expenditure on science and technology is utilized as an indicator of technological level. Transportation (*Trans*): Transportation activities encompass vehicular travel and the movement of goods. Increased transportation volume is indicative of greater transportation activities and traffic flow, which can contribute to heightened pollutant emissions (Mazzanti et al., 2008). The city's freight volume is used as a means to control for the influence of transportation. Environmental regulations (*Regu*): Environmental regulations refer to government-imposed restrictions and management measures aimed at mitigating pollutant emissions. Stringent environmental regulations can incentivize businesses and residents to adopt more environmentally friendly practices, resulting in reduced pollutant emissions (Lutsey and Sperling, 2008). The proportion of investment in industrial pollution control relative to industrial value-added is utilized to reflect the intensity of environmental regulations. Green governance capacity (*Green*): Green governance capacity pertains to a city's management and capabilities in terms of environmental protection and sustainable development. Higher green governance capacity indicates improved environmental management, planning, and policy implementation, contributing to the reduction of pollutant emissions (Henderson et al., 2012; Keller and Levinson, 2002). The city's rate of municipal solid waste treatment is used as an indicator of its green governance capacity.

In order to enhance the precision and comprehensibility of our analyses, we employed logarithmic transformations on all variables.

4. Results

4.1. Baseline analysis

The results presented in Table 1 illustrate a gradual decline in pollutant emissions intensity associated with urban openness. In the first column, the analysis focuses solely on the impact of urban openness as the main explanatory variable, revealing a significant coefficient of −0.206 at 1% significance level. This indicates a strong negative effect of urban openness on pollutant emissions intensity.

In the second column, additional control variables are introduced, while still observing a significantly negative coefficient for urban openness. Furthermore, in the third column, time controls and city controls are incorporated. Remarkably, the regression coefficient for urban openness remain statistically significant at −0.094. These findings indicate that, when holding other factors constant, regions with higher

Table 1
Benchmark regression results.

	(1)	(2)	(3)
Openness	−0.206***	−0.049***	−0.094***
	(0.008)	(0.010)	(0.010)
Pgdp		−0.360***	−0.134***
		(0.016)	(0.011)
Pop		−0.592***	−0.153***
		(0.021)	(0.035)
Stru		−0.213***	−0.130***
		(0.023)	(0.017)
R&D		0.092***	0.021
		(0.011)	(0.019)
Tec		−0.320***	−0.054***
		(0.016)	(0.017)
Trans		0.427***	−0.051***
		(0.015)	(0.008)
Regu		0.001	−0.010***
		(0.008)	(0.003)
Green		0.003	0.001
		(0.004)	(0.001)
_cons	−5.872***	−2.499***	−2.961***
	(0.020)	(0.157)	(0.226)
TE	No	No	Yes
CE	No	No	Yes
N	8284	7307	7290
adj. R^2	0.073	0.452	0.953

Note: Robust standard errors are clustered at the city level and provided in parentheses. The dependent variable is *PEI*. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. TE and CE refer to time and city fixed effects, respectively. The same as below.

levels of openness exhibit lower levels of pollutant emissions intensity.

Overall, even after considering multiple variables and accounting for fixed effects, the coefficient for *Openness* experiences minimal changes. This suggests that the association between urban openness and pollutant emissions intensity remains robust. Consequently, it can be concluded that higher levels of openness are consistently associated with lower levels of pollutant emissions intensity. Since the implementation of China's economic reform and opening-up policy, cities have progressively embraced greater openness to the global arena. This reform has spurred rapid economic expansion, drawing a substantial influx of international companies and foreign direct investment (FDI). With the surge in FDI, international trade has surged significantly, forging stronger ties between Chinese cities and global markets. This heightened connectivity has compelled Chinese companies to not only pursue economic gains but also address environmental issues to adhere to international environmental standards.

4.2. Endogeneity concerns

Addressing the endogeneity concern is crucial in establishing the causal relationship between urban trade openness and pollutant emissions intensity. To mitigate the potential reverse causality, we employ instrumental variable methods in this study. Specifically, we utilize two instrumental variables: High speed rail (*HSR*) and road density (*Road*).

High-speed rail (HSR), characterized by its rapid and convenient transportation, significantly facilitates economic interactions and the movement of people between cities, thus closely intertwining with urban openness. However, the introduction of HSR does not directly impact air pollution levels, rendering it an ideal instrument variable. In this study, a *HSR* value of 1 indicates that the city opens high-speed rail in a given year, the value is 1, whereas a value of 0 signifies otherwise. Additionally, road density reflects the development of the internal road network within cities, enhancing transportation convenience and potentially increasing urban openness. Importantly, road density does not have a direct causal relationship with pollutant emissions intensity, making it a suitable instrumental variable to address endogeneity concerns.

The first-stage regression results in Column (1) in Table 2 indicate a significant correlation between the instrumental variables (*HSR* and *Road*) and urban openness. This confirms that the selected instruments are capturing the variation in urban openness effectively. In the second stage, Column (2) shows that urban openness has a significant negative impact on pollutant emissions intensity, consistent with our baseline findings. Moreover, *Kleibergen-Paap F* statistic of 63.371 indicates that the instrumental variables used are unlikely to be weak instruments, and *Hansen J* statistic of 6.989 (P = 0.008) and *Kleibergen-Paap LM* of 123.985 (P = 0.000) indicate not overidentification and under-identification (Bazzi and Clemens, 2013). Therefore, the two-stage least squares (2SLS) results suggest that our baseline findings regarding the effect of urban openness on pollutant emissions intensity are robust and not driven by severe endogeneity issues.

Table 2
Results for the 2SLS approach.

	(1)	(2)
	First	Second
Openness		−0.190***
		(0.059)
HSR	0.048***	
	(0.014)	
Road	0.147***	
	(0.011)	
Pgdp	−0.440***	−0.324***
	(0.013)	(0.021)
Pop	−0.330***	−0.521***
	(0.029)	(0.025)
Stru	0.130***	−0.142***
	(0.019)	(0.040)
R&D	−0.004	0.089***
	(0.019)	(0.015)
Tec	0.039**	−0.279***
	(0.017)	(0.024)
Trans	0.048***	0.362***
	(0.011)	(0.017)
Regu	0.015***	−0.025***
	(0.005)	(0.009)
Green	−0.001	−0.009**
	(0.002)	(0.004)
_cons	4.426***	−3.574***
	(0.237)	(0.435)
TE	Yes	Yes
CE	Yes	Yes
Kleibergen-Paap rk LM		123.985
Kleibergen-Paap rk Wald F		63.371
Hansen J		6.989
N	7247	7247
adj. R^2	0.956	0.516

Notes: *HSR* and *Road* are instrumental variables.

4.3. Robustness checks

Alternative measures. To test the robustness of our results, we use alternative measures of key variables and re-estimate the baseline regressions. First, in addition to sulfur dioxide, industrial smoke dust (*Dust*) and nitrogen oxides (*NOx*) are major pollutants in cities. Therefore, we substitute the original dependent variable with industrial smoke dust emissions intensity (measured as industrial smoke dust emissions per unit of industrial output) and nitrogen oxide emissions intensity (measured as nitrogen oxide emissions per unit of industrial output). Moreover, we replace the core explanatory variable, *Openness*, with nighttime light data. The brightness and distribution of nighttime lights often reflect the level of economic activity in cities, with higher brightness indicating increased commercial, industrial, and service activities (Henderson et al., 2012). This aligns with the concept of urban openness. The regression results after variable substitution are presented in Columns (1) to (3) of Table 3. We observe that the negative impact of urban openness on pollutant emissions intensity remains significant, indicating the robustness of our baseline analysis.

Adding additional control variables. Foreign direct investment (FDI) is an important economic factor that can influence industrial structure, technological progress, and management standards in cities (Su and Liu, 2016). To account for its potential impact, we include FDI as a control variable in our model. The results are reported in Column (4) of Table 3, where the coefficient for urban openness remains negative and statistically significant. This suggests that our main findings hold even after controlling for FDI. Additionally, variations in environmental policies, industrial policies, and trade policies across different provinces can also affect the relationship between urban openness and pollutant emissions intensity. To address this, we introduce a control variable representing provincial policies, computed by multiplying the province code by the year. The results, presented in Column (5) of Table 3, show that the coefficient for urban openness remains negative and statistically significant, indicating the robustness of our findings when controlling for provincial policies.

Eliminating extreme samples. Cities of very large or small size often showcase distinctive characteristics and vitality in contrast to typical cities. The level of economic activity, industrial structure complexity, and population density can differ significantly. To improve the robustness of our relationship analysis applicable to ordinary cities, we exclude extreme samples. Following the approach of Pan et al. (2021), we exclude cities with a total population of more than 10 million and less than 1 million. The sample of excluded cities includes: *Chongqing, Shanghai, Beijing, Chengdu, Guangzhou, Shenzhen, Wuhan, Tianjin, Tianjin, Xi'an, Zhengzhou, Zhengzhou, Shijiazhuang, Linyi, Changsha, Dongguan, Qingdao,* etc. The results are reported in Column (6) of Table 3,

Table 3
Robustness tests.

	(1)	(2)	(3)	(4)	(5)	(6)
Openness	−0.062***	−0.069***	−0.008**	−0.092***	−0.054***	−0.096***
	(0.014)	(0.010)	(0.003)	(0.010)	(0.010)	(0.011)
Pgdp	−0.103***	−0.109***	−0.094***	−0.131***	−0.098***	−0.143***
	(0.013)	(0.010)	(0.010)	(0.011)	(0.010)	(0.013)
Pop	−0.205***	−0.217***	−0.119***	−0.148***	−0.102***	−0.182***
	(0.036)	(0.030)	(0.036)	(0.035)	(0.028)	(0.035)
Stru	−0.134***	−0.124***	−0.143***	−0.130***	−0.123***	−0.162***
	(0.019)	(0.014)	(0.017)	(0.017)	(0.015)	(0.019)
R&D	0.067***	0.090***	0.020	0.027	−0.018	−0.018
	(0.023)	(0.023)	(0.019)	(0.020)	(0.019)	(0.026)
Tec	−0.062***	−0.135***	−0.060***	−0.050***	−0.013	−0.026
	(0.022)	(0.018)	(0.017)	(0.017)	(0.017)	(0.018)
Trans	−0.051***	−0.050***	−0.058***	−0.047***	−0.013	−0.070***
	(0.009)	(0.007)	(0.008)	(0.008)	(0.009)	(0.009)
Regu	−0.002	−0.000	−0.012***	−0.011***	−0.010***	−0.013***
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Green	−0.002	0.005***	0.001	0.001	−0.001	0.000
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
FDI				−0.023**		
				(0.010)		
_cons	−4.738***	−5.114***	−3.273***	−2.924***	−3.641***	−2.544***
	(0.250)	(0.227)	(0.221)	(0.227)	(0.215)	(0.318)
TE	Yes	Yes	Yes	Yes	Yes	Yes
CE	Yes	Yes	Yes	Yes	Yes	Yes
PE	No	No	No	No	Yes	No
N	7290	7110	7426	7290	7230	6404
adj. R^2	0.958	0.978	0.950	0.951	0.960	0.951

Note: The dependent variables in columns (1)–(2) are the emission intensity of industrial smoke and dust (*Dust*) and the emission intensity of nitrogen oxides (*NOx*), respectively. In column (3), the *Openness* variable is replaced by night lighting data. In column (4), the foreign direct investment is added as a control variable. In column (5), we add provincial policy effect (PE), which is obtained by multiplying provincial code and year. In column (6), the urban samples with a population of more than 10 million and less than 1 million are excluded.

Table 4
Heterogeneity results.

	(1)	(2)	(3)	(4)	(5)	(6)
	High-TCE	Low-TCE	High-Urban	Low-Urban	High-ER	Low-ER
Openness	−0.001	−0.069***	−0.015	−0.085***	−0.076***	0.006
	(0.012)	(0.016)	(0.011)	(0.015)	(0.014)	(0.015)
Pgdp	−0.027**	−0.334***	−0.028***	−0.279***	−0.191***	−0.031**
	(0.011)	(0.037)	(0.010)	(0.028)	(0.020)	(0.012)
Pop	0.037	−0.516***	−0.004	−0.349***	−0.360***	0.037
	(0.032)	(0.088)	(0.032)	(0.061)	(0.053)	(0.041)
Stru	−0.043***	−0.342***	−0.044**	−0.275***	−0.190***	−0.081***
	(0.015)	(0.050)	(0.020)	(0.032)	(0.027)	(0.021)
R&D	0.006	−0.083*	0.038	−0.049	−0.025	0.021
	(0.024)	(0.045)	(0.026)	(0.038)	(0.034)	(0.025)
Tec	0.025	0.027	0.000	−0.035*	−0.021	0.019
	(0.029)	(0.021)	(0.034)	(0.019)	(0.019)	(0.031)
Trans	−0.007	−0.189***	−0.007	−0.122***	−0.060***	−0.006
	(0.009)	(0.024)	(0.011)	(0.016)	(0.013)	(0.012)
Regu	0.006*	−0.048***	0.007	−0.036***	−0.000	−0.012**
	(0.004)	(0.013)	(0.005)	(0.007)	(0.013)	(0.006)
Green	−0.000	0.007	0.001	0.008***	0.003	0.004**
	(0.001)	(0.007)	(0.002)	(0.003)	(0.003)	(0.002)
_cons	−4.762***	1.272	−5.067***	0.383	−2.342***	−4.765***
	(0.189)	(0.849)	(0.216)	(0.657)	(0.410)	(0.256)
TE	Yes	Yes	Yes	Yes	Yes	Yes
CE	Yes	Yes	Yes	Yes	Yes	Yes
N	3553	3737	2351	4939	4708	2572
adj. R^2	0.991	0.941	0.990	0.947	0.948	0.985

Note: This table presents the regression results of the heterogeneity analysis based on trade dependence and technical complexity of export trade. Column (1) presents the results for cities with high technical complexity of export (High-TCE), while column (2) presents the results for cities with low technical complexity of export (Low-TCE). The classification of high and low categories is based on the national average. Column (3) displays the results for cities with high urbanization (High-Urban), while Column (4) presents the results for cities with low urbanization (Low-Urban). Column (5) displays the results for cities with high environmental regulation (High-ER), while Column (6) presents the results for cities with low environmental regulation (Low-ER). The distinction between high and low categories is based on the national average.

demonstrating the robustness of the relationship between urban openness and pollutant emission intensity in ordinary cities after eliminating extreme cases.

4.4. Heterogeneity analysis

To account for potential variations in across city attributes, we conduct a heterogeneity analysis. This analysis considers the differences in trade complexity, urbanization, and environmental regulation among cities.

(1) Trade Complexity

Trade complexity can influence a city's industrial structure and environmental needs (Rafique et al., 2022). Based on the methodology introduced by Hausmann et al. (2007), we calculate the Technical Complexity of Export (TCE) and conduct a grouped regression using this index. Table 4 presents the results of the grouped regression analysis, revealing that the impact of urban openness on pollutant emission intensity is more pronounced in cities with low trade complexity, as demonstrated in columns (1) and (2), which aligns with our prior expectations. Cities with high levels of trade complexity often entail complex industrial and value chains, which are distinguished by increased technological content and environmental standards (Costinot, 2009). The influence of urban openness on the intensity of pollutant emissions in these cities may be less significant due to their implementation of comparatively higher environmental standards and technological measures to mitigate such emissions (Jiang and Liu, 2023). Conversely, cities with low trade complexity may rely more on traditional industries and basic products, allocating fewer resources to environmental protection (Le et al., 2022). As a result, urban openness has a more substantial effect on the intensity of pollutant emissions in such cities. Cities with a high level of trade complexity often possess strong environmental governance capabilities and regulatory mechanisms, which enable them to manage and control pollutant emissions more effectively. Thus, urban openness might not be the primary determinant in such cities, but rather a contributing factor, working in conjunction with other environmental governance measures. On the contrary, cities with limited trade complexity may possess weaker environmental governance capabilities, resulting in urban openness having a more significant impact on pollutant emissions intensity.

(2) *Urbanization*

The relationship between openness and pollutant discharge may also vary with urbanization levels (Brajer et al., 2011). We measure urbanization by the proportion of urban population to the total population. The results of the grouped regression analysis are presented in Table 4, where Columns (3) and (4) demonstrate that urban openness has a more significant effect in reducing pollutant emissions intensity in low urbanization cities, aligning with our expectations. Cities with high urbanization rates are characterized by extensive industrial and commercial development, encompassing a wide range of industries and activities. These cities have likely implemented various environmental protection measures and technological advancements to address the environmental challenges associated with urbanization and economic growth (Satterthwaite, 1997). Consequently, urban openness may not be the primary determining factor in highly urbanized cities, as other factors such as technological advancements and the implementation of environmental policies may have a greater impact on pollutant emissions. On the other hand, low urbanization cities rely more on traditional agriculture or natural resource exploitation, resulting in a greater influence of urban openness on pollutant emissions intensity. Moreover, highly urbanized cities tend to have higher population densities and stable industrial structures, leading to more pollution sources and emission activities (Liang et al., 2019). In such cases, the impact of urban openness on pollutant emissions intensity may be relatively smaller. Conversely, low urbanization cities with lower population densities and smaller urban scales have fewer pollution sources and emission activities, making it easier to observe the influence of urban openness on pollutant emissions intensity.

(3) *Environmental regulation*

The potential heterogeneous effect of environmental regulation is also important in examining the relationship between trade openness and pollution emissions. The results of the grouped regression analysis are presented in Table 4, where columns (5) and (6) indicate that for cities with high environmental regulation, the effect of reduced urban openness on pollutant emission intensity is more pronounced, in line with our expectations. Cities with a heightened level of environmental regulation tend to adopt a proactive stance towards environmental protection, dedicating substantial resources and efforts to curbing pollutant emissions (Galli et al., 2020). In this context, urban openness emerges as an effective tool for promoting environmental protection and emission reduction. Consequently, in cities with a strong environmental regulation, the impact of urban openness on pollutant emissions intensity is anticipated to be significant. Furthermore, cities with high environmental regulation are more inclined to implement stringent environmental protection policies and measures, such as restricting the development of highly polluting industries, promoting clean energy utilization, and advocating for sustainable transportation. These policies and measures synergize with the influence of urban openness, resulting in a more effective reduction of pollutant emissions. Conversely, cities with low environmental regulation may lag behind in implementing environmental protection measures, leading to a less pronounced impact of urban openness on pollutant emissions intensity. Moreover, cities with high environmental regulation often prioritize environmental education and public awareness campaigns, fostering a deeper understanding and involvement in environmental protection (Hirazawa and Yakita, 2005). In such cities, urban openness finds greater acceptance and comprehension, and when coupled with proactive environmental regulation, it significantly affects pollutant emissions intensity.

4.5. Underlying mechanisms

We further explore the mechanisms through which urban openness influences pollutant emissions intensity. Specifically, we examined the role of local green innovation and environmental awareness as potential mediators. In line with Hypothesis 2, we hypothesized that urban openness would enhance local green innovation and promote the adoption of greener production processes. To test this hypothesis, we utilized the number of green patents filed in the current year as an indicator of local green innovation capacity (*GreeInno*). The results of the channel analysis for green innovation are presented in columns (1) and (2) of Table 5. The findings reveal a positive and significant coefficient for *Openness* in column (1), indicating that greater urban openness is associated with increased local green innovation. Moreover, column (2) shows a negative and significant coefficient for *GreeInno*, indicating that higher levels of local green innovation are linked to a reduction in pollutant emissions intensity. Taken together, these results support the proposed mediating mechanism of green innovation outlined in Hypothesis 2.

Similarly, in line with Hypothesis 3, we posited that urban openness would bolster local environmental awareness, leading to a decrease in pollutant emissions intensity. To examine this hypothesis, we employed the frequency of environmental terms in the work reports of prefecture-level cities as a proxy for local environmental awareness. We theorized that increased openness to international trade strengthens the connection between cities and the global community, resulting in heightened environmental awareness, changes in supply chains and production methods, a greater emphasis on environmentally friendly choices, and

Table 5
Mechanism analysis.

	(1)	(2)	(3)	(4)
	GreeInno	*PEI*	*EnviAware*	*PEI*
GreeInno		−0.044***		
		(0.005)		
EnviAware				−0.014***
				(0.002)
Openness	0.483***	−0.085***	0.169***	−0.084***
	(0.035)	(0.012)	(0.061)	(0.012)
Pgdp	0.173***	−0.156***	−0.187**	−0.165***
	(0.047)	(0.014)	(0.090)	(0.013)
Pop	0.670***	−0.198***	−0.152	−0.255***
	(0.106)	(0.037)	(0.125)	(0.038)
Stru	−0.294***	−0.171***	0.092	−0.177***
	(0.056)	(0.021)	(0.098)	(0.019)
R&D	−0.209***	−0.014	0.071	0.022
	(0.072)	(0.026)	(0.077)	(0.023)
Tec	0.316***	−0.043**	0.066	−0.074***
	(0.047)	(0.018)	(0.070)	(0.018)
Trans	0.207***	−0.040***	0.016	−0.052***
	(0.038)	(0.010)	(0.054)	(0.009)
Regu	−0.007	−0.012***	−0.026	−0.011***
	(0.014)	(0.004)	(0.025)	(0.004)
Green	−0.054***	−0.000	0.037***	0.003
	(0.006)	(0.002)	(0.011)	(0.002)
_cons	0.519	−2.392***	10.445***	−2.476***
	(0.976)	(0.317)	(1.186)	(0.278)
TE	Yes	Yes	Yes	Yes
CE	Yes	Yes	Yes	Yes
N	5800	5800	5881	5881
adj. R^2	0.889	0.946	0.365	0.950

Note: This table presents the results of the mediating mechanisms of green innovation (*GreeInno*) and environmental awareness (*EnviAware*) in transmitting the influence of urban openness (*Openness*) to pollutant emission intensity (*PEI*). Columns (1) and (3) display the effects of *Openness* on *GreeInno* and *EnviAware*, respectively. Columns (2) and (4) show the effects of *Openness* and the corresponding intermediary variables on *PEI*.

an inclination to adopt cleaner and low-carbon production methods, ultimately leading to reduced pollutant emissions. The results of the channel analysis for environmental awareness are presented in columns (3) and (4) of Table 5. Column (3) indicates a positive and significant coefficient for *Openness*, suggesting that greater urban openness is associated with increased levels of environmental awareness. Furthermore, column (4) reveals a negative and significant coefficient for environmental awareness, indicating that higher levels of local environmental awareness are linked to a reduction in overall pollutant emissions intensity. These findings provide support for the proposed mediating mechanism of environmental awareness outlined in Hypothesis 3.

5. Conclusions and discussion

Using data from 286 Chinese cities between 1990 and 2019 as the research setting, this study investigates the impact of urban openness on pollutant emission intensity and has illustrated several important findings.

First, this study enhances understanding of the nexus between urban openness and environmental pollution. It substantiates previous conjectures regarding the potentially positive environmental impacts of openness while meticulously analyzing the underlying mechanisms. This analysis offers a novel and comprehensive academic perspective for exploring the symbiotic evolution of urban openness and environmental conservation in the era of globalization. By adopting a macroscopic and systematic approach, the research evaluates the environmental ramifications of urban openness policies. It provides a scientific foundation and strategic insights that can inform policymakers, facilitating informed decision-making in environmental management and urban development strategies.

Second, this study highlights the critical role of environmental heterogeneity in elucidating the relationship between urban openness and pollutant emission intensity. Emphasizing the significance of this relationship, the study underscores the necessity of delving into the diverse factors of environmental heterogeneity across cities. These factors encompass variations in trade complexity, levels of urbanization, and the strength of environmental regulations, among others. Such disparities not only significantly influence the strength of this relationship but also have the potential to alter its direction, thereby constituting an essential component of the analytical framework. This theoretical insight imparts valuable lessons for both scholars and policymakers: when analyzing and formulating policies, careful consideration of the distinctive environmental contexts and conditions of each city is crucial to ensure the efficacy and applicability of strategies.

Third, this study contributes novel insights into the mediating role of green innovation and environmental awareness in the relationship between urban openness and pollutant emission intensity. This innovative finding not only enhances the theoretical framework concerning the impact of urban openness on environmental quality but also establishes a robust theoretical basis for understanding how cities can facilitate positive advancements in environmental quality through economic restructuring and societal attitudes. Specifically, the study emphasizes the beneficial impacts of urban openness in fostering green innovation and fostering public environmental awareness. It further elucidates how these processes indirectly lead to a reduction in pollutant emission intensity. These findings introduce fresh theoretical perspectives and profound practical implications into the exploration of pathways toward sustainable urban development.

Fourth, this paper enhances the research framework concerning the nexus of urban development and the environment. It establishes a comprehensive analytical framework to investigate the association between urban openness and pollutant emission intensity. This framework not only systematically incorporates the multidimensional factors influencing this complex relationship but also intricately exposes the internal mechanisms and dynamic pathways among these factors. This theoretical advancement not only expands the scope and depth of research on the urban development-environment relationship but also establishes a more robust and comprehensive theoretical underpinning for future studies. It guides the field towards a more refined and systematic trajectory of development.

Based on the findings, this paper proposes several policy recommendations. Foremost is the imperative to bolster urban openness to catalyze environmentally sustainable development. Policymakers should actively deepen cities' internationalization efforts, encompassing initiatives such as strengthening international trade partnerships, attracting foreign direct investment, and fostering the presence of multinational corporations. Concurrently, efforts should focus on optimizing the structure of urban openness. Through strategic policy guidance and incentives, priority should be given to channeling foreign investments and advanced technologies into green and low-carbon industries. This approach aims to expedite the transition of urban economies towards high-quality development, thereby achieving sustainable optimization and enhancement of environmental quality.

Furthermore, there should be a concerted effort to promote green innovation and enhance environmental awareness. The government ought to implement a series of innovation incentives, including subsidies for research and development, tax exemptions, and innovation grants, aimed at invigorating enterprises and scientific institutions engaged in green technological innovation. Concurrently, attention should be directed towards advancing environmental education, fostering public and corporate awareness of environmental protection through diverse channels. Advocating for green consumption and promoting a low-carbon lifestyle are crucial components to cultivate a conducive societal environment for widespread participation in environmental conservation efforts.

Lastly, enhancing the environmental regulatory framework is essential for ensuring the effective implementation of policies. The government should prioritize the establishment of a scientifically rigorous, efficient, and transparent environmental regulatory system. This entails bolstering real-time monitoring and stringent oversight of industrial pollutant emissions, alongside establishing a robust environmental monitoring network and information disclosure mechanism to ensure the accuracy and timeliness of environmental data. Moreover, imposing stricter penalties for infractions and increasing the costs associated with violations are imperative measures to enforce environmental laws effectively, thereby fostering a conducive ecological and environmental framework that underpins the city's sustainable development.

In future research, the relationship between urban openness and pollutant emissions intensity needs to be further explored. It is crucial to conduct comprehensive analyses of the underlying factors and mechanisms, with particular emphasis on key domains such as green innovation, environmental regulation, and economic structure. Through rigorous empirical studies, the aim is to clarify how these factors directly or indirectly influence changes in pollutant emission intensity within the context of urban openness. Simultaneously, the significant influence of socio-economic factors, such as urban residents' lifestyles and consumption patterns, on environmental pollution cannot be overlooked. Future research should focus on analyzing the independent and interactive roles of these socio-economic factors in environmental pollution processes. Furthermore, there is a need to explore how urban openness can indirectly regulate pollutant emission intensity by shaping residents' behavioral patterns. Such research endeavors will not only contribute to enriching and refining the pertinent theoretical framework but also offer a robust scientific foundation and decision-making support for crafting and executing more precise and effective environmental policies.

CRediT authorship contribution statement

Chao Zhong: Writing – original draft. **Hongbo Cai:** Supervision, Conceptualization. **Lin Liu:** Investigation. **Rui Xue:** Writing – review & editing. **Yuli Shan:** Supervision, Investigation.

Declaration of competing 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.

Data availability

Data will be made available on request.

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