

How Does New Quality Productive Forces Empower the Synergistic Enhancement of Urban Pollution Reduction and Carbon Mitigation?

-- Empirical Evidence from Chinese Cities

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Abstract

Drawing on panel data from 242 Chinese cities spanning 2011–2022, this paper explores whether and how new quality productive forces facilitate the joint achievement of pollution reduction and carbon mitigation goals. The evidence confirms a positive empowering effect of these forces on urban synergistic performance. Mediation effect analysis indicates that this empowerment primarily operates through green technology innovation, resource allocation effects, and digital financial inclusion. Heterogeneity analysis shows that the synergistic effect of new quality productive forces on pollution reduction and carbon mitigation is more pronounced in ordinary cities, non-resource-based cities, and regions with higher levels of digital infrastructure. Grouping based on the two-dimensional framework of "digital foundation-environmental regulation" demonstrates that the empowering effect of new quality productive forces is strongest under "digital-driven" and "dual-high" scenarios, while it is limited under the "pressure-induced" scenario. This reflects the ineffectiveness of governance models that rely solely on administrative pressure without adequate digital capacity support. This study provides empirical evidence for understanding the green connotations and regional heterogeneity of new quality productive forces, and offers policy insights for differentially promoting urban green transformation.

Keywords

New Quality Productive Forces; Carbon Emissions; Synergistic Pollution Reduction and Carbon Mitigation.

1. Introduction

One of the central tenets of Chinese-style modernization is the harmonious coexistence between humans and nature. The report of the 20th National Congress of the Communist Party of China states, "We must promote the construction of a Beautiful China, advance the coordinated reduction of carbon emissions, pollution reduction, green expansion, and growth, prioritize ecological conservation, promote economical and intensive use of resources, and pursue green and low-carbon development. We must actively and prudently work toward the goals of carbon peak and carbon neutrality, gradually transition to a dual-control system over both the total amount and intensity of carbon emissions." The Central Committee of the Communist Party of China and the State Council's Opinions on Promoting High-Quality Urban Development stress the need to "advance the green and low-carbon transformation of urban development and promote energy conservation and carbon reduction in production." However, at the current stage, difficulties in optimizing urban energy structures, low efficiency in synergistic pollution reduction and carbon mitigation, and imperfect institutional mechanisms

remain key constraints hindering the achievement of China's dual-carbon strategic goals, improving people's well-being, and enhancing their quality of life. The Emerging Economies Carbon Dioxide Emissions Report 2025 shows that in 2022, fossil energy consumption accounted for 92.4% of China's primary energy consumption structure; between 2010 and 2022, carbon emissions from fossil energy consumption in China increased from 7357.7 million tonnes to 9845.4 million tonnes, a rise of 33.8%. The growth in energy consumption driven by industrialization and urbanization has led to an overall upward trend in carbon dioxide emissions, which have yet to peak. Therefore, exploring how to promote the synergistic enhancement of pollution reduction and carbon mitigation, deepen pollution prevention and control, improve people's sense of happiness, and achieve sustainable development constitutes an inherent requirement for realizing Chinese-style modernization. New quality productive forces represent a leap in productive capacity, characterized by high efficiency and high quality, inherently embodying the features of green productive forces. This is because advanced energy-saving and carbon-reduction technologies stemming from key and disruptive breakthroughs in new quality productive forces can empower the green transformation of industrial structures and high-quality economic development. Moreover, innovations and breakthroughs in digital-intelligent technologies brought about by new quality productive forces can effectively drive the growth of green industries, which will further promote the greening and decarbonization of the socio-economy. By greening, automating, intelligencing, and networking production processes, new quality productive forces optimize production structures, encourage enterprises to extend the recycling time of assets and resources, improve resource-use efficiency, reduce costs and resource consumption[1], and thus enhance the efficiency of pollution reduction and carbon mitigation from the production and supply sides. Therefore, investigating the impact and mechanisms of new quality productive forces on the synergy of pollution reduction and carbon mitigation is of great significance for deepening the value connotation of new quality productive forces, promoting the green transformation of industrial structures, and sustaining high-quality economic development.

2. Literature Review

The concept of productive forces traces back to the assertion by the English classical economist William Petty that "land is the mother of wealth, and labour the father and the active principle[2]." Subsequently, various schools of economic thought have expounded on the issue of productive forces from distinct perspectives, such as the "labor productivity" theory of Smith and Ricardo, and the productive forces theory of List. Building upon classical economic theory, Karl Marx linked productive forces to the development of science, clarifying that productive forces encompass science, and that labor productivity develops continuously with the advancement of science and technology.

New quality productive forces refer to the capacity to utilize and transform nature with high efficiency and quality, catalyzed by strategic emerging industries and future industries under the conversion and integration of scientific and technological innovation resources[3]. They are endowed with distinct features such as innovation-driven development, green and low-carbon orientation, open integration, and human-centered implication[4], with the practical pathways focused on strengthening overall scientific and technological innovation capabilities and constructing a modern industrial system[5]. Some scholars have developed indicator systems based on the classic Marxist theory of the three elements of productive forces to measure the level of new quality productive forces at the provincial level[6] or within enterprises[7]. Regarding the impact of new quality productive forces, numerous scholars have analyzed, both theoretically and empirically, their effects on cross-regional capital flows of enterprises[8],

common prosperity[9], high-quality economic development[10], new-type industrialization[11], as well as integrated urban-rural development[12].

Compared to the theoretical construction of new quality productive forces, the academic discourse in the field of pollution reduction and carbon mitigation highlights greater practical complexity. Current research primarily centers on the effects of environmental regulation, forming two major theoretical strands: "forced emission reduction" and the "green paradox"[13]. The former[14],[15],[16]focuses on the driving role of policy instruments, revealing the emission reduction effectiveness of institutional designs such as low-carbon city pilots and central environmental protection inspections. The latter warns of the risks of regulatory failure, with studies[17][18]pointing out the unintended consequences that may arise from competition among local governments. Regarding influencing factors, academia has mainly proposed solutions from two dimensions: institutional design and industrial transformation. At the level of institutional innovation, some studies emphasize restructuring central-local fiscal relations[19], and refining the performance assessment system for officials[20]. The dimension of industrial transformation focuses on pathways such as building a low-carbon industrial system[21]and upgrading the industrial structure[22].

However, the aforementioned approaches cannot fully address the environmental pollution problems caused by various complex factors, as the effectiveness of environmental governance requires the effective coupling of technological approaches with institutionalism. Pure "technocracy" may lead to policy distortions, while pure "institutional governance" may be inadequate for the effectiveness of complex environmental governance. The "newness" of new quality productive forces lies precisely in its focus on new technologies, new economies, and new business models. By achieving breakthroughs in key and disruptive technologies, it provides a stronger innovative driving force for the development of productive forces and breaks away from the path dependence on massive resource inputs and high resource consumption, thereby empowering the governance of environmental pollution from an institutionalist perspective. So, can China's issues of pollution reduction and carbon mitigation be studied from the angle of government governance coupled with technological embedding? New quality productive forces offer a novel approach to this significant contemporary challenge. The potential marginal contributions of this paper are as follows: Firstly, it integrates the contemporary proposition of new quality productive forces with environmental governance issues, verifying the positive empowering effect of new quality productive forces on the synergy of pollution reduction and carbon mitigation, and revealing the transmission pathways through green technology innovation, energy-saving effects, and digital financial inclusion. Secondly, by utilizing panel data from prefecture-level and above cities, the research findings possess greater generalizability and robustness. Thirdly, conducting heterogeneity analysis based on the two-dimensional framework of "digital foundation-environmental regulation" not only identifies the effectiveness differences of new quality productive forces in different types of cities but also provides empirical evidence for constructing a digitally empowered, classified policy implementation model for urban green transformation.

3. Theoretical Analysis and Research Hypotheses

3.1. New Quality Productive Forces and Urban Synergy in Pollution Reduction and Carbon Mitigation

New quality productive forces provide direction for promoting the green transformation of the industrial structure, achieving high-quality economic development, and realizing the "dual carbon" goals. At its core, new quality productive forces driven by key technological breakthroughs facilitate the deep integration of digital technologies, advanced artificial intelligence, big data analytics, and the Internet of Things with traditional factors of production.

This endows production factors with digital and intelligent characteristics, thereby enhancing total factor productivity. Specifically, the digital nature of production factors can help enterprises reduce market information search and matching costs, improving the market matching efficiency of the entire industrial chain and enhancing synergy among various production stages. Consequently, this boosts production efficiency in both consumption and production[23], reducing unnecessary energy consumption as well as pollutant and carbon emissions in the process. Furthermore, new quality productive forces can propel industrial greening and green industrialization. On one hand, the key technological innovations involved in new quality productive forces can optimize and reshape the means of labor within secondary industry enterprises, promoting the optimization of traditional manufacturing processes and the upgrading of equipment. This helps move away from outdated, high-energy-consumption, and low-efficiency production models reliant on obsolete technologies[24]. On the other hand, the inherent implication of green productive forces sets energy conservation and low-carbon development as goals, fostering the development and growth of digital industries, energy-saving and carbon-reduction industries, new energy, and circular economy industries. This facilitates the shift from old to new drivers of socio-economic development, breaking the path dependency on traditional extensive economic growth. Based on the above analysis, this paper proposes the following research hypothesis:

H1: New quality productive forces contribute to the synergistic enhancement of urban pollution reduction and carbon mitigation.

3.2. Analysis of Influence Mechanisms

3.2.1. Green Technology Innovation

The high-tech industries catalyzed by new quality productive forces, such as new energy, intelligent manufacturing, and artificial intelligence, can effectively drive the development of green and low-carbon industries, achieving green industrialization and industrial greening, thereby adjusting partial imbalances in the traditional industrial structure. The optimization and upgrading of the industrial structure can, through a triple mechanism of policy guidance promoting related industries, attracting social capital participation, and fostering regional competition and cooperation[25], significantly facilitate the formation of spatial spillover effects in regional technological innovation efficiency[26]. Industries like new energy, intelligent manufacturing, and AI, belonging to high-tech and strategic information industries, generate a human capital linkage effect upon their formation. This attracts an influx of a large number of highly skilled and highly educated talents, continuously optimizing the human capital structure[27] and providing strong talent and intellectual support for urban innovative development. On the other hand, key technological innovations and transformations can be applied to the energy supply side, product production side, and consumption side, fundamentally changing the economic operational model and promoting pollution reduction and carbon mitigation. Regarding the energy supply side, green technology innovation can accelerate the rapid development of the new energy consumption sector, speeding up the transformation in energy consumption areas represented by new energy vehicles, and reducing dependence on traditional high-energy-consumption, high-pollution energy sources. Furthermore, green technology innovation empowers industrial, construction, and manufacturing enterprises to improve and phase out outdated production equipment and processes, research and develop equipment with green energy-saving effects, and achieve the re-engineering of production processes and techniques, thereby reducing energy consumption and carbon emissions from the production side. Based on this, the following hypothesis is proposed:

H2a: New quality productive forces promote urban synergy in pollution reduction and carbon mitigation through green technology innovation.

3.2.2. Resource Allocation

Under the digital platform-based industrial organization model reshaped by new quality productive forces, operations can effectively address information asymmetry issues, achieve rational flow of factor resources, minimize dissipation and loss during the flow process, improve resource allocation efficiency, and significantly reduce various costs such as search and management for enterprises[28]. This alleviates the financial constraints faced by enterprises in their production and operational activities from both cost-reduction and efficiency-enhancement perspectives, providing economic support for encouraging enterprise technological innovation. Based on this, the following hypothesis is proposed:

H2b: New quality productive forces empower urban synergy in pollution reduction and carbon mitigation by improving resource allocation efficiency and reducing energy consumption.

3.2.3. Digital Financial Inclusion

The technological innovation brought about by new quality productive forces needs to align with green transition demands and requires effective long-term capital support to mitigate risks. A large number of small and medium-sized enterprises (SMEs) with emission reduction potential and disruptive innovation capabilities, green low-carbon industries, and green technology innovation projects have long faced financing constraints due to insufficient coverage by formal financial services[29]. On the other hand, constrained by information asymmetry, high service costs, and significant risk management challenges, the traditional financial service system struggles to provide effective financial support for these dispersed, long-cycle green activities. Digital financial inclusion reconstructs the financial service paradigm through digital means such as big data, artificial intelligence, and blockchain, breaking many limitations of traditional financial services, significantly improving the service efficiency and quality of financial institutions[30]. With its wide coverage, low cost, and precise allocation efficiency, it establishes a market-based transmission channel between new quality productive forces and green development. It accurately identifies green value through data-driven methods, breaking through information asymmetry barriers; expands service boundaries via digital platforms, activating the emission reduction potential of micro-entities; and relies on fintech innovations to transform environmental benefits into market-based incentives. This systematically addresses the difficulties in identifying, reaching, and incentivizing green investments, providing indispensable market-based support for new quality productive forces to deeply empower the synergistic enhancement of pollution reduction and carbon mitigation, and guiding capital flow towards energy conservation, emission reduction, and sustainable development[31]. Specifically, as digital financial inclusion significantly lowers the threshold for financial services and expands public participation in environmental protection[32], dispersed SMEs, communities, and even households can conveniently access products such as green credit and government subsidies. This effectively supports their emission reduction actions like equipment energy-saving retrofits, activating the pollution reduction and carbon mitigation potential at the micro level. Based on this, the following hypothesis is proposed:

H2c: New quality productive forces positively influence urban synergy in pollution reduction and carbon mitigation by enhancing the level of digital financial inclusion.

4. Research Design

4.1. Sample Selection and Data Sources

This study conducts empirical research using panel data from 242 prefecture-level and above cities in China spanning from 2011 to 2022. Given data availability, the sample period ends in 2022. The data are primarily sourced from the China City Statistical Yearbook, the China

Statistical Yearbook, the China Regional Statistical Yearbook, the Emissions Database for Global Atmospheric Research (EDGAR) by the European Union, the China Energy Statistical Yearbook, and the Chinese Research Data Services Platform (CNRDS). For instances of missing indicator data, the linear interpolation method was employed for imputation. To mitigate the influence of outliers, all continuous variables were winsorized at the 1st and 99th percentile levels.

4.2. Variable Selection and Definitions

4.2.1. Dependent Variable

The synergistic efficiency of pollution reduction and carbon mitigation measures the extent to which carbon dioxide emissions are reduced alongside atmospheric pollutants (see Table 1). Regarding the measurement scale for urban synergistic efficiency in pollution reduction and carbon mitigation, this paper draws on the research of Guo Pei[33], selecting the Data Envelopment Analysis (DEA) method to estimate this synergistic efficiency. An input-output evaluation system for synergistic pollution reduction and carbon mitigation efficiency is constructed, selecting capital, labor, and energy as input indicators, represented by capital stock, urban employment, and energy consumption, respectively. Gross Domestic Product (GDP) is chosen as the desirable output indicator. Carbon dioxide emissions and PM2.5 concentration are selected as undesirable output indicators. PM2.5 concentration is the most significant factor affecting air quality in China and dominates among various atmospheric pollutants. Existing studies[34][35]often use it as a proxy variable for urban atmospheric pollutants. The specific variables are detailed in Table 1.

Table 1. Evaluation Indicator System for Synergistic Pollution Reduction and Carbon Mitigation Efficiency

Tier-1 Indicator	Tier-2 Indicator	Variable Explanation
Input	Capital	Capital input is represented by capital stock, calculated using the perpetual inventory method. The formula is: $K_{i,t} = K_{i,t-1} (1 - \delta_{i,t}) + I_{i,t}$, where $K_{i,t}$ denotes the capital stock of city i in year t (unit: 10,000 yuan); $\delta_{i,t}$ denotes the capital depreciation rate of city i in year t; $I_{i,t}$ denotes the new capital investment of city i in year t (unit: 10,000 yuan).
	Labor	Represented by the number of urban employed persons (unit: 10,000 persons).
	Energy	Urban direct energy consumption mainly includes natural gas and liquefied petroleum gas. Indirect energy consumption mainly includes electricity consumption. This paper converts all energy consumption into standard coal equivalent.
Output	Desirable Output	Desirable output is represented by Gross Domestic Product (GDP) (unit: 10,000 yuan).
	Undesirable Output	Undesirable outputs include carbon dioxide emissions and other atmospheric pollutant emissions. Carbon dioxide emission data is sourced from the Emissions Database for Global Atmospheric Research (EDGAR) (unit: tons). Other atmospheric pollutant emissions are represented by the annual average PM2.5 concentration (unit: $\mu\text{g}/\text{m}^3$).

4.2.2. Explanatory Variable

Level of New Quality Productive Forces Development. Proceeding from the classic Marxist theory of productive forces and integrating the value connotations of new quality productive forces adapted to the Chinese context and the present era, this paper draws on the approach of existing research[36] to construct a comprehensive evaluation indicator system for new quality

productive forces across three major dimensions: new quality laborers, new quality means of labor, and new quality objects of labor. The comprehensive evaluation indicator system for new quality productive forces is shown in Table 2.

Table 2. Comprehensive Evaluation Indicator System for New Quality Productive Forces

Objective Layer	Tier-1 Indicator	Tier-2 Indicator	Tier-3 Indicator	Attribute	Weight	
New Quality Productive Forces	New Quality Laborers	Human Capital	Number of Students in Regular Higher Education Institutions / Resident Population	Positive	0.083	
		Number of Laborers	Proportion of Employees in Information Transmission, Computer Services, and Software Industries	Positive	0.056	
		Labor Productivity	Average Wage of Employed Persons	Positive	0.018	
	New Quality Objects of Labor	Digital Industry		Industrial Robot Penetration Rate	Positive	0.137
				Postal Service Revenue / GDP	Positive	0.086
				Telecommunication Service Revenue / GDP	Positive	0.046
				Share of Scientific and Technological Investment	Positive	0.083
		Environmental Protection		Green Coverage Rate in Built-up Areas	Positive	0.002
				Harmless Treatment Rate of Municipal Solid Waste	Positive	0.003
				Industrial Sulfur Dioxide Emissions / GDP	Negative	0.001
	New Quality Means of Labor	Infrastructure		Collection Size of Public Libraries	Positive	0.173
				Ratio of Internet Broadband Access Ports to Total Regional Population	Positive	0.036
				Ratio of Mobile Phone Subscribers to Total Regional Population	Positive	0.012
		Digital-Intelligent Level		Number of Artificial Intelligence Enterprises	Positive	0.244
				Digital Financial Inclusion Index	Positive	0.021

4.2.3. Control Variables

With reference to existing related studies[37], this paper selects the following variables as control variables: (1) Economic development level (Econ). It is represented by the logarithm of GDP per capita. (2) Government scale (Gov). It is represented by the ratio of general public budget expenditure to regional GDP. (3) Foreign direct investment level (FDI). It is represented by the ratio of actually utilized foreign direct investment in the year to regional GDP. (4) Financial development (Finan). The ratio of financial institution loans to regional GDP is used as an indicator to measure the degree of financial development. (5) Population density (lnpd). It is represented by the ratio of the year-end resident population to the regional area.

4.3. Model Construction

To investigate the effect of new quality productive forces on synergistic pollution reduction and carbon mitigation, this paper constructs a general baseline regression model for their relationship as follows:

$$Coor_{it} = \alpha_0 + \alpha_1 Nqp_{it} + \alpha_2 Controls_{it} + \mu_i + \nu_t + \epsilon_{it}$$

In the equation: $Coor_{it}$ represents the level of synergistic pollution reduction and carbon mitigation for city i in period t ; Nqp_{it} represents the new quality productive forces index for city i in period t ; $Controls_{it}$ represents a series of control variables, including the degree of financial development (Finan), government scale (Gov), foreign direct investment level (Fdi), economic development level (Econ), and population density (Inpd); $\alpha_0, \alpha_1, \alpha_2$ are parameters to be estimated; μ_i represents the individual fixed effects in the model; ν_t represents the time fixed effects in the model; ε_{it} represents the random disturbance term. The descriptive statistics for the main variables are presented in Table 3 below.

Table 3. Descriptive Statistics of Variables

Variable Name	Variable Symbol	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Synergistic Pollution Reduction and Carbon Mitigation	Coor	2904	0.063	0.046	0.021	0.331
New Quality Productive Forces	Nqp	2904	0.077	0.045	0.024	0.26
New Quality Laborers	Nql	2904	0.124	0.104	0.029	0.518
New Quality Objects of Labor	Nqo	2904	0.068	0.038	0.027	0.227
New Quality Means of Labor	Nqm	2904	0.067	0.049	0.012	0.322
Economic Development Level	Econ	2904	10.81	0.551	9.553	12.02
Government Scale	Gov	2904	0.191	0.087	0.077	0.573
Foreign Direct Investment Level	FDI	2904	0.016	0.016	0	0.069
Financial Development Level	Finan	2904	2.596	1.185	1.027	6.905
Population Density	Inpd	2904	5.875	0.807	3.439	7.483

5. Empirical Results and Analysis

5.1. Baseline Regression Results

The baseline estimates are presented in Table 4. Column (2) displays the results with the inclusion of year and region fixed effects, control variables, and the core explanatory variable. The coefficient for new quality productive forces is significant at the 1% level, indicating that their development plays a substantial role in promoting urban synergy between pollution reduction and carbon mitigation. Hypothesis 1 is thus validated. Furthermore, examining the sub-dimensional indicators of new quality productive forces, the estimated coefficients for both new quality laborers and new quality means of labor on urban synergistic pollution reduction and carbon mitigation are significantly positive, while that for new quality objects of labor is not significant. The main reason is that new quality objects of labor, such as data, are inherently "passive." They must be analyzed and decided upon by laborers, and processed and applied through means of labor to create value. In the absence of powerful means of labor and high-quality laborers, even substantial investments in data resources may fail to be effectively activated and transformed due to an "absence of capacity." New quality means of labor exhibit the strongest driving effect because they represent the direct material force enabling synergistic pollution reduction and carbon mitigation. New quality means of labor are a marker of productive forces development, directly embodying the advancement of production tools. Intelligent means of labor can optimize production processes in real-time, improve energy and resource utilization efficiency, and directly reduce pollution and carbon emissions from the production side. The ability to provide immediate and precise intervention in production links

through technological tools makes new quality means of labor the most effective pathway for advancing pollution reduction and carbon mitigation. The green skills and environmental awareness possessed by high-quality laborers, however, must be translated into actual pollution reduction and carbon mitigation outcomes through their research and development activities, management decisions, and operational behaviors. Regarding the control variables, sustained economic growth enhances fiscal capacity and capital accumulation, enabling cities to undertake the large-scale infrastructure and R&D investments necessary for the green and low-carbon transition. Secondly, the advancement of industrial structure accompanying economic development promotes the gradual replacement of high-energy-consumption traditional industries by capital, green and low-carbon industries, and high-tech industries. The negative regression coefficient for government intervention indicates that government intervention in the market can sometimes be inefficient, suggesting a greater need to rely on market forces.

Table 4. Baseline Regression Results

Variable	(1)	(2)	(3)	(4)	(5)
	Coor	Coor	Coor	Coor	Coor
Nqp	0.578*** (0.075)	0.563*** (0.074)			
Nql			0.187*** (0.035)		
Nqo				-0.003 (0.029)	
Nqm					0.704*** (0.076)
Econ		0.009** (0.004)	0.002 (0.004)	0.000 (0.005)	0.009** (0.004)
Gov		-0.057*** (0.017)	-0.069*** (0.017)	-0.080*** (0.018)	-0.045*** (0.015)
FDI		-0.158** (0.068)	-0.147** (0.073)	-0.175** (0.073)	-0.183*** (0.064)
Finan		-0.006*** (0.002)	-0.008*** (0.002)	-0.008*** (0.002)	-0.006*** (0.001)
Inpd		0.010** (0.005)	0.011** (0.005)	0.011* (0.006)	0.004 (0.003)
cons	0.019*** (0.006)	-0.107* (0.056)	-0.012 (0.059)	0.035 (0.064)	-0.084* (0.049)
City	×	√	√	√	√
Year	×	√	√	√	√
N	2904	2904	2904	2904	2904
Adj. R ²	0.752	0.762	0.752	0.743	0.787

Note: Robust standard errors are in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The same applies below.

5.2. Mediation Effect Test

Based on the theoretical mechanism analysis, this paper posits that new quality productive forces enhance the level of urban synergistic pollution reduction and carbon mitigation by driving and leading green innovation, optimizing production processes to improve energy efficiency, and promoting digital financial inclusion. Therefore, an empirical analysis of the

theoretical mechanisms proposed above is conducted by constructing a mediation effect model[38]. The mediation effect model is specified as follows:

$$Med_{it} = \beta_0 + \beta_1 Nqp_{it} + \beta_2 Controls_{it} + \mu_i + \nu_t + \epsilon_{it}$$

5.2.1. Green Technology Innovation

This study utilizes two indicators-green invention patent applications (IV) and green invention patents granted (IG)-to capture the extent of green innovation[39]. Findings from columns (3) and (4) of Table 5 demonstrate that the coefficients for new quality productive forces on green technology innovation are positive and pass the 1% significance test, implying that the growth of these forces fosters an improvement in green technology innovation.

The essence of new quality productive forces is green productive forces, and the renewal and iteration of green productive forces rely on key breakthroughs in green technologies such as "zero-carbon" and "carbon sequestration." These breakthroughs, in turn, empower the entire spectrum and full process of industrial construction, intelligent manufacturing, and even people's production and daily life. They vigorously promote the shift of production and lifestyle towards green and low-carbon development, facilitate clean energy production and energy structure transformation, and spur the emergence of new energy and strategic emerging industries, thereby aiding the optimization and upgrading of traditional industrial structures. This continuously reduces energy consumption and provides strong momentum for achieving low-carbon transformation and development of the economy and society[40].

5.2.2. Resource Allocation

The energy-saving effect reflects the proportion of energy consumption required per unit of GDP output; a higher proportion indicates a poorer energy-saving effect. This paper measures the level of energy conservation using the ratio of total electricity consumption to GDP and the ratio of ten thousand tons of standard coal equivalent to GDP, respectively. The results in columns (1) and (2) of Table 5 show that the coefficients for new quality productive forces are -1.583 and -4.665, both significant at the 1% level, indicating that new quality productive forces enhance the energy-saving effect.

5.2.3. Digital Financial Inclusion

Table 5. Results of Mediation Analysis

Variable	(1)	(2)	(3)	(4)	(5)
	Energy-saving Effect 1	Energy-saving Effect 2	Green Patent Applications	Green Patents Granted	Digital Financial Inclusion
Nqp	-1.583*** (0.351)	-4.665*** (0.439)	3.030*** (0.734)	4.330*** (0.865)	1.389*** (0.127)
cons	3.467*** (0.476)	4.217*** (0.684)	-3.252*** (0.929)	-3.781*** (1.252)	0.581*** (0.147)
Control Variables	√	√	√	√	√
City	√	√	√	√	√
Year	√	√	√	√	√
N	2904	2904	2904	2904	2904
Adj. R ²	0.759	0.747	0.935	0.917	0.995

The digital financial inclusion data used in this paper are sourced from the Peking University Digital Financial Inclusion Index[41]. To ensure this index maintains the same unit of measurement as other indicators selected in this paper, the percentage value of the index divided by 100 is used as the raw data. The result in column (6) of Table 5 indicates that the

development of new quality productive forces significantly enhances the level of digital financial inclusion.

5.3. Robustness Tests

5.3.1. Instrumental Variable Approach

To mitigate potential issues of bidirectional causality or simultaneity bias between new quality productive forces and the level of synergistic pollution reduction and carbon mitigation, this paper draws on the approach of Li Zhanping[42]. The new quality productive forces index lagged by one period is used as an instrumental variable, and estimation is conducted using the two-stage least squares method. The results in column (1) of Table 6 pass the underidentification and weak instrument tests. The second-stage regression results show that the regression coefficient of the core explanatory variable remains significantly positive at the 1% level, confirming the robustness of the baseline regression results.

5.3.2. Exclusion of Municipality Samples

Significant differences in policy orientation may lead to variations in the level of new quality productive forces in municipalities directly under the central government compared to other regions. Therefore, a robustness test was conducted by excluding municipalities from the sample. The regression results in column (3) of Table 6 show that the direction of the effect of new quality productive forces on urban synergistic pollution reduction and carbon mitigation remained unchanged. The comprehensive index of new quality productive forces rejected the null hypothesis at the 1% significance level.

5.3.3. Introduction of Province-Year Interaction Effects

In a more stringent specification, we include province-year fixed effects to absorb unobserved provincial characteristics that vary over time. The results in Table 6, column (4) demonstrate that the coefficient for new quality productive forces is still positive and significant at the 1% level, confirming the stability of the conclusion.

5.3.4. Subsample Regressions

Table 6. Robustness and Endogeneity Test Results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	First Stage of IV Approach	Second Stage of IV Approach	Excluding Municipalities	Province×Year FE	Low-Level Subgroup	High-Level Subgroup
	Nqp	Coor	Coor	Coor	Coor	Coor
IV	0.731*** (0.049)					
Nqp		0.198*** (0.071)	0.629*** (0.071)	0.57*** (0.075)	0.009 (0.068)	0.341*** (0.098)
cons			-0.121** (0.053)	0.015 (0.068)	-0.201*** (0.046)	0.13 (0.135)
Control Variables	√	√	√	√	√	√
City	√	√	√	√	√	√
Year	√	√	√	√	√	√
Province×Year	×	×	×	√	×	×
Kleibergen-Paap rk LM	65.981 [0.000]					
Kleibergen-Paap rk Wald F	222.65 {16.38}					
N	2662	2662	2856	2820	1444	1440
Adj. R ²	0.966	0.068	0.774	0.814	0.885	0.759

Note: Values in square brackets [] are p-values; values in curly braces {} are the critical values for the Stock-Yogo weak identification test at the 10% level.

A heterogeneity analysis is performed by categorizing the sample into two subgroups according to whether the level of new quality productive forces is above or below the median. The regression outcomes show positive and significant effects in the above-median group, but not in the below-median group. These results provide additional evidence supporting the robustness of the finding that new quality productive forces contribute positively to coordinated pollution and carbon reduction.

5.4. Heterogeneity Analysis

5.4.1. Heterogeneity in Administrative Hierarchy

This paper divides cities into two groups based on administrative hierarchy: municipalities and provincial capitals versus ordinary cities, and conducts grouped regressions. The findings indicate that the positive influence of new quality productive forces on pollution-carbon synergy is pronounced in ordinary cities (significant at 1%), yet it remains insignificant in provincial capitals and directly-administered municipalities. Ordinary cities are mostly in the industrial upgrading stage of late industrialization, where the combination of traditional production factors is not yet solidified. When new quality means of labor intervene as an exogenous shock, they can replace old equipment and rapidly reconfigure production factors. A unit of technological input can leverage a larger proportion of energy efficiency improvements. In contrast, provincial capitals and municipalities exhibit post-industrial characteristics, with factor allocation approaching Pareto optimality. Technological innovation there manifests more as incremental improvements to existing equipment, which limits the application and expansion of new quality productive forces.

5.4.2. Heterogeneity in Resource Endowment

The differences in urban resource endowments largely determine their development paths and industrial structure, leading to varying agency and adaptability when faced with empowerment by new technologies and new quality productive forces. Based on the list of resource-based cities published in the National Sustainable Development Plan for Resource-Based Cities (2013-2020), this paper divides the sample cities into resource-based cities and non-resource-based cities. Observing the results in columns (6) and (7) of Table 5, it can be found that new quality productive forces have a significant promoting effect on synergistic pollution reduction and carbon mitigation in non-resource-based cities, while the effect is not significant in resource-based cities. The reasons are as follows: In resource-based cities, factor allocation has long been entrenched in traditional production capacity and resource-oriented capacity. The sunk costs of specialized assets significantly slow down the pace of technological generational replacement, and technological iteration faces higher opportunity costs. In contrast, the human capital structure in non-resource-based cities is more compatible with the demands of emerging industries, enabling faster technology diffusion rates through skill reshaping. Furthermore, policies in non-resource-based cities are more easily aligned with support systems for emerging industries, and they can accelerate technology penetration through market-based tools like green credit. In contrast, transition policies in resource-based cities are often constrained by the dual objectives of maintaining employment stability and increasing fiscal revenue, facing greater policy tension between environmental regulation and technological incentives.

5.4.3. Heterogeneity in Digital Infrastructure and Environmental Regulation Pressure

What are the differences in the performance of new quality productive forces among cities with varying levels of digital infrastructure readiness and environmental regulation pressure? To deeply reveal the complex interaction between the development of new quality productive forces and urban characteristics related to pollution reduction and carbon mitigation, a variable for digital infrastructure level is introduced. This is constructed using three indicators for the

current year at the prefecture level: internet users per 100 people, mobile phone subscribers per 100 people, and per capita telecommunications business volume[43], calculated using the entropy method. Based on the median of this index, the sample is divided into high and low digital infrastructure level groups. Regarding environmental regulation pressure, a dummy variable is generated with a value of 1 if a sample city was a low-carbon city pilot in that year, and 0 otherwise. This paper further constructs a two-dimensional analytical framework centered on "digital foundation–environmental pressure," and categorizes the research subjects into four typical types accordingly: the first is the "dual-high" type, characterized by high levels of both digital infrastructure and environmental regulation; the second is the "dual-low" type, where both are at low levels; the third is the "digital-driven" type, featuring a high level of digital infrastructure but relatively weak environmental regulation; and the fourth is the "pressure-induced" type, marked by weak digital infrastructure but stringent environmental regulation. The results from columns (5) to (6) of Table 7 show that new quality productive forces significantly enhance the level of synergistic pollution reduction and carbon mitigation in cities belonging to the "dual-high" and "digital-driven" groups. Cities in the "dual-high" group possess both "capacity" and "motivation." The digital foundation provides technical means, while environmental regulation creates market demand and policy pressure. These two forces combine to jointly amplify the pollution reduction and carbon mitigation effectiveness of new quality productive forces. The promoting effect is not significant in the "dual-low" group, primarily because such cities lack both the digital foundation for applying new technologies and the policy pressure driving green transformation. Consequently, the development of new quality productive forces and their empowering effect on pollution reduction and carbon mitigation lose their core driving force. Cities in the "pressure-induced" group face strong environmental regulation pressure from higher authorities, but their weak digital infrastructure and traditional industrial structure severely constrain the absorption and application of new quality productive forces. In this situation, although local governments and enterprises have the willingness to meet assessment requirements, the lack of intelligent and precise governance tools often forces them to adopt costly but short-lived end-of-pipe treatment measures. There may even be "pro forma" rectifications merely to cope with inspections[44]. Excessively high performance pressure can, in fact, reduce the environmental governance efficiency of local governments [45].

Table 7. Heterogeneity Analysis Results

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Provincial Capitals & Municipalities	Ordinary Cities	Resource-based Cities	Non-resource-based Cities	Dual-high Group	Dual-low Group	Digital-driven Group	Pressure-induced Group
	Coord	Coord	Coord	Coord	Coord	Coord	Coord	Coord
Nqp	0.063	0.379***	0.046	0.687***	0.428***	-0.004	0.503***	-0.114**
	(0.161)	(0.067)	(0.042)	(0.090)	(0.162)	(0.045)	(0.143)	(0.047)
cons	-0.730***	-0.185***	-0.278***	0.239***	0.180	0.192***	-0.242*	-0.063
	(0.279)	(0.056)	(0.044)	(0.091)	(0.241)	(0.065)	(0.135)	(0.122)
Control Variables	√	√	√	√	√	√	√	√
City	√	√	√	√	√	√	√	√
Year	√	√	√	√	√	√	√	√
N	336	2568	1104	1800	665	971	765	405
Adj. R ²	0.805	0.793	0.735	0.782	0.801	0.876	0.660	0.868

6. Research Conclusion and Policy Implications

6.1. Main Conclusion

This research employs a panel dataset covering 242 prefecture-level and above cities in China from 2011 to 2022 to examine the effect of new quality productive forces on the synergy between pollution abatement and carbon reduction. The empirical evidence demonstrates a notable promotional impact, which holds up under various robustness tests and endogeneity corrections. Mechanistically, these forces operate by advancing green technology innovation, optimizing energy-saving performance, and deepening digital financial inclusion at the urban level. Analysis based on the two-dimensional framework of "digital foundation - environmental regulation" finds that the promoting effect is most prominent in "dual-high" cities (high digital foundation - high environmental regulation) and "digital-driven" cities (high digital foundation - low environmental regulation), indicating that digital infrastructure is key to unleashing the green efficacy of new quality productive forces. In contrast, "pressure-induced" cities (low digital foundation - high environmental regulation) reflect the limitations of governance models that rely solely on administrative pressure without adequate digital capacity support. Furthermore, the effect is more pronounced in ordinary cities and non-resource-based cities, revealing structural differences arising from regional resource endowments and developmental stages.

6.2. Policy Recommendations

6.2.1. Strengthening Policy Support

A multi-dimensional policy system encompassing economic incentives, market regulation, technological innovation, and regional coordination will be established. Fiscal subsidies and tax incentives will be leveraged to channel capital, talent, and data factors toward green and low-carbon sectors. Meanwhile, the institutional environment aligned with new quality productive forces will be enhanced, including strengthening intellectual property protection, optimizing the green finance system, and establishing cross-departmental coordination mechanisms. This systematic policy framework is designed to support the comprehensive integration and deep application of new quality productive forces in pollution reduction and carbon cutting.

6.2.2. Enhance Scientific and Technological Research Efforts to Overcome Key Technological Bottlenecks in Green and Low-carbon Development and Improve Urban Technological Innovation Capabilities.

Increase public R&D investment to support in-depth basic scientific research and applied technology research, and gradually improve the green finance and fiscal support systems that underpin technological innovation development. Resource-based cities should promote green process technology transformation, establish strict emission standards, and implement market mechanisms such as carbon trading systems to form effective constraints and incentives. Non-resource-based cities, on the other hand, should build vibrant green innovation ecosystems by establishing regional green technology trading platforms, strengthening the market-oriented operation of intellectual property, and guiding venture capital towards green start-ups.

6.2.3. Strengthen Cross-regional Collaboration, Break Down Information Barriers, and Enhance the Inclusiveness and Precision of Support within the Digital Financial Ecosystem.

Increase innovation in financial products and reinforce market incentives, vigorously encouraging financial institutions to develop precise products based on dynamic data, such as green innovation vouchers linked to carbon footprints, low-carbon supply chain finance, and sustainability-linked loans. This transforms the environmental benefits of enterprises into tangible financing advantages. Simultaneously, employ measures such as fiscal interest

subsidies and establishing green finance risk compensation funds to disperse risks for financial institutions and stimulate their endogenous motivation to serve small, medium, and micro-sized green enterprises and innovative projects.

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