Research On the Influence Mechanism of Digital Infrastructure on Urban Environmental Governance Efficiency Based on Panel Data

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Abstract. Under the dual background of high-quality development and ecological civilization construction, digital infrastructure development and environmental governance efficiency improvement have become critical issues in China's economic and social development. This study employs panel data from 235 Chinese cities to empirically verify the significant positive impact of digital infrastructure on environmental governance efficiency. The findings reveal that technological innovation and public ecological awareness function as mediating effects, while industrial upgrading plays a moderating role. Notably, this positive influence demonstrates heterogeneity, being less pronounced in economically developed cities compared to underdeveloped regions, and weaker in environmentally focused cities than in non-environmentally focused ones. The research innovatively illuminates the mechanisms and heterogeneous characteristics through which digital infrastructure affects environmental governance efficiency, thereby providing valuable theoretical foundations and policy implications for enhancing environmental governance practices in China.

Keywords: Digital Infrastructure; Environmental Governance Efficiency; Mediation Effect; Moderating Effect.

1. Introduction

According to a report by China's National Bureau of Statistics, in 2023, 136 of China's 339 cities at and above the prefecture level will have air quality exceeding standards, accounting for 40.5%; Acid rain was in 98 cities, accounting for 28.9%. The Songhua River basin is still lightly polluted, with 7.9% of coastal waters classified as Class IV or worse water quality. Class III, IV, and V ecological environment quality accounted for 40.5%. In addition, there was a 19.9% increase in marine dumping compared to 2022, and environmental problems remain serious. In the context of high-quality development, it has become urgent to develop new productive forces and improve the efficiency of ecological governance.

In the new wave of technological revolution and industrial transformation, constructing a new generation of agile, secure, and controllable digital infrastructure is fundamental to achieving widespread digital technology applications, developing new productive forces, and accelerating the digital and intelligent transformation of traditional industries. High-quality development requires governments at all levels to strengthen digital infrastructure and vigorously develop the digital economy while improving environmental governance efficiency to enhance ecological quality comprehensively. In practice, can the construction of digital infrastructure improve ecological governance efficiency and meet the demands of high-quality economic development? This paper uses data from 235 cities in China from 2011 to 2020 to measure and evaluate the level of digital infrastructure and environmental governance efficiency. Using a two-way fixed-effect model, this study analyzes the impact of digital infrastructure on environmental governance efficiency and its internal mechanisms, verifying the significant role of digital infrastructure in improving ecological governance efficiency and providing policy recommendations.

2. Literature Review and Research Hypotheses

The literature review examines three key aspects: measurement approaches, impact effects, and mechanisms. From this foundation, specific research hypotheses are developed.

Digital infrastructure encompasses new-generation information facilities characteristic of the digital economy, including 5G networks, data centers, AI, and industrial internet. These technologies facilitate market integration[1] and support enterprise green transformation[2]. This study employs a comprehensive evaluation method using entropy weighting of indicators including optical cable lines, mobile switching capacity, robot installations, and internet access points.

Environmental governance efficiency represents the input-output ratio in environmental management processes. While scholars have applied various quantification models (Super-SBM, two-stage DEA Stackelberg, entropy-DEA undesirable output, and random-effects Tobit[3-6]), this research adopts the input-output ratio method with the DEA-SBM model.

The development of digital infrastructure like 5G networks and industrial internet strengthens technological application capabilities, enhancing corporate environmental governance capacity and social responsibility[7], which consequently improves environmental governance efficiency.

The construction of digital infrastructure such as 5G networks and the industrial Internet provides strong support for the application of digital technologies, and the continuous improvement of digital infrastructure can improve the ability of enterprises to carry out environmental governance and assume social responsibility[8], thereby improving the efficiency of environmental governance. Drawing on these insights from the literature, this study formulates hypothesis 1: Digital infrastructure construction promotes the improvement of environmental governance efficiency.

The utilization of digital infrastructure has promoted technological innovation. The extensive use of digital platforms has accelerated the dissemination of technological innovation and enhanced the overall social innovation level. Technological innovation plays a crucial role in environmental governance by improving decision-making and execution, such as reducing industrial pollution through green technological innovation. Moreover, the interaction term generated between technological innovation and industrial structure will promote the improvement of carbon emission efficiency[9], thereby enhancing the efficiency of environmental governance. This relationship suggests hypothesis 2 of this research: digital infrastructure construction improves environmental governance efficiency by enhancing the level of technological innovation.

Digital infrastructure such as the Internet and big data also enables the public to access environmental information more easily. For instance, business executives can cultivate ecological awareness through digital infrastructure. The ecological awareness of executives can prompt enterprises to establish internal environmental management systems, enhance resource utilization efficiency, reduce long-term operating costs, and bring about a win-win situation of economic and ecological benefits for the enterprises[10]. This, in turn, promotes the efficiency of ecological governance. This mechanism leads to hypothesis 3 of the present study: digital infrastructure improves environmental governance efficiency by enhancing public environmental awareness.

The construction of digital infrastructure such as 5G networks and industrial internet has provided strong support for the application of digital technologies and given rise to emerging industries. It has significantly enhanced production efficiency and optimized the industrial structure. In the wave of industrial structure transformation, the proportion of traditional high-energy-consuming and high-pollution industries such as steel, chemical engineering, and power has gradually decreased[10], thereby improving the efficiency of environmental governance. Based on this understanding, this paper proposes hypothesis 4: digital infrastructure improves environmental governance efficiency by promoting industrial structure upgrading.

3. Model and Data Sources

3.1. Econometric Model

To analyze the effect of digital infrastructure on environmental governance efficiency and test the proposed hypotheses, this study constructs the following model:

$$Y_{it} = a_0 + a_1 X_{it} + \sum_{j=1}^{6} \theta_j Z_{jit} + \mu_i + \delta_t + \varepsilon_{it} \tag{1}$$

Where: i represents individual cities, t represents the yea, Y_{it} is the dependent variable (environmental governance efficiency in the city i in year t), X_{it} is the level of digital infrastructure in the city i in year t, Z_j represents the control variables, μ_i and δ_t are the city and year fixed effects, respectively, ε_{it} is the random error term.

3.2. Variable Definitions

This study examines environmental governance efficiency as the dependent variable, calculated through a non-radial DEA-SBM model that integrates input-output disparities. Capital investment is measured by local government ecological protection expenditures while labor input is gauged via employment figures in water conservancy, environmental management, and public utilities sectors. Outputs are differentiated into desired outcomes—industrial solid waste recycling rates, domestic waste harmless treatment rates, centralized sewage treatment efficiency, and green space coverage—and undesired outcomes including industrial wastewater discharge, sulfur dioxide emissions, and industrial particulate releases.

The independent variable, digital infrastructure development, is evaluated using a hybrid index combining principal component analysis and entropy weighting. This index synthesizes per capita telecommunications revenue to reflect service capacity, internet penetration and mobile user density to characterize network accessibility, and fiber optic cable density as a marker of infrastructure robustness.

Mechanistic pathways are explored through technological innovation, represented by regional patent grants, and public environmental awareness, derived from Baidu Search Index frequencies for pollution-related keywords. The framework employs multidimensional metrics and blended methodologies to ensure measurement precision, enabling systematic investigation into how digital infrastructure enhances environmental governance through technological advancement and societal engagement.

3.3. Data Sources

The data used in this paper comes from the China City Statistical Yearbook (2011–2021), the China Urban and Rural Construction Statistical Yearbook, the China Environmental Statistical Yearbook, the China Science and Technology Statistical Yearbook, and provincial (municipal, autonomous regions) statistical yearbooks. Gross domestic product (GDP) data is adjusted using the GDP deflator provided by the National Bureau of Statistics. Non-ratio control variables are logarithmically transformed, and missing data are filled using interpolation methods. After excluding cities with a large amount of missing data, the final sample consists of 235 cities with suitable data for empirical analysis.

The dependent variable (environmental governance efficiency) and the core independent variable (digital infrastructure) both have small standard deviations of 0.070 and 0.042, respectively. This suggests that the sample statistics closely represent the overall population, and the data is suitable for empirical analysis.

4. Empirical Results and Analysis

4.1. Baseline Regression Results

Table 1 reports the regression results on the impact of digital infrastructure on environmental governance efficiency. The coefficients remain significantly positive across all models, even when control variables are added. This indicates that the enhancement effect of digital infrastructure on environmental governance efficiency is not only statistically significant but also robust to econometric tests. The results in column (3) of Table 1 show that for every 1% increase in the level of digital infrastructure, environmental governance efficiency improves by 0.297%. Improved digital infrastructure facilitates faster and more accurate collection of ecological data, leading to more scientific decision-making, more effective execution, and stronger oversight, thus enhancing governance efficiency.

The coefficients of the control variables indicate that, from 2011 to 2020, economic development, openness to trade, and population density negatively affected environmental governance efficiency. Fiscal decentralization and traditional infrastructure showed no significant impact, while government R&D spending had a significant positive effect.

Table 1: Baseline Regression Results

Variable	(1)	(2)	(3)
Digital Infrastructure	0.269***	0.631***	0.297***
	(0.104)	(0.113)	(0.105)
Economic Development Level		-0.044***	-0.041***
		(0.015)	(0.015)
Degree of Openness		-0.006***	-0.005**
		(0.002)	(0.002)
Fiscal Decentralization		-0.031	0.022
		(0.023)	(0.027)
Population Density		-0.016	-0.054
		(0.037)	(0.039)
Government R&D Spending		0.009**	0.007*
		(0.004)	(0.004)
Traditional Infrastructure		0.015**	0.004
		(0.006)	(0.008)
Constant	0.857***	1.096***	1.524***
	(0.062)	(0.281)	(0.298)
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	No	Yes
Observations	2350	2350	2350
R-squared	0.244	0.204	0.251

Notes: Robust standard errors in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

4.2. Robustness Checks

4.2.1 Instrumental Variable (2SLS) Estimation for Endogeneity Testing

To address endogeneity, this study used 2SLS regression with instrumental variables (city-to-Hangzhou distance × postal volume). Results confirm digital infrastructure's positive impact remains significant (KP-LM significant at 1%, Cragg-Donald F=128.638>16.38), demonstrating robust findings after controlling for endogeneity. Robust standard errors in parentheses. [ ] denotes p-values, {} denotes critical value at the 10% level.

Table 2: Endogeneity Test Results

Variable	**(1)**	**(2)**
Digital Infrastructure	1.494***	
	(0.416)	
Instrumental Variable		0.006***
		(0.001)
Control Variables	Yes	Yes
City Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
Kleibergen-Paap rk LM Stat		48.872 [0.000]
Cragg-Donald Wald F Stat		128.638 {16.38}
Observations	2350	
R-squared	0.024	

4.2.2 Robustness Tests Using Alternative Measurement Methods and Sample Changes

To further validate the robustness of the baseline regression results, this study first alters the measurement methods for the independent and dependent variables and conducts an OLS regression to check for measurement error effects. The results of the robustness test are presented in Table 3. Column (1) shows the results when the dependent variable (environmental governance efficiency) is measured using the method of Sun Haojie (2008), while Column (2) shows the results when the digital infrastructure variable is calculated using the entropy method. Additionally, in Column (3), this study removes the four direct-administered municipalities (Beijing, Shanghai, Tianjin, and Chongqing) from the sample to check for potential sample-specific effects.

As shown in Table 4, regardless of whether this study changes the variable measurement methods or modifies the sample, the coefficients for digital infrastructure remain significantly positive, consistent with the baseline regression results. This further confirms the positive effect of digital infrastructure on environmental governance efficiency, supporting the robustness of the baseline results and verifying Hypothesis 1.

Table 3: Robustness Test Results

Variable	**(1)**	**(2)**	**(3)**
Digital Infrastructure	0.187**	0.190***	0.408***
	(0.088)	(0.070)	(0.145)
Economic Development Level	-0.027*	-0.040***	-0.042***
	(0.014)	(0.015)	(0.015)
Degree of Openness	-0.005***	-0.005**	-0.005**
	(0.002)	(0.002)	(0.002)
Fiscal Decentralization	0.035	0.021	0.023
	(0.025)	(0.027)	(0.027)
Population Density	-0.040	-0.061	-0.051
	(0.039)	(0.039)	(0.039)
Government R&D Spending	0.003	0.007*	0.007*
	(0.004)	(0.004)	(0.004)
Traditional Infrastructure	0.007	0.004	0.004
	(0.007)	(0.008)	(0.008)
Constant	1.382***	1.724***	1.452***
	(0.293)	(0.291)	(0.306)
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Observations	2350	2350	2310
R-squared	0.248	0.250	0.251

4.3. Heterogeneity Analysis

The previous section demonstrated the positive effect of digital infrastructure on environmental governance efficiency. In this section, this study further explores whether this effect varies across different regions by dividing the sample into environmentally focused and non-environmentally focused cities, as well as economically developed and underdeveloped cities. This study then conducts regressions using Equation (1) to examine the regional heterogeneity of the impact of digital infrastructure on environmental governance efficiency.

Table 4 presents the results of the heterogeneity analysis. In Columns (1) and (2), both environmentally focused and non-environmentally focused cities show significantly positive coefficients for digital infrastructure, but the coefficient for non-environmentally focused cities is larger. Columns (3) and (4) show that both economically developed and underdeveloped cities have significantly positive coefficients for digital infrastructure, but the coefficient for economically underdeveloped cities is larger. These results confirm that while digital infrastructure improves environmental governance efficiency across all regions, the magnitude of the effect varies depending on regional characteristics.

Table 4: Heterogeneity Analysis Results

Variable	**(1)**	**(2)**	**(3)**	**(4)**
Digital Infrastructure	0.182**	1.351**	0.175**	1.656***
	(0.086)	(0.561)	(0.086)	(0.607)
Economic Development Level	-0.022	-0.059***	-0.037**	-0.037
	(0.017)	(0.023)	(0.017)	(0.023)
Degree of Openness	-0.005*	-0.004	-0.008**	-0.003
	(0.003)	(0.003)	(0.003)	(0.002)
Fiscal Decentralization	0.054	-0.040	0.019	-0.005
	(0.035)	(0.044)	(0.025)	(0.054)
Population Density	-0.070*	-0.027	-0.043	-0.023
	(0.042)	(0.070)	(0.040)	(0.077)
Government R&D Spending	0.012	0.007	0.013**	0.008
	(0.008)	(0.005)	(0.006)	(0.005)
Traditional Infrastructure	-0.000	0.008	0.007	0.004
	(0.012)	(0.010)	(0.009)	(0.011)
Constant	1.475***	0.927*	1.473***	0.487
	(0.378)	(0.529)	(0.381)	(0.589)
City Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	1020	1330	1130	1220
R-squared	0.189	0.293	0.257	0.262

Notes: Environmentally focused and non-environmentally focused cities are classified according to the "National Environmental Protection '11th Five-Year Plan'" issued by the State Council in 2007. Economically developed and underdeveloped cities are classified based on the "2020 Commercial Attractiveness City Rankings."

5. Mechanism Testing

To further analyze the channels through which digital infrastructure construction promotes environmental governance efficiency, this paper conducts mechanism tests by examining the causal relationships between digital infrastructure and the mediating variables: technological innovation level and public environmental awareness. The results of the mechanism test are shown in Table 5.

As shown in Columns (1) and (2) of Table 5, the coefficients for digital infrastructure are significantly positive for both technological innovation level and public environmental awareness, suggesting that the construction of digital infrastructure enhances both variables. As discussed earlier, improved technological innovation reduces pollutant emissions and increases production efficiency, while higher public environmental awareness promotes government and corporate accountability in environmental governance. These findings support Hypotheses 2 and 3.

Column (3) in Table 5 presents the regression results for the moderating variable of industrial structure upgrading. After centering both the core explanatory variable (digital infrastructure) and the moderating variable (industrial structure upgrading) to eliminate potential multicollinearity, the coefficient for the interaction term between digital infrastructure and industrial structure upgrading is significantly positive at the 5% level, indicating a positive moderating effect of industrial upgrading on the relationship between digital infrastructure and environmental governance efficiency. This confirms Hypothesis 4.

Table 5: Mechanism Test Results

Variable	**(1)**	**(2)**	**(3)**
Technological Innovation	1.142**		
	(0.556)		
Public Environmental Awareness		1.316***	
		(0.427)	
Industrial Structure Upgrading			0.020*
			(0.011)
Digital Infrastructure × Industrial Structure Upgrading			0.353**
			(0.160)
Economic Development Level	0.045	0.103*	-0.037**
	(0.081)	(0.058)	(0.015)
Degree of Openness	0.040***	0.001	-0.005**
	(0.012)	(0.008)	(0.002)
Fiscal Decentralization	-0.047	-0.065	0.019
	(0.123)	(0.097)	(0.027)
Population Density	-0.238	0.658**	-0.042
	(0.314)	(0.263)	(0.040)
Government R&D Spending	0.225***	0.048***	0.008**
	(0.024)	(0.016)	(0.004)
Traditional Infrastructure	-0.111**	0.114***	0.003
	(0.045)	(0.031)	(0.008)
Constant	3.508	-4.052**	1.595***
	(2.164)	(1.754)	(0.293)
City Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Observations	2350	2350	2350
R-squared	0.966	0.929	0.255

6. Research Conclusions and Policy Recommendations

6.1. Research Conclusions

This study analyzes data from 235 Chinese cities to assess how digital infrastructure influences environmental governance efficiency. Results demonstrate that digital infrastructure significantly enhances environmental governance efficiency through three channels: advancing technological innovation, elevating public ecological awareness, and driving industrial structure upgrades.

Heterogeneity analysis reveals these effects persist across cities with varying environmental priorities and economic development levels, though impacts are stronger in non-environmentally focused cities and economically underdeveloped regions.

6.2. Policy Recommendations

In order to improve the efficiency of environmental governance and support the green transformation of industry, the following three policy actions are recommended.

First, expand investment in digital infrastructure to bridge rural-urban and regional disparities, and leverage government-market cooperation to achieve equitable spatial distribution.

Second, by increasing R&D funding and applying digital technologies to phase out polluting industries, reduce energy consumption, and promote innovative infrastructure and industrial upgrading.

Finally, public environmental data platforms can be developed to share standards, gather feedback, and improve governance transparency, fostering collaboration between governments, businesses, and citizens.

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