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How do Digital-green Policy Synergies Facilitate Urban Pollution Abatement and Carbon Emission Reduction?

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Abstract

Based on panel data of 262 prefecture-level cities in China from 2012 to 2023, and taking the synergistic implementation of the National Big Data Comprehensive Pilot Zone (NBDCPZ) policy and the Low-Carbon City Pilot (LCCP) policy as a quasi-natural experiment, this paper employs a multi-period difference-in-differences (DID) method to investigate the impact of Digital-green policy synergies on urban pollution and carbon reduction. The study finds that the synergistic implementation of the two policies significantly drives urban pollution and carbon reduction. Mechanism analysis shows that Digital-green policy synergies facilitate urban pollution and carbon reduction through green innovation effects and factor reallocation effects. Further analysis reveals that, compared with single-pilot policies, the dual-pilot policy has a more significant and persistently stronger effect on pollution and carbon reduction. Moreover, regarding the policy implementation sequence, implementing LCCP first followed by NBDCPZ leads to a more significant reduction in urban pollution and carbon. Based on the above findings, this paper proposes recommendations such as promoting the synergistic deployment of the two pilot policies, unblocking the transmission channels of green technology innovation and factor allocation, and optimizing the pilot policy planning.

Keywords

National Big Data Comprehensive Pilot Zone; Low-Carbon City; Policy Synergies; Pollution and Carbon Reduction.

1. Introduction

The report of the 20th National Congress of the Communist Party of China explicitly calls for "promoting green development," and the Fourth Plenary Session of the 20th Central Committee further demands that "guided by the goals of achieving carbon peaking and carbon neutrality, efforts should be made to synergistically advance carbon reduction, pollution mitigation, green expansion, and economic growth." As a result, the synergistic enhancement of pollution and carbon reduction has become a core task in China's ecological civilization construction. Against this backdrop, the implementation of NBDCPZ and LCCP represents two distinct governance approaches: one driven by digital technology, the other led by green regulation. The former relies on the agglomeration of data factors to improve the level of refined environmental management, while the latter uses carbon emission constraints to promote urban green transformation. Whether the combined implementation of these two policies at the city level can generate synergistic governance forces and promote the synergistic enhancement of pollution and carbon reduction is a critical issue for testing the effectiveness of policy design and driving high-quality development.

Regarding the influencing factors and governance pathways of pollution and carbon reduction, existing studies have explored aspects such as the scale, structure, and factor allocation of economic activities. Increases in per capita GDP and expansion of export scale may exacerbate

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carbon emissions (Wang et al., 2024; Barrows and Ollivier, 2021), whereas industrial structure upgrading (Yang et al., 2021), economic agglomeration (Du and Hao, 2025), and green technological progress (Wu et al., 2024) positively contribute to energy conservation and emission reduction[1-5]. Moreover, the misallocation of capital and labor factors not only reduces resource allocation efficiency but may also indirectly increase carbon emission intensity by inhibiting the diffusion of green technologies and intersectoral factor mobility (Chen and Hu, 2011; Yuan and Xia, 2025)[6, 7]. In terms of governance pathways, existing research mainly follows two main lines: technology-enabled approaches and institution-led regulations. From the technological dimension, the improvement of digital infrastructure can optimize energy structures (Zhang et al., 2023); the application of big data technology helps integrate production processes and thereby improve energy utilization efficiency (Zhou et al., 2025); and the development of digital finance suppresses urban pollution and carbon emissions by reducing information asymmetry (Li and Peng, 2025)[8-10]. From the institutional dimension, environmental regulation instruments are generally regarded as key levers for pollution and carbon reduction. LCCP has significantly reduced urban carbon emissions by setting carbon emission constraints, promoting industrial structure upgrading, and facilitating green technological progress (Li and Yao, 2024; Cao and Ren, 2024)[11, 12]. The carbon emissions trading policy, through price signals, guides corporate emission reduction behavior and achieves synergistic control of pollution reduction and carbon reduction at a relatively low social cost (Cao and Qiu, 2025)[13].

The synergistic effect of the two governance instruments-technology and regulation-is concretely embodied in policy practice as the coordinated advancement of NBDCPZ and LCCP. These two policies represent typical pathways of digital technology empowerment and environmental institutional regulation, respectively, and their individual impacts on pollution and carbon reduction have been systematically examined. Regarding NBDCPZ, its construction can significantly reduce carbon emission intensity and improve green total factor productivity by optimizing the allocation of capital and labor factors as well as industrial structure (Lyu et al., 2024), and by promoting green technology innovation (Wu et al., 2025)[14, 5]. Regarding LCCP, it significantly reduces urban carbon emissions through green technological progress and industrial structure adjustment (Li and Yao, 2024; Cao and Ren, 2024), and achieves synergistic enhancement of pollution and carbon reduction through government regulation and public participation (Ge et al., 2025)[11, 12, 15]. At the industrial structure level, LCCP raises the levels of industrial structure upgrading, rationalization, and ecologization through technological innovation effects and incentive effects (Song and Zhang, 2025)[16]. At the technological innovation level, it promotes technological innovation by optimizing industrial structure, easing financing constraints, and enhancing economic density (Zhu and Lee, 2022)[17].

In summary, existing studies have examined the governance pathways for pollution and carbon reduction from the perspectives of technology-enabled approaches and institution-led regulations, yet insufficient attention has been paid to the synergistic effects of the dual-pilot policy combining NBDCPZ and LCCP. Moreover, the deeper issues concerning the mechanisms and policy mix remain to be further revealed. Accordingly, this paper intends to make the following marginal contributions. First, from the perspective of policy synergy, it incorporates the dual-pilot policy of NBDCPZ and LCCP into a unified analytical framework to investigate the impact of the superimposition of two governance approaches-digital technology-driven and green regulation-led-on the synergistic enhancement of urban pollution and carbon reduction. Second, it reveals the mechanisms of the dual-pilot policy from two dimensions: green innovation effects and factor reallocation effects, examining whether it achieves pollution and carbon reduction by promoting green technology innovation and improving resource allocation efficiency. Third, it further quantifies and compares the policy effect differences between single-pilot and dual-pilot policies, and explores the effect differentiation of the two pilots

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under different implementation sequences, thereby providing empirical support for optimizing the policy mix and pilot layout.

2. Theoretical Analysis and Research Hypotheses

The synergistic implementation of NBDCPZ and LCCP constitutes a new form of urban governance characterized by the deep integration of digital technology empowerment and green institutional constraints. Since its launch in 2015, NBDCPZ has been implemented in batches, conducting systematic experiments centered on tasks such as data resource management and sharing, data center integration, and big data industry agglomeration, with the aim of enhancing data governance capacity. LCCP, initiated in 2010, requires pilot regions to set targets for reducing carbon emission intensity and, in some cases, peak emission targets. It carries out institutional explorations in areas such as carbon market construction, carbon inclusion mechanisms, and piloting of advanced low-carbon technologies, aiming to drive urban greening through binding target constraints. When the two policies are implemented jointly in the same city, they generate significant synergistic forces for pollution and carbon reduction through mutually reinforcing objectives and complementary instruments. On the one hand, NBDCPZ provides key technical support for the precise implementation of low-carbon policies. By building integrated data sharing platforms and promoting the digitalization of environmental monitoring and carbon emission accounting, it significantly enhances the ability to identify and dynamically track carbon emission sources, enabling carbon constraints to accurately target high-emitting entities. On the other hand, the emission reduction targets and compliance pressure of LCCP create a demand for the application of big data technology in environmental governance, and guide the transformation of digital infrastructure toward green and low-carbon directions. Without carbon emission constraints, the high energy consumption of digital infrastructure may lead to a digital rebound effect, whereby efficiency gains are offset by the expansion of energy consumption (Zhou et al., 2025)[9]. By setting total volume and intensity targets, LCCP compels NBDCPZ to adopt energy-saving technologies and clean energy, steering digital technology toward precise applications oriented toward pollution and carbon reduction. Based on this, this paper proposes Hypothesis 1.

Hypothesis 1: Digital-green policy synergies can empower urban pollution and carbon reduction.

Green technology innovation is an important pathway for driving urban pollution and carbon reduction. By optimizing energy structures, improving production processes, and promoting clean energy, it can reduce pollutant and carbon emissions while enhancing resource utilization efficiency (Wu et al., 2024; Li and Yao, 2024)[5, 11]. However, green technology innovation is characterized by high investment, long cycles, high risks, and positive externalities, leading to insufficient innovation incentives for firms under market mechanisms. The synergistic implementation of NBDCPZ and LCCP can address this dilemma from both the technology supply side and the institutional demand side, thereby generating green innovation effects. From the technology supply side, NBDCPZ reduces the information search costs and collaborative innovation costs associated with green technology R&D by building integrated data sharing platforms and promoting the digitalization of carbon emission accounting (Zhang et al., 2023)[8]. This enables firms to access frontier information on environmental technologies and integrate R&D resources more efficiently, thereby accelerating the output of green technologies. From the institutional demand side, LCCP creates compliance pressure by setting carbon emission intensity and total volume targets, supplemented by instruments such as carbon markets. The Porter hypothesis suggests that well-designed environmental regulations can induce innovation offset effects, whereby firms proactively innovate to offset compliance costs. When the two policies are implemented jointly, low-carbon regulations

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clarify the demand direction for green innovation, while big data technology reduces the implementation costs and trial-and-error risks of innovation. Firms, on the one hand, face clear emission reduction constraints and carbon price signals, and on the other hand, can leverage digital platforms to precisely identify emission reduction opportunities and quickly access technical solutions. As a result, they are more willing and able to engage in green innovation activities. Consequently, the green technology innovation fostered by Digital-green policy synergies translates low-carbon constraints into tangible improvements in production processes and energy structures, thereby driving urban pollution and carbon reduction.

Factor allocation efficiency is a key factor influencing the performance of urban pollution and carbon reduction. When factors of production such as capital and labor deviate from their optimal allocation due to information asymmetry, market segmentation, or policy intervention, factor misallocation occurs. This misallocation first manifests as a decline in total factor productivity (Chen and Hu, 2011), and then indirectly increases carbon emission intensity and pollution levels by inhibiting the diffusion of clean technologies and intersectoral factor mobility (Yuan and Xia, 2025)[6, 7]. Specifically, high-emission, low-efficiency firms occupy excessive resources, while innovation actors in green and low-carbon fields face difficulties in financing and shortages of talent, leading to resource misallocation and efficiency losses in emission reduction. Therefore, alleviating capital misallocation and labor misallocation-enabling factors to flow from low-efficiency, high-pollution sectors to high-efficiency, green and low-carbon sectors-has become an important pathway for achieving pollution and carbon reduction. The synergistic implementation of NBDCPZ and LCCP can effectively alleviate factor misallocation from both the information matching side and the institutional guidance side, thereby generating factor reallocation effects. With respect to capital misallocation, NBDCPZ reduces information asymmetry between financial institutions and firms by building integrated data sharing and credit evaluation platforms, allowing capital to flow more precisely to green and low-carbon projects and reducing credit rationing caused by adverse selection. At the same time, LCCP guides capital away from high-pollution, high-energy-consumption industries toward clean production and energy conservation and environmental protection sectors through carbon emission intensity constraints and green finance incentives. The synergy between the two policies prevents capital from being locked into low-efficiency traditional sectors, thereby alleviating capital misallocation. With respect to labor misallocation, NBDCPZ improves the matching efficiency of the labor market through digital platforms, reducing job search costs for workers, and enabling labor with green skills to more easily agglomerate in low-carbon industries. LCCP, through industrial restructuring and the creation of green jobs, strengthens the willingness of labor to shift from high-pollution industries to the service sector and green manufacturing. The dual effects of information transparency and institutional guidance reduce labor misallocation caused by market frictions, making the marginal product of labor more balanced. As capital misallocation and labor misallocation are gradually alleviated, resource allocation efficiency improves, and the energy consumption and pollution emissions per unit of output decline, thereby driving urban pollution and carbon reduction. Based on the above, this paper proposes Hypothesis 2.

Hypothesis 2: Digital-green policy synergies empower urban pollution and carbon reduction through green innovation effects and factor reallocation effects.

3. Research Methods

3.1. Model Construction

To examine how Digital-green policy synergies affect urban pollution and carbon reduction, a staggered DID model is constructed in this paper for empirical analysis.

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$$score_{it} = \alpha + \beta did_{it} + \theta controls_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (1)$$

Where, i and t denote city and year, respectively;$score_{it}$represents the pollution and carbon reduction level of city i in year t; the core explanatory variable $did_{it}$is a dummy variable for the joint implementation of NBDCPZ and LCCP, which is assigned a value of 1 if city i implements both policies simultaneously in year t, and 0 otherwise;$controls_{it}$is a set of control variables affecting urban pollution and carbon reduction levels;$\delta_i$and $\mu_t$denote city fixed effects and year fixed effects, respectively; and ε_{it} is the random error term capturing other unobservable influencing factors. The coefficient β is the main parameter of interest. If β is significantly negative, it indicates that the dual-policy synergy helps drive urban pollution and carbon reduction, and vice versa.

3.2. Variables Definition

3.2.1. Explained Variables

The explained variable in this paper is the pollution and carbon reduction level (*score*). Following existing studies (Ma et al., 2024), an environmental pollution index is calculated using the improved entropy-weighted TOPSIS method based on three indicators[19]: total urban wastewater discharge, SO_2 emissions, and soot emissions. The urban carbon emission level is measured by aggregating carbon emissions from sources including electricity consumption, gas and liquefied petroleum gas (LPG) use, and transportation. Since both the environmental pollution index and the carbon emission level are reverse indicators, the pollution and carbon reduction level is measured as the product of the two (Yin et al., 2024)[20]. This approach is more consistent with the principle of "common sources of carbon and pollution" and better aligns with the systemic and holistic nature of pollution and carbon reduction governance (Jiang and Deng, 2025)[21].

3.2.2. Core Explanatory Variables

The core explanatory variable in this paper is the dummy variable for the dual-pilot policy combining NBDCPZ and LCCP, denoted as *did*. It is assigned a value of 1 if a city is designated as both a big data pilot zone and a low-carbon city pilot in a given year, and 0 otherwise. In addition, for comparative analysis, two single-pilot dummy variables are introduced: *d*id1 for the NBDCPZ single pilot and did2 for the LCCP single pilot. Each of these variables is assigned a value of 1 if a city is designated as the corresponding pilot policy in a given year, and 0 otherwise.

3.2.3. Control Variables

Following existing literature, the following control variables are selected in this paper(Wu et al., 2024; Lyu et al., 2024)[5, 14]: (1) Economic density (*lnpgdp*), which is measured as the ratio of gross regional product to administrative area, taken in logarithmic form; (2) Population mobility rate (*people*), which is measured as the ratio of the difference between resident population and registered population to registered population; (3) Financial development level (*tech*), which is measured as the ratio of deposits and loans of financial institutions to gross regional product; (4) Science and technology level (*market*), which is measured as the ratio of science and technology expenditure to local general public expenditure; (5) Fiscal pressure (*fis*), which is measured as the ratio of the difference between general government expenditure and general government revenue to gross regional product; (6) Urbanization rate (*income*), which is measured as the ratio of urban resident population to total resident population.

3.3. Data Description and Descriptive Statistics

The city-level data used in this paper are collected from the China City Statistical Yearbook, the CSMAR database, the CNRDS database, and the statistical bulletins of various provinces and cities. After cleaning and merging, an unbalanced panel dataset of prefecture-level cities in

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China from 2010 to 2023 is finally obtained. Descriptive statistics for the above variables are presented in Table 1.

Table 1. Descriptive statistics of the main variables

Variable	Sample size	Mean	Standard value	Minimum	Maximum
score	3251	11.64	1.740	3.988	17.00
did	3276	0.105	0.307	0	1
lnpgdp	3180	7.383	1.281	3.335	12.06
people	3240	0.0147	0.354	-0.461	4.203
fin	3276	2.783	1.262	0.635	21.30
tech	3276	0.00311	0.00269	1.80e-05	0.0220
fis	3276	0.130	0.104	-0.0104	0.806
urban	3276	0.583	0.146	0.181	1

4. Results and Analysis

4.1. Baseline Regressions

As shown in columns (1) and (2) of Table 2, regardless of whether control variables are added, the dual-pilot policy significantly drives urban pollution and carbon reduction at the 1% level. However, after the inclusion of control variables, the coefficient of the core explanatory variable decreases, indicating that the control variables selected in this paper are reasonable and effectively mitigate the interference of city-specific heterogeneity on the empirical results, thereby eliminating, to some extent, fluctuations caused by other factors.

To exclude the influence of outliers on the estimation results, column (3) of Table 2 presents the results after winsorizing continuous variables at the 1% level. Column (4) of Table 2 adjusts the standard errors to a higher-dimension (province) level to eliminate unobservable factors at the provincial level. The above results show that the dual-pilot policy significantly drives urban pollution and carbon reduction. Thus, Hypothesis 1 is verified.

Table 2. Baseline regression results

Variables	(1)	(2)	(3)	(4)
	score	score	score	score
did	-0.4374***	-0.3323***	-0.2488**	-0.3323*
	(0.1329)	(0.1278)	(0.1224)	(0.1650)
cons	11.6880***	4.2838**	4.4470**	4.2838**
	(0.0140)	(1.6811)	(1.9710)	(1.7490)
controls	no	yes	yes	yes
FE	yes	yes	yes	yes
cluster	city	city	city	province
N	3251	3121	3121	3121
adj. R2	0.8575	0.8629	0.8669	0.8629

Note: ***, **, * denote significant at the 1%, 5%, and 10% levels, respectively.， FE are city and year fixed effects. The same applies below.

4.2. Robustness Tests

4.2.1. Parallel Trend Test

In the DID model, the parallel trend assumption is a core prerequisite, which requires that there is no systematic difference in the trend of the explained variable between the treatment group

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and the control group prior to policy implementation. Following the approach of Beck et al. (2010), dummy variables from the 4th year before the policy to the 4th year after the policy are constructed, and the variable did in Model (1) is replaced to re-conduct the regression analysis[22]. The results of the parallel trend test are shown in Figure 1. The regression coefficients for all pre-policy periods are insignificant, indicating that there is no significant difference in the pollution and carbon reduction levels between the treatment and control groups, thus satisfying the parallel trend assumption. From the perspective of dynamic post-treatment effects, the regression coefficient becomes significantly negative immediately after policy implementation, and this inhibitory effect gradually strengthens over time. This indicates that the dual-pilot policy effectively drives pollution and carbon reduction in the pilot areas, and that the policy effect is sustained over the long term.

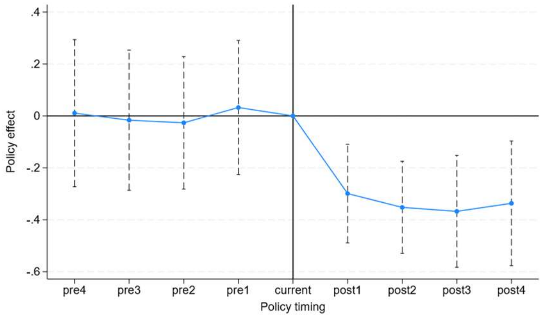

Figure 1. Parallel trend test

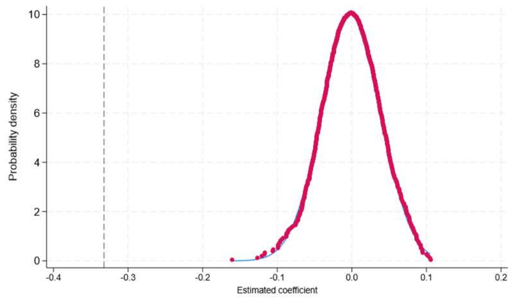

Figure 2. Placebo test

4.2.2. Placebo Test

To overcome estimation bias caused by omitted variables, a placebo test is conducted following the approach of Li et al. (2016)[23]. Specifically, pseudo-policy variables are constructed by randomly selecting pilot cities and randomly setting pilot years, which are then used to replace the did variable in Model (1) for regression, and this procedure is repeated 1,000 times. Figure 2 presents the distribution of the simulated estimated coefficients of the dual-pilot policy on urban pollution and carbon reduction levels. It is found that the estimated coefficients from the random samples are mostly concentrated around zero, which differs substantially from the baseline estimate of -0.3323. This indicates that the baseline estimation results are not driven by random chance and are relatively robust.

5. Mechanism Analysis

To further explore the internal mechanism through which the synergy of NBDCPZ and LCCP affects urban pollution and carbon reduction, empirical tests are conducted based on the aforementioned theoretical analysis from mechanistic pathways including green innovation effects and factor reallocation effects.

5.1. Green Innovation Effect

Based on the theoretical analysis above, the synergy of the dual-pilot policy enables firms to have both the ability and the willingness to engage in green technology innovation through technology supply and institutional demand, thereby driving urban pollution and carbon reduction. To test this mechanism, the following mediation model is constructed based on Model (1):

$$mediator_{it}=\alpha+\beta did_{it}+\theta controls_{it}+\delta_i+\mu_t+\varepsilon_{it} \quad (2)$$

$$score_{it}=\gamma_0+\gamma_1 mediator_{it}+\gamma_2 did_{it}+\gamma_3 controls_{it}+\delta_i+\mu_t+\varepsilon_{it} \quad (3)$$

In Models (2) and (3), $mediator_{it}$ represents the mediating variable, β is the effect of did_{it} on the mediating variable, γ_1 denotes the effect of the mediating variable on urban pollution and carbon reduction($score_{it}$), and γ_2 denotes the effect of the dual-pilot policy(did_{it}) on urban pollution and carbon reduction($score_{it}$). The meanings of other symbols are the same as those in Model (1).

Table 3. Mechanism test of green innovationeffect

Variables	green patent applications		green patent grants	
	(1)	(2)	(3)	(4)
	ga	score	gl	score
did	1.0981**	-0.2050*	0.5974**	-0.2426**
	(0.4407)	(0.1146)	(0.2376)	(0.1154)
ga		-0.1156***		
		(0.0198)		
gl				-0.1497***
				(0.0300)
cons	-7.0136**	3.4781**	-6.2656***	3.3480**
	(3.1256)	(1.6690)	(2.1729)	(1.6975)
controls	yes	yes	yes	yes
FE	yes	yes	yes	yes
cluster	city	city	city	city
N	3144	3121	3144	3121
adj. R2	0.8499	0.8668	0.7929	0.8662
Bootstrap	-0.1273***		-0.0897***	
95% confidence interval	(-0.1749， -0.0797)		(-0.1310， -0.0484)	

Specifically, following existing studies (Wang and Xia, 2026), the number of green patent applications and the number of green patent grants are used as proxy variables for green technology innovation, and are incorporated into Model (2) and Model (3), respectively, for testing[18]. The empirical results are shown in Table 3. The implementation of the dual-pilot policy significantly increases both the number of green patent applications and the number of green patent grants, indicating that green technology innovation is promoted. Moreover, the coefficients of both variables in Model (3) are significantly negative, suggesting that green technology innovation plays an important mechanistic role in the process through which the dual-pilot policy drives urban pollution and carbon reduction. In addition, the bootstrap test statistic is significantly negative, confirming the existence of this mechanistic pathway. The reason is that the data sharing platforms and digital accounting capabilities provided by NBDCPZ effectively reduce firms' R&D costs for green technologies in areas such as cleaner production and energy substitution. Meanwhile, in line with the Porter hypothesis, the carbon emission intensity and total volume targets set by LCCP compel firms to transform compliance pressure into innovation incentives, leading to a significant increase in green patent applications and grants. The practical application of green technologies further optimizes the energy structure and production processes, resulting in a synergistic reduction in carbon and pollutant emissions, thereby significantly driving urban pollution and carbon reduction.

5.2. Factor Reallocation Effect

As noted above, Digital-green policy synergies drive urban pollution and carbon reduction by improving factor allocation efficiency. Since urban factor allocation efficiency cannot be measured directly, indicators of capital distortion and labor distortion are constructed following existing studies (Bai and Liu, 2018), and urban factor allocation efficiency is indirectly reflected from the two dimensions of capital misallocation and labor misallocation[24]. A lower resource distortion indicates higher urban factor allocation efficiency. Then, based on the median level at the beginning of the sample period, the sample is divided into low distortion and high distortion groups. Theoretically, if the dual-pilot policy drives urban pollution and carbon reduction by improving resource allocation efficiency-that is, by alleviating factor distortions-then this policy effect should be more pronounced in the high distortion group. The subgroup regression results are shown in Table 4, which are consistent with theoretical expectations.

The reason is that NBDCPZ reduces information asymmetry through data sharing and credit evaluation platforms, while LCCP guides capital away from high-pollution, low-efficiency sectors through carbon emission constraints. Their synergy leaves greater room for improvement in cities with severe initial capital distortion, making the policy effect more significant in the high capital distortion group. With respect to labor factors, digital platforms improve the matching efficiency of the labor market, and LCCP creates green jobs. The more severe the initial labor misallocation in a city, the greater the market frictions, and the stronger the marginal improvement effect of the policy. Thus, labor misallocation is significantly reduced in the high labor distortion group.

Table 4. Mechanism test of factorreallocation effect

Variables	Total samples	capital distortion		labor distortion	
		lower	higher	lower	higher
	(1)	(2)	(3)	(4)	(5)
	score	score	score	score	score
did	-0.2012	-0.1090	-0.4523***	-0.2654	-0.3610**
	(0.1401)	(0.1788)	(0.1664)	(0.1749)	(0.1813)
da	-0.3201				
	(0.2248)				
daxdid	-0.8511**				
	(0.4052)				
cons	3.8130**	2.7825	5.3377**	2.8325	4.0154*
	(1.7005)	(2.7170)	(2.1259)	(2.9370)	(2.2966)
controls	yes	yes	yes	yes	yes
FE	yes	yes	yes	yes	yes
cluster	city	city	city	city	city
N	3098	1452	1646	1444	1654
adj. R2	0.8651	0.8662	0.8623	0.8508	0.8766

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6. Analysis of Synergistic Effects

6.1. Comparison of the Dual Pilot and Single Pilot Policies

To test whether the dual-pilot policy outperforms single-pilot policies in terms of pollution and carbon reduction effects, a comparative analysis is conducted. Specifically, by excluding the sample affected by NBDCPZ, the impact of LCCP alone on urban pollution and carbon reduction is examined. To account for potential endogeneity issues and capture dynamic effects, the empirical results with a one-period lag of the explanatory variable are further tested. The results are shown in columns (1) and (2) of Table 5. The coefficients of LCCP are negative but insignificant, and the absolute value of the coefficient for the lagged one-period policy variable decreases. Similarly, the impact of NBDCPZ alone on urban pollution and carbon reduction is examined, and the results are shown in columns (3) and (4) of Table 5. The contemporaneous coefficient of NBDCPZ is significantly negative, while the coefficient for the one-period lag remains significantly negative, but both its significance and absolute value decline. The absolute value of the contemporaneous coefficient of NBDCPZ is higher than that in the baseline regression, indicating that after excluding the interference of LCCP, the independent emission reduction effect of NBDCPZ becomes more prominent. However, this does not affect the overall conclusion that the synergistic effect of the dual-pilot policy outperforms single-pilot policies. Finally, cities that do not implement any pilot policy are excluded, retaining only the sample of cities that implement at least one type of pilot policy. Using dual-pilot cities as the treatment group and single-pilot cities as the control group, the synergistic effect of the dual-pilot policy relative to single-pilot policies is directly tested. The results are presented in columns (5) and (6) of Table 5. The coefficient of the dual-pilot policy is significantly negative, and the coefficient for the one-period lag is also significantly negative, with a larger absolute value.

LCCP focuses primarily on reducing carbon emission intensity, with relatively weak direct constraints on traditional pollutants such as industrial SO_2 and soot (Cao and Ren, 2024)[12]. Moreover, relying on traditional monitoring methods, it suffers from information asymmetry and high regulatory costs. Under emission reduction pressure, firms tend to adopt end-of-pipe treatment rather than fundamental green technology innovation (Li and Yao, 2024)[11]. As a result, LCCP struggles to simultaneously achieve significant progress in both carbon emissions and industrial pollution, and its effect on the comprehensive pollution and carbon reduction indicator is not significant. Over time, its policy effectiveness further weakens. NBDCPZ, in its initial stage, improves resource allocation efficiency and pollution monitoring capabilities through data platforms and industrial digitalization, thereby significantly driving pollution and carbon reduction. However, the digital rebound effect that may be induced by digital infrastructure causes the pollution and carbon reduction effect to attenuate as the lag period extends. In contrast, the dual-pilot policy achieves a two-way complementarity between institutional constraints and technological empowerment. The binding carbon targets set by LCCP provide a green orientation for the application of big data technology, curbing the rebound effect. NBDCPZ, by digitalizing carbon emission accounting and networking environmental monitoring, reduces the information costs and innovation trial-and-error costs of low-carbon regulations, activating the innovation offset effect. The synergy between the two policies enables the sustained release of green technology innovation and factor allocation optimization, so that the pollution and carbon reduction effect accumulates and strengthens over time, significantly outperforming single-pilot policies.

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Table 5. Comparison of the dual pilot and single pilot policies

Variables	LCCP		NBDCPZ		dual-pilot	
	no lag	lag 1 period	no lag	lag 1 period	no lag	lag 1 period
	(1)	(2)	(3)	(4)	(5)	(6)
	score	score	score	score	score	score
did1	-0.0127					
	(0.1818)					
ldid1		-0.0068				
		(0.1617)				
did2			-0.5023***			
			(0.1887)			
ldid2				-0.3262*		
				(0.1933)		
did					-0.2554*	
					(0.1461)	
ldid						-0.4279***
						(0.1505)
cons	2.7395	2.7675	4.0202**	4.1584**	6.0660**	7.7418**
	(1.8214)	(1.8696)	(1.9628)	(2.0395)	(2.9573)	(3.2149)
controls	yes	yes	yes	yes	yes	yes
FE	yes	yes	yes	yes	yes	yes
cluster	city	city	city	city	city	city
N	2202	2017	1778	1629	1749	1602
adj. R2	0.8517	0.8563	0.8573	0.8634	0.8705	0.8714

6.2. Comparison of the Pilot Sequence

To investigate whether the order of implementation of the two policies produces differentiated pollution and carbon reduction effects, it is necessary to compare the two pathways: "NBDCPZ before LCCP" and "LCCP before NBDCPZ." Accordingly, two samples are constructed. In the first sample, cities that implement NBDCPZ before LCCP are treated as the treatment group, while non-dual-pilot cities serve as the control group. Similarly, a second sample is constructed to test the policy effect of the pathway "LCCP before NBDCPZ." In addition, to better assess the dynamic effects of the policies, empirical tests with a one-period lag of the explanatory variable are conducted for both pathways. The results are shown in Table 6. Compared with the policy effect of the "LCCP before NBDCPZ" pathway, the absolute value of the policy coefficient under the "NBDCPZ before LCCP" pathway is larger, and the results with a one-period lag indicate that the effect of the dual-pilot policy strengthens over time.

The reason for this difference lies in the distinct functional orientations of the two policies. NBDCPZ focuses on the construction of digital infrastructure and the application of big data technology, while LCCP focuses on binding carbon emission targets. If a city implements NBDCPZ before LCCP, then by the time LCCP is subsequently introduced, it already possesses mature capabilities in carbon emission accounting and pollution monitoring, enabling the precise implementation of carbon constraints. Therefore, the pollution and carbon reduction effect is strong, consistent, and sustained. In contrast, if a city implements LCCP before NBDCPZ, it lacks digital technology support in the initial stage, resulting in high regulatory costs, low implementation efficiency, and limited policy effectiveness (Li and Yao, 2024)[11]. When NBDCPZ is later introduced, the digital upgrade of governance instruments allows the earlier institutional pressure to be released, and the effect with a one-period lag is enhanced. However, because LCCP was implemented first without technological support, some high-emission industries may have formed path dependencies, reducing the overall pollution and carbon reduction potential. This suggests that the sequence of technology first, followed by institutions, is more conducive to unlocking the synergistic dividends of Digital-green policy synergies.

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Table 6. Comparison of the pilot sequence

Variables	NBDCPZbeforeLCCP		LCCP before NBDCPZ	
	no lag	lag 1 period	no lag	lag 1 period
	(1)	(2)	(3)	(4)
	score	score	score	score
did1	-1.0610***		-0.3087**	
	(0.1182)		(0.1292)	
ldid1		-1.0379***		-0.4221***
		(0.1164)		(0.1312)
_cons	3.9059**	4.0669**	4.2192**	4.7905***
	(1.8389)	(1.8650)	(1.6938)	(1.7352)
controls	yes	yes	yes	yes
FE	yes	yes	yes	yes
cluster	city	city	city	city
N	2620	2400	3109	2848
adj. R2	0.8563	0.8610	0.8627	0.8670

7. Conclusion and Suggestions

Based on an unbalanced panel dataset of 262 prefecture-level cities in China from 2012 to 2023, this paper empirically examines the impact of Digital-green policy synergies on urban pollution and carbon reduction. The main findings are as follows. First, Digital-green policy synergies significantly drive urban pollution and carbon reduction, and this result remains robust after a series of endogeneity and robustness tests. Second, mechanism tests confirm that Digital-green policy synergies drive urban pollution and carbon reduction through green effects and factor effects. Third, further analysis reveals that, compared with single-pilot policies, the dual-pilot policy has a more significant effect on urban pollution and carbon reduction. Moreover, implementing NBDCPZ before LCCP is more conducive to driving urban pollution and carbon reduction than the reverse order. Based on the above findings, the following policy implications are drawn.

First, the synergistic implementation of the two pilot policies should be promoted. On the one hand, cities that have already implemented a single pilot should be screened, and those with appropriate conditions should be prioritized for inclusion in the other type of pilot, thereby forming a coordinated layout of digital infrastructure and carbon emission constraints. The data sharing platforms and carbon emission accounting systems of NBDCPZ should be directly linked to the emission reduction targets of LCCP. At the same time, LCCP cities should be required to incorporate energy-saving retrofits of data centers and the use of clean energy into their assessment frameworks. On the other hand, policy evaluation indicators should shift from focusing solely on carbon emission intensity or patent counts to a comprehensive index covering pollution and carbon reduction, so as to avoid the marginal diminishing returns of a single-path approach.

Second, the transmission channels of green technology innovation and factor allocation should be unblocked. An open green technology information platform should be established within NBDCPZ, integrating frontier technologies and R&D collaboration information in the fields of cleaner production and energy substitution, so as to reduce firms' search costs. On this basis, carbon market price signals and carbon emission accounting data should be used to guide bank credit toward firms with intensive green patents, thereby alleviating capital misallocation. At the same time, relying on digital platforms, the matching efficiency of the labor market should be improved. In combination with the green jobs created by LCCP, green skills training programs should be set up in dual-pilot cities to facilitate the transfer of labor from high-pollution industries to clean sectors.

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Third, the pilot policy planning should be optimized. For cities not yet included in the dual-pilot policy, priority should be given to implementing LCCP first to establish carbon emission constraints, followed by the introduction of NBDCPZ, so that digital technology can precisely empower the institutional pressure. For cities that have already implemented NBDCPZ first, it is necessary to promptly supplement low-carbon target constraints to prevent the carbon rebound effect caused by the lack of total volume control. Advancing the sequence of low-carbon constraints first followed by digital empowerment enables the organic integration of institutional pressure and technological support, thereby unlocking greater synergistic dividends for pollution and carbon reduction.

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