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An Empirical Study of the Relationship Between FDI and Ecological Environment Pollution-Panel Data Analysis Based on Shandong Province

Shuoyuan Zhang[1], Bosong Yu[1], Xiangmei Li[2], Yongyan Zhao[1], Mingjin Zou[1], Weiguo Sun[3,*]

1 College of Civil Engineering and Transport, Northeast Forestry University, Harbin, China
2 Beijing Urban Construction Engineering Co., LTD, Beijing, China
3 College of Civil Engineering and Transport, Northeast Forestry University, Harbin, China

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ABSTRACT

As China's economic liberalisation continues to advance, foreign direct investment (FDI) has emerged as a pivotal factor in driving economic growth. Nevertheless, with the rapid progression of industrialisation and urbanisation, the environmental implications of FDI, particularly in relation to pollution, have garnered significant attention within both academic and policy-making circles. Utilising panel data from 16 prefecture-level cities in Shandong Province spanning the period from 2016 to 2022, this study develops a hybrid model integrating Generalised Least Squares (GLS) and Gradient Boosting Regression (GBR) to investigate the influence of FDI on sulphur dioxide (SO_2) emissions and its nonlinear dynamics. The findings reveal a multifaceted relationship between FDI and SO_2 emissions. In the initial stages, FDI inflows exhibit a positive correlation with SO_2 emissions, reflecting a "pollution haven" effect, whereas the anticipated pollution mitigation effects are not yet evident. After accounting for variables such as per capita income and industrial output, the impact of FDI on environmental degradation remains substantial, albeit moderated by regional policy frameworks and technological advancements. Importantly, increased fiscal expenditure amplifies the effectiveness of policy interventions in enhancing environmental quality, while technological innovation and financial investment collectively contribute to the reduction of pollutants. In conclusion, this study offers policy recommendations aimed at improving the quality of FDI inflows, bolstering governmental policy support, and facilitating the green transition of industries, with the goal of achieving a harmonious balance between economic growth and environmental sustainability.

1. Introduction

FDI has been a significant contributor to economic development since the initiation of China's reform and opening-up policies. In the contemporary context, as the imperative for green development gains momentum, China's economic growth is transitioning towards a phase of high-quality development. The Twentieth National Congress of the Communist Party of China (CPC) has

* *Corresponding author.*
E-mail address: davisun7811@163.com

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underscored the critical importance of green transformation, sparking extensive discourse on the environmental implications of FDI as a key driver of economic progress. Shandong Province, being a major industrial hub, has witnessed a continuous expansion in the scale of FDI. However, this growth has been accompanied by increasingly prominent environmental challenges. This study focuses on examining the impact of FDI on SO_2 emissions, integrating the Environmental Kuznets Curve (EKC) hypothesis and employing a hybrid model to analyse its non-linear characteristics. The findings aim to provide a robust foundation for the formulation of policies that align economic growth with environmental sustainability.

2. Literature Review

FDI has served as a critical driver of China's economic growth, facilitating industrial upgrading and employment expansion through the introduction of capital, advanced technologies, and managerial expertise. However, the reliance on a resource-intensive development model has exacerbated environmental degradation, particularly through heightened resource consumption and increased pollutant emissions during periods of rapid industrialisation and urbanisation. Since the 19th National Congress of the CPC, the nation has prioritised green development, advocating for policies such as the establishment of green production systems and the promotion of clean energy. Against this backdrop, investigating the relationship between FDI and environmental pollution holds significant practical relevance.

The existing literature on FDI and environmental pollution presents three primary hypotheses. The first is the "pollution haven" hypothesis, which posits that developing countries may lower environmental standards to attract FDI, resulting in the relocation of pollution-intensive industries and the creation of "pollution havens." The second is the "pollution halo" hypothesis, which suggests that FDI can improve the host country's environmental governance capabilities through technological spillovers and knowledge transfer. The third is the Environmental Kuznets Curve (EKC) hypothesis, which proposes an inverted U-shaped relationship between pollution levels and per capita income. According to this hypothesis, economic growth initially exacerbates environmental pollution, but technological advancements and structural changes eventually lead to environmental improvement as income levels rise.

International scholars have made substantial progress in advancing research on the Environmental Kuznets Curve (EKC), particularly in terms of methodological innovation and the expansion of variables. Since [1] first introduced the concept of the EKC in 1993, subsequent studies have sought to validate its applicability and explore its boundary conditions. For instance, [2] found that the inverted U-shaped relationship between carbon emissions and economic growth in OECD countries weakened when the share of clean energy exceeded 30%, highlighting how green transitions can accelerate the inflection point of the EKC. This finding provides cross-country evidence supporting the notion that green transitions expedite the EKC's turning point. In terms of regional heterogeneity, [3] analysed state-level data in the United States and confirmed that regions with stringent environmental regulations, such as California, reach the EKC peak earlier, underscoring the interaction between geography and policy. Additionally, research on the EKC in the context of globalisation has yielded new insights. [4] demonstrated through cross-country panel analysis that the synergy between FDI and international trade could advance the peak of carbon emissions by 10–15 years, though effective environmental regulations are necessary to prevent the formation of "pollution havens." This finding builds on the foundational work of [5] by emphasising the pivotal role of institutional quality. Recent studies have also enhanced model complexity. For example, [6] employed quantile regression to reveal that the EKC is more pronounced in high-income countries, while low-income countries exhibit a linear increase in pollution due to technological lock-in effects. Meanwhile, [7] integrated machine learning into EKC analysis, uncovering that urbanisation and democratisation processes influence environmental quality through non-linear pathways. This suggests that traditional linear models may underestimate the moderating effects of cultural and political factors on environmental outcomes.

In China, while FDI contributes to economic growth, its environmental implications have sparked considerable debate. Recent domestic research has increasingly examined the relationship between FDI and environmental pollution within the framework of the EKC hypothesis, incorporating regional disparities and policy contexts. For instance, [8] employed a spatial econometric model using panel data from cities in the Yangtze River Delta to identify the dual impact of FDI on environmental pollution, namely the pollution haven effect and the technology spillover effect, highlighting that variations in environmental regulations across regions significantly influence these effects. Similarly, [9] analysed panel data from China and found that FDI's impact on SO_2 emissions exhibits notable regional heterogeneity. [10] further demonstrated that this regional variation manifests in contrasting effects: the eastern region experiences a ‘pollution halo’ effect due to stringent environmental regulations, whereas the central and western regions continue to exhibit a ‘pollution refuge’ phenomenon. An empirical study of Shandong Province by [11] indicated that when regional GDP per capita surpasses 80,000 yuan, the technology spillover effect of FDI begins to mitigate pollutant emissions, offering a quantitative foundation for advancing high-quality economic development in Shandong Province.

However, the validity of the EKC hypothesis remains contentious. [12] identified substantial discrepancies in the EKC patterns of O_3 and PM2.5, suggesting that single-pollutant analyses may oversimplify the complexity of environmental pressures. [13] argued that conventional EKC models fail to adequately account for spatial spillover effects, necessitating a coordinated regional governance approach. Recent research has expanded the applicability of the EKC framework; for example, [14] found that the widespread adoption of renewable energy can alter the traditional EKC trajectory and bring forward the turning point for environmental quality improvements, offering a theoretical basis for aligning FDI with clean energy objectives under Shandong Province’s ‘double carbon’ target.

Broadly, both domestic and international scholars have examined the EKC hypothesis primarily through data-driven analyses, with earlier studies employing simplified models to explore the relationship between per capita income and environmental pollution, often overlooking factors such as FDI. Subsequent empirical studies, utilising time-series and panel data have sought to validate the inverted U-shaped relationship. However, the reliance on per capita income alone presents limitations, prompting researchers to adopt more sophisticated methodologies, including correlation tests, cointegration analysis, and linkage equations, to capture the broader impact of economic growth, FDI, and other variables on environmental pollution. While no consensus has been reached within the academic community, these studies provide valuable insights into future research, particularly regarding the environmental consequences of FDI, where further investigation remains necessary.

3. FDI and the Status of Environmental Pollution

3.1. Status of FDI in China

With the advancement of reform and opening-up, China’s investment landscape and market conditions have progressively improved, attracting diverse forms of foreign investment. As illustrated in Figure 1, the total actual FDI absorbed by China from 1998 to 2024 amounts to 630.762 billion US dollars, demonstrating an overall upward trend. According to the Report on Green, Low-Carbon, and High-Quality Development of Shandong Province [15], FDI in Shandong Province grew at an average annual rate of 8.2% between 2020 and 2022. However, industrial SO_2 emissions remained among the highest nationwide during this period, underscoring the pressing need for pollution control measures. This study utilises panel data from 16 prefecture-level cities in Shandong Province from 2016 to 2022 to empirically examine the relationship between FDI and ecological environment development in the region.

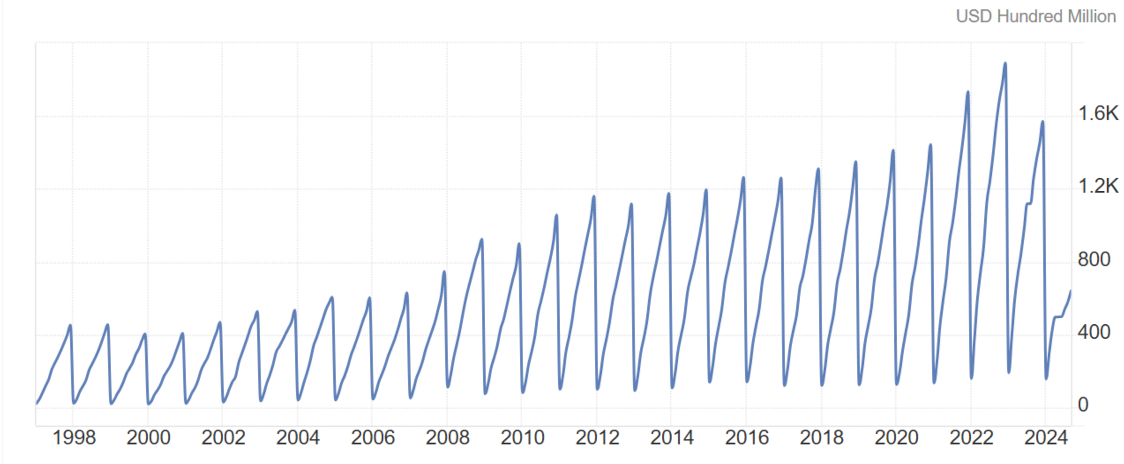


Fig.1. Value of Foreign Direct Investment in China, 1998-2024
Source: Own study

3.2. Assessment of the Extent of Environmental Pollution

This study evaluates environmental pollution from two perspectives: resource conservation and environmental protection. Resource conservation encompasses energy efficiency and waste recycling, while environmental protection considers waste treatment capacity and ecological preservation. FDI facilitates technological advancements, enabling enterprises to enhance production efficiency, optimise energy use, and minimise waste emissions. Simultaneously, scientific and technological progress drives industrial transformation from pollution-intensive sectors to green, energy-efficient industries, fostering greater corporate emphasis on environmental protection and ecological sustainability.

4. Data Selection and Model Design

4.1. Variable Selection and Data

4.1.1. Explanatory Variable

The explanatory variable in this study is the SO_2 emissions of 16 prefecture-level cities in Shandong Province. Despite China's ongoing efforts to adjust and optimise its energy structure, the growth rate of coal consumption has significantly slowed in recent years. However, coal still accounts for over 50% of the country's total energy consumption. The combustion of sulphur-containing fuels, primarily coal, remains a major contributor to SO_2 pollution. Therefore, in estimating the baseline model, SO_2 emissions are used as a measure of environmental pollution, based on data from the Statistical Yearbook of Shandong Province (2016–2022), which has been manually compiled.

4.1.2. Core Explanatory Variables

This study selects urban foreign investment flows in real terms (FDI) as the core explanatory variable in the model. Existing research commonly employs either FDI stock or flow to measure the scale of FDI. However, due to the unavailability of city-level FDI stock data in Shandong Province and issues related to comparability in estimation methods, this study utilises FDI flows as a proxy for FDI.

4.1.3. Control Variable

- Per capita income (PCI) serves as a key indicator of the average economic standard of a region's population. While rising PCI can drive higher consumption levels, leading to increased resource use and pollution emissions, it can also enhance environmental awareness and encourage the adoption of eco-friendly technologies and pollution control measures.
- Gross Domestic Product (GDP) represents the overall economic activity within a region. Economic growth, particularly when accompanied by industrialisation, can contribute to higher pollution levels. Controlling for GDP allows for a distinction between pollution driven by FDI and that resulting from broader economic expansion.
- Gross industrial output (IO) measures a region's industrial production capacity and serves as a crucial indicator of industrialisation. FDI often facilitates industrial development by introducing capital, technology, and managerial expertise, which may, in turn, influence environmental pollution.
- Industrial solid waste utilisation (ISWU) reflects a region's capacity for waste management. Higher utilisation rates indicate stronger environmental governance and more effective waste reduction efforts. In this study, ISWU is included as a control variable to account for variations in technological capabilities related to pollution management.

4.1.4. Policy Variables

Local fiscal output (LFO) reflects the government's policy response to environmental pollution influenced by FDI and serves as a key indicator of the financial support allocated by local authorities to achieve objectives related to economic development and environmental protection.

4.2. Data Description

This study utilises panel data from 16 cities in Shandong Province from 2016 to 2022 as the research sample, with each variable detailed in Table 1.

Table 1
Description of Variables

Nature of the Variable	Variable Symbol	Variable Name	Meaning of Variables and Units
Explanatory Variable	Ln SO_2	SO_2 Emissions	SO_2 Emissions by Municipality (tonnes)
Core Variable	Ln FDI	Overseas Foreign Direct Investment (OFDI)	Actual Use of Foreign Investment (US$ million)
Control Variable	Ln PCI	Per Capita Income	Level of Economic Development of Municipalities (yuan per person)
	Ln GDP	Gross Local Product	Size of Regional Economy (billion yuan)
	Ln IO	Gross Industrial Output	Intensity of Regional Industrial Activity (billions of dollars)
	Ln ISWU	Industrial Solid Waste Utilization	Technical Utilization Efficiency (tonnes)
Policy Variables	Ln LFO	Local Financial Outputs	Intensity of Local Financial Inputs (billion yuan)

To mitigate the impact of heteroskedasticity on the analysis, logarithmic differencing is applied to the variables listed in Table 2. Consequently, all variables referenced hereafter represent their transformed values. The primary data sources include the Statistical Yearbook of Shandong Province and the statistical yearbooks of various cities. For variables involving nominal values, adjustments are made to reflect real values in constant 2016 US dollars.

Table 2
Descriptive Statistics for Each Variable

Variable	Mean	Std.dev.	P50	Min	Max
Ln SO_2	-0.021	0.517	-0.155	-0.795	0.995
Ln FDI	0.19	1.355	-0.151	-2.679	2.236
Ln PCI	-0.28	0.884	-0.219	-2.679	0.182
Ln GDP	0.086	0.702	-0.232	-0.823	0.853
Ln IO	0.086	0.702	-0.232	-0.823	0.853
Ln ISWU	0.028	1.033	-0.205	-1.832	1.96
Ln LFO	0.0647	0.5063	0.0661	-0.9714	0.9161

4.3. Benchmark Modelling

4.3.1. Baseline Model

To examine the direct impact of FDI on the ecological environment, specifically SO_2 emissions in Shandong Province, the GLS model is first constructed to assess the relationship between FDI and SO_2 emissions. To minimise the influence of other factors, the study also incorporates the GBR model to capture nonlinear relationships and variable interactions, reducing the prediction error of SO_2 emissions. A fusion model is then employed by integrating both approaches for analysis. Following existing research, the model construction process is conducted using logarithmic transformations of the variables, as outlined below.

$$lnSO2_{i,t} = \beta_0 + \beta_1 \cdot lnFDI_{i,t} + \beta_2 \cdot ln\varphi_{i,t} + \beta_3 \cdot lnGDP_{i,t} + \beta_4 \cdot ln\theta_{i,t} + \beta_5 \cdot \sigma_{i,t} + \epsilon_{i,t} \quad (1)$$

Where: (1) denotes the GLS model, i represents the cities of Shandong Province, t denotes time, $\varphi_{i,t}$ denotes the per capita income, $\theta_{i,t}$ denotes the total industrial output value, $\sigma_{i,t}$ denotes the amount of industrial solid waste utilization, β_0 denotes the constant term, β_1 , β_2 , β_3 , β_4 denote the regression coefficients of the foreign direct investment and the selected control variables respectively, and $\epsilon_{i,t}$ denotes the random error term.

$$\overline{y}_{GBR} = \sum_{m=1}^{M} \gamma_m \cdot f_m(x) \quad (2)$$

Eq. (2) represents the GBR model, M denotes the number of decision trees, γ_m denotes the learning rate of each decision tree, and $f_m(x)$ denotes the prediction of the mth tree.

$$\overline{y}_{fusion} = \omega_1 \cdot \overline{y}_{GLS} + \omega_2 \cdot \overline{y}_{GBR} \quad (3)$$

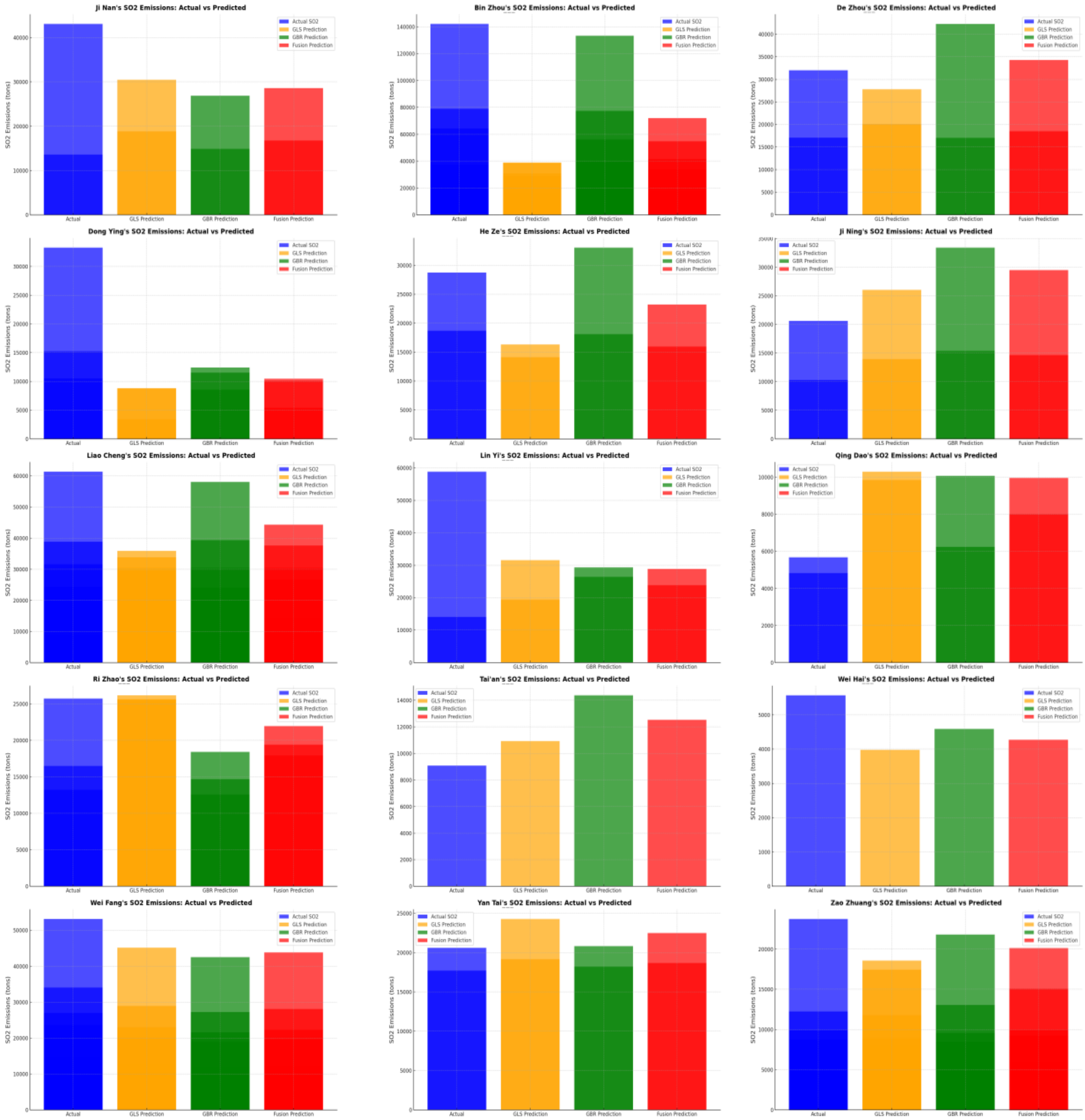
Eq. (3) represents the fusion model of GLS and GBR using weighted average method, where $\omega_1 + \omega_2 = 1$.

4.3.2. Model Checking

Before conducting empirical analyses, the feasibility of the fusion model must be tested. This study employs three models—the GLS model, the GBR model, and the fusion model—for cross-sectional comparisons, with model performance assessed using metrics such as R^2 and mean squared error (MSE). As shown in Table 3, the GLS model yields an R^2 of 0.44, indicating that FDI and the control variables account for 44% of the logarithmic variance in SO_2 emissions. The MSE of 0.225 suggests that the GLS model maintains relatively stable predictive performance. The GBR model demonstrates a higher R^2 and a lower MSE than the GLS model, suggesting superior predictive and explanatory capability. The fusion model outperforms both individual models in terms of R^2 and MSE, highlighting its synergistic ability to capture both linear and nonlinear relationships. Furthermore, model performance comparisons extend to the predicted and actual SO_2 values across 16 cities, as illustrated in Figure 2. The results indicate that the fusion model achieves the closest alignment between predicted and actual values in most cities. Additionally, the fusion model enhances predictive accuracy and mitigates extreme errors when handling outliers and unexpected variations. Therefore, this study adopts the fusion model for empirical analysis.

Table 3
Model Performance Comparison Results

Model	MSE	R^2
GLS(Ln)	0.225	0.440
GBR (Ln)	0.176	0.561
Fusion(Ln)	0.173	0.568



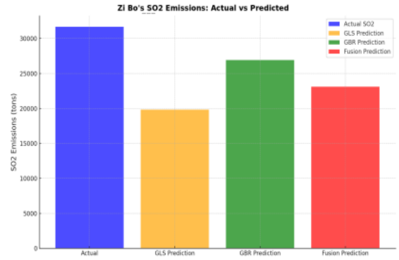


Fig.2. Comparison of Predicted Actual Values of SO2 in 16 Prefecture-Level Cities

5. Empirical Results and Analyses

5.1. Benchmark Analysis

The regression results, after controlling for individual effects without the inclusion of control variables, are presented in Table 4. The correlation between actual SO_2 emissions and FDI across cities in Shandong Province is -0.01, while the correlation between predicted SO_2 emissions and FDI is 0.04. This indicates a weak direct relationship between FDI and SO_2 emissions, though the fusion model may enhance the ability to capture this relationship.

Table 4
FDI Impact Results

Correlation Type	Correlation Coefficient
Ln(FDI) vs Actual SO2	-0.010
Ln(FDI) vs Predicted SO2	0.035

The results of the regression with control variables are shown in Table 5, where industrial solid waste utilization $Ln\_\sigma_{i,t}$ and per capita income $Ln\_\varphi_{i,t}$ have high importance in the fusion model, suggesting that these two variables play a key role in predicting SO2 emissions.

Table 5
Results of the Impact of Control Variables

Variable	Fusion_Importance
Ln_FDI	0.038***
$Ln\_\varphi_{i,t}$	0.371***
Ln_GDP	0.192***
$Ln\_\theta_{i,t}$	0.097***
$Ln\_\sigma_{i,t}$	0.299***

Note: *, ** and *** indicate significance at the 10 per cent, 5 per cent and 1 per cent levels, respectively, and are the same as in the table below unless otherwise indicated.

FDI has low importance but still contributes to the model. The evident "pollution paradise" effect supports the initial hypothesis, likely due to the early-stage inflow of foreign capital in Shandong Province. Limited experience led to high production growth, increased energy consumption, and rising SO_2 emissions. At first, energy-saving technologies lagged, and enterprises failed to implement efficient measures promptly. Meanwhile, foreign investment pushed firms to invest in energy-saving R&D, but short-term energy demand in high-consumption industries intensified SO_2 emissions. The 16 prefecture-level cities in Shandong Province vary significantly in natural resources, ecological conditions, labour supply, and technological capital, influencing their ability to attract foreign investment. Less developed areas have accelerated industrialisation and urbanisation through FDI but have become "safe havens" for highly polluting foreign firms due to weak environmental regulations and inadequate SO_2 emission controls. Late implementation of environmental policies, insufficient supervision, and low carbon control standards have further intensified local pollution. Among control variables, economic growth has increased per capita income, with a positive economic development coefficient indicating that economic activity drives SO_2 emissions. Rising demand for natural gas and electricity, along with expanding consumer needs, has further intensified energy consumption and pollution. While GDP growth fosters industrialisation, contributing to higher SO_2 emissions, increases in gross industrial output and industrial solid waste utilisation have improved industrial structure, optimised resource allocation, and enhanced overall productivity, reducing pollutant emissions.

5.2. Robustness Check

The model faces two endogeneity issues. First, omitted variable bias arises as SO_2 emissions are influenced by multiple factors, some of which may be unaccounted for. To mitigate this, control variables are included. Second, heterogeneity across cities in economic conditions, resources, and energy structures may obscure or exaggerate influencing factors, affecting result accuracy. To address these issues, this study validates the fusion model's performance through city-based grouping. Three robust testing methods are employed: assessing mean and variance using random sampling and evaluating model performance after adjusting GBR hyperparameters. The robust test results are presented in Table 6. The grouped validation results show a mean (R^2 = 0.619), suggesting moderate consistency across cities, while the standard deviation (0.356) indicates considerable variation in some cases. Random resampling validation yields a mean (R^2 = 0.806), closely aligning with the original model, with a low standard deviation (0.035), demonstrating strong stability across samples. Sensitivity analysis of GBR hyperparameters reveals that after adjustment, the fusion model's performance declines (R^2 = 0.565), indicating that parameter selection influences the model. Overall, the combined methods confirm the stability and reliability of the regression analysis.

Table 6
Robustness Tests

Robustness Test	Value
Group-wise R^2 Mean	0.619***
Group-wise R^2 Std	0.356***
Bootstrap R^2 Mean	0.806***
Bootstrap R^2 Std	0.035***
GBR Sensitivity R^2	0.565***

6. Further Discussion

This study considers that government intervention (LFO) may alter the impact of FDI on SO_2 emissions. To further examine this relationship, following the approach of [16], policy variables and their interaction with technological factors ($\ln\delta_{i,t} \cdot \ln\sigma_{i,t}$) are incorporated into Equation (1), leading to the construction of the moderating effect model (4).

$$lnSO2_{i,t} = \beta_0 + \beta_1 lnFDI_{i,t} + \beta_2 ln\varphi_{i,t} + \beta_3 lnGDP_{i,t} + \beta_4 ln\theta_{i,t} + \beta_5 ln\sigma_{i,t} + \beta_6 ln\delta_{i,t} + \beta_7 (ln\delta_{i,t} \cdot ln\sigma_{i,t}) + \epsilon_{i,t} \quad (4)$$

In equation (4),$\sigma_{i,t}$ is the policy variable and $\ln\delta_{i,t} \cdot \ln\sigma_{i,t}$ is the interaction term between the policy variable and technology utilization efficiency. As the model includes interaction terms, multicollinearity may bias the estimation results. To address this, the study centres the interaction term variable in Model (4) by subtracting the sample mean, resulting in a centred moderated effects model.

$$lnSO2_{I,t} = \beta_0 + \beta_1 lnFDI_{I,t} + \beta_2 ln\varphi_{I,t} + \beta_3 lnGDP_{I,t} + \beta_4 ln\theta_{I,t} + \beta_5 ln\sigma_{I,t} + \beta_6 ln\delta_{I,t} + \beta_7 (ln\delta_{I,t} - \overline{ln\delta_{I,t}}) \times (ln\sigma_{I,t} - \overline{ln\sigma_{I,t}}) + \epsilon_{I,t} \quad (5)$$

With the introduction of policy variables, Model (6) is developed based on Model (2), while the fusion model remains unchanged.

$$\overline{y}_{GBR} = f(lnFDI_{i,t}, ln\varphi_{i,t}, lnGDP_{i,t}, ln\theta_{i,t}, ln\sigma_{i,t}, ln\delta_{i,t}, ln\delta_{i,t} \cdot ln\sigma_{i,t}) \quad (6)$$

The fusion model was employed for analysis (see Table 7). The results indicate that the policy variable (local fiscal output) and its interaction with technological factors (industrial solid waste utilisation) hold high importance. This suggests that local fiscal policy exerts both direct and indirect effects on SO_2 emissions, confirming its moderating role in enhancing environmental quality through improved technological efficiency.

Table 7
Results of the Impact of Policy Variables

Variable	GBR_Importance
Ln FDI	0.040***
Ln$\varphi_{i,t}$	0.315***
Ln GDP	0.162***
Ln$\theta_{i,t}$	0.031***
Ln$\sigma_{i,t}$	0.294***
Ln$\delta_{i,t}$	0.045***
Ln$\sigma_{i,t}$ · Ln$\delta_{i,t}$	0.110***

The utilisation of industrial solid waste exhibits a more pronounced effect on reducing SO_2 emissions when supported by appropriate policy measures. Notably, higher financial expenditure directed towards technological upgrading and the adoption of environmentally friendly equipment demonstrates the greatest significance in mitigating emissions. Among all variables examined, this factor contributes the most to the prediction of SO_2 emissions, underscoring the critical role of technological advancement in driving environmental improvement. The substantial weight of the interaction term involving policy variables further suggests that local financial expenditures indirectly enhance environmental quality by improving technological efficiency, such as increasing the efficiency of waste utilisation. The inclusion of policy variables not only increases the coefficient of determination (R^2) but also reduces the MSE of the model, indicating an enhanced ability to explain variations in SO_2 emissions and yielding more accurate predictive outcomes. These findings align with the observations of [17], who highlight that the emission reduction effects of FDI are significantly amplified when regional technological capabilities surpass a certain threshold. This corroborates the results of this study, which emphasise that financial support plays a pivotal role in improving technological efficiency and, consequently, environmental outcomes.

6.1. The Role of Policy in Regulating the Relationship Between Technology Levels and the Environment

1. Enhanced Technological Efficiency: Increased local fiscal expenditures may support R&D, environmental infrastructure, or enterprise subsidies, improving industrial solid waste utilisation. The model indicates a negative correlation between efficient technology use and SO_2 emissions, confirming that policy-driven technological advancements significantly enhance environmental quality.

2. Regional Variations in Policy Effectiveness: Economically developed cities (e.g., Qingdao and Jinan) benefit more from policy interventions due to greater financial capacity and advanced technology, leading to more pronounced environmental improvements. Less developed regions may require stronger policy support to bridge technological gaps.

3. Non-Linear Policy Effects: The interaction term (policy × technology level) captures the marginal impact of policy on environmental improvement. The diminishing marginal effect suggests that policy interventions must align with technological levels to maximise environmental benefits.

7. Conclusions and Policy Recommendations

7.1. Conclusion

To advance its green development strategy, Shandong Province must move beyond traditional foreign investment models and establish a robust environmental regulatory framework. Using panel data from 16 prefecture-level cities, this study employs fixed-effects and threshold regression models to examine the relationship between FDI and SO_2 emissions, considering per capita income, industrial output, and GDP. Findings indicate that: (1) FDI has intensified SO_2 emissions, reinforcing the "pollution paradise" phenomenon, while technology spillover effects remain weak. (2) Industrialisation has progressed, refining industrial structures and reducing FDI-induced environmental resource consumption. (3) Improved utilisation of industrial solid waste has enhanced resource efficiency and corporate environmental awareness, yielding economic benefits. (4) Increased fiscal expenditure has bolstered economic benefits, but its effect on FDI-related emissions intensifies with scale. Overall, Shandong Province remains in a "pollution shelter" phase, with no significant "pollution halo" effect from FDI.

7.2. Policy Recommendations

Shandong Province should enhance foreign investment access standards and prioritise capital quality over scale. Strengthening environmental and technological requirements for FDI is essential, alongside adopting green financial policy tools such as low-interest loans or subsidies for environmentally sustainable investments. Restrictions should be placed on FDI in highly polluting industries, such as iron and steel and petrochemicals, while efforts should focus on attracting investment in sectors like high-end manufacturing, pharmaceuticals, and services to mitigate the worsening of the "pollution shelter" effect. Encouraging innovation and entrepreneurship is crucial for revitalising urban development. As Shandong navigates the transition phase of the Fourteenth Five-Year Plan, fostering "dual innovation" is key to achieving "dual carbon" objectives. Cities with strong innovation foundations should develop green industrial chains, such as Qingdao advancing tidal energy technology based on its marine research strengths. In contrast, cities with weaker innovation bases should integrate their existing industries with low-carbon technologies, such as Linyi adopting a "wood + biomass" model to lower transition costs. Local governments should provide policy guidance and tax incentives to reduce the financial burden on technology-based entrepreneurship. Investing in human capital is essential for optimising and upgrading industrial structures. Cities should develop targeted talent attraction programmes, such as expanding the "Taishan Scholars" initiative, and increase investment in education to align vocational training with "dual carbon" objectives. Enhancing workforce quality will support industrial upgrading, promote technological advancements, reduce reliance on foreign capital, and mitigate the impact of FDI on carbon emissions.

7.3. Reassessment

This study examines the relationship between FDI and SO_2 emissions in Shandong Province, revealing that the region remains in the "pollution shelter" stage, with FDI failing to significantly reduce environmental pollution and the "pollution halo" effect being negligible. Thus, industrial upgrading is necessary, shifting from high-pollution sectors to environmentally sustainable industries to achieve balanced economic and environmental development. A key limitation of this research is its focus on a single pollutant, SO_2. Future studies should broaden the scope to include other major industrial pollutants, such as CO_2, nitrogen oxides, and particulate matter, while also considering spatial effects.

A more comprehensive analysis of carbon emissions and environmental dynamics would provide a stronger foundation for formulating effective environmental policies and industrial strategies, supporting the coordinated development of the economy and ecological sustainability in Shandong Province.

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