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Article

Effect of Digital Economy Enabling Pollution and Carbon Reduction in China

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ABSTRACT

Since the introduction of China's "dual carbon" goals, achieving synergistic pollution and carbon reduction has become a critical task for promoting ecological civilization and high-quality development. As the digital economy expands rapidly, its role in facilitating green transformation has attracted increasing attention. Drawing on panel data from 31 Chinese provinces during 2015–2024, this study conceptualizes the digital economy from two dimensions—digital infrastructure and digital commerce application. The entropy method is employed to construct composite indices for both dimensions, and a two-way fixed effects model is applied to investigate their effects on pollution and carbon reduction. The results show that the growth of digital infrastructure has a significant negative effect on pollution and carbon reduction, likely due to intensive energy use and emissions during its construction and operation. Similarly, the development of digital commerce application also exhibits a negative effect, probably because of increased energy consumption from e-commerce logistics, data center operations, and enterprise digital transformation. Both dimensions currently hinder progress in pollution and carbon reduction, with digital infrastructure having a stronger adverse impact. Policy efforts should focus on promoting green and energy-efficient development of digital infrastructure, accelerating the low-carbon transformation of digital commerce applications, and establishing an integrated evaluation framework linking digital economy development with pollution and carbon reduction. Such measures can provide targeted support for regional green transformation and sustainable development. This paper aims to answer whether the digital economy promotes or inhibits pollution and carbon reduction in China, and whether this effect operates through digital infrastructure or digital commerce application.

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Research Highlights

- The digital economy is decomposed into infrastructure and commerce dimensions.
- Composite indices are constructed using the entropy method.
- Digital infrastructure hinders pollution and carbon reduction.
- Digital commerce application hinders pollution and carbon reduction.
- Distinct environmental effects exist across digital economy dimensions.

1. Introduction

1.1. Research Background

The report of the 20th National Congress of the Communist Party of China suggests that we should promote carbon reduction, pollution control, ecological protection, and economic development together, and green and low-carbon economic and social development. At present, the Chinese economy has entered a stage of high-quality growth after rapid growth and the simultaneous implementation of pollution control and carbon reduction have now become a pressing issue in the context of regional transformation. The steel and chemical sectors face acute pressure to reduce emissions. Moreover, the prospects for pollution control in key regions such as Beijing–Tianjin–Hebei and the Yangtze River Delta remain challenging. The traditional end of pipe treatment options has not worked to solve the problem of curbing emissions in the long run. Historical records indicate that the industrial sector of China has, over the years, accounted for more than 65% of the total energy use in the nation, and coal combustion was an important component of this. The concentrations of major air pollutants, namely, SO_2 and NO_x are extremely high. Conversely, the digital economy has become one of the engines of green progress. The digital economy of China has exceeded 60 trillion yuan in 2024 according to statistics given by the China Academy of Information and Communications Technology with almost half or around 45% of the GDP and the digital infrastructure is strengthened and the number of individuals involved in digital commerce increases. However, much of the existing literature treats the digital economy as a unified phenomenon and does not consider different processes by which digital infrastructure and digital commerce could result in such an outcome. Indeed, mass deployment and maintenance of digital infrastructure need large quantities of electricity, which could be linked to high carbon emissions but the emergence of digital commerce could trigger the digitalization of businesses and enhance the efficiency of distributing resources, hence, making them low-carbon [1, 2]. One of the strong points of the given paper is its approach to dividing the digital economy into two parts, the infrastructure and services. In May 2026, four government agencies (the National Development and Reform Commission) released the Action Plan on the Promotion of Mutual Empowerment between Artificial Intelligence and Energy. There will definitely be great help in this thesis with the recommendation provided therein regarding speeding up the process of greening and low-carbon transition of computing infrastructure.

1.2. Research Significance

1.2.1. Theoretical Significance

This paper integrates the digital economy and reduction of pollution and carbon emission into a single analytic framework. This connection can assist in extending the scope of the study of the digital economy and enhance the value and complexity of environmental economics. In contrast to most of the other past researchers who considered environmental impact of the digital economy as a single phenomenon, this paper considers it as a kind of empowerment and focuses on the contribution of the digital economy to the lowering of pollution and carbon emissions. It assists to have a clearer picture of the relationship between the digital economy and green development. Based on the theory, it has added to the clarification of what digital technologies do in changing the energy use system in China and enhancing resource efficiency and tackling the issue of environmental pollution in particular, thus offering a broader view on digital empowerment as the means of saving the ecology and the environment; Nevertheless, relying on the circumstances within China, the empirical research on the inter-provincial level could be utilized to indicate the high rate of development of the digital economy and the growth of its pollution reduction and carbon reduction during the dual carbon goal implementation in China, and this might be useful to others to get an idea of how simultaneous development of digitalization and greening can be implemented. Lastly, the present paper will reveal some processes underlying and the future trends in the context of power provided by the digital economy over pollution and carbon reduction. It will develop a strong basis to the creation of theories concerning the digital economy and environmental regulation and ensure that further studies will be conducted in the area.

1.2.2. Practical Significance

Also, the significance of the research performed in this paper is equally important. Alternatively, during the period of active implementation of the Dual Carbon program in China and the rapid growth of the digital economy, it is possible to conduct an empirical study on the ways in which different roles played by digital infrastructure and digital commerce applications can assist to reduce emissions and carbon intensity, and this could form a strong basis that would enable governments at all levels to develop focused or differentiated digital low-carbon policies. Nonetheless, concerning the creation of digital infrastructure, it is necessary to make sure that it is green and low-carbon in essence so that the additional energy usage and the carbon footprint are not produced due to the realization of the concept of digitalization; whereas, in relation to digital commerce applications, it is vital to intensify the digitalization of enterprises to take full advantage of the benefits of digitalization, including improving energy mix and increasing the efficiency of resources use. Moreover, the results of the current research might become the standard to the high-energy-consuming and high-emission industries (steel and chemical industries) that should direct some of their attention to the optimization of energy consumption structure and clean regulation of emissions of pollutants in the course of their digitalization. The statement that the analysis of panel data of 31 Chinese provinces over the years (2015–2024) shows the diversity in regional impacts of the different elements of the digital economy on reducing pollution and carbon emissions. It makes it possible to develop green development policies relying on the digital economy in accordance with local requirements, which makes it possible to establish Beautiful China and implement the objectives of dual carbon.

1.3. Research Content and Methods

The paper will use the concept that digital economy may also be applied to counteract pollution and carbon emissions as a point of departure of discussion, and then explore and contrast what role digital infrastructure and digital commerce applications play in meeting such objectives. Main contents are the following subjects discussed in the paper:

Theoretical framework and formulation of the variables. This section will discuss some concepts that are related to the topic including digital economy and reduction of pollution and carbon emissions, and it will present their importance regarding digital infrastructure and digital commerce usage and ways they can be used to attain the stated goals.

The next step was the computation of composite indices and the construction of an indicator system. The author in the paper builds the indicator systems of pollution and carbon reduction impact and a digital economy based on the panel data of 31 provinces in China over the course of 2015–2024. The entropy approach is used within these systems to provide objective weights to different indicators and then define composite indices related to the general condition of pollution and carbon reduction, digital infrastructure and digital commerce applications.

Lastly, empirical research and hypothesis testing. The current paper uses a two-fixed-effects panel data regression approach to perform empirical analyses both with composite indices derived in this paper: (1) to find out how the composite index of digital infrastructure affects the composite index of pollution and carbon reduction; (2) to find out how the composite index of digital commerce application affects the composite index of pollution and carbon reduction. In addition, there is another set of explanatory variables including per capita GDP, urbanization level, share of the secondary sector, and total amount of imports and exports by foreign-invested companies that are employed as control variables in order to reduce their effect on outcomes. Furthermore, to reinforce the findings of the regressions, the cluster-robust standard errors, the Hausman test and multicollinearity tests are also conducted.

To sum up, the results of the research and recommendations to policy-makers. Using the empirical evidence, we examine the impacts and disparities between different factors of the digital economy on lowering emissions and carbon as well as formulate the main research conclusions. In this case, we provide explicit policy recommendations according to the growth of the Chinese digital economy and environmental protection requirements, such as promoting the greening of digital infrastructure, digital commerce, etc., to decrease emissions and carbon, and the differentiation of regional policies, which will make it possible to implement the combination of the digital economy with the green development in an organic manner. The research framework of this article is shown in Figure 1.

Based on the above research content, the core research question of this paper is: Does the current stage of China's digital economy promote or inhibit pollution and carbon reduction? If an effect exists, does it operate through digital infrastructure or digital commerce application? Do the two dimensions differ in their direction and magnitude of impact? This paper empirically examines these questions by constructing composite indices and applying a two-way fixed effects model.

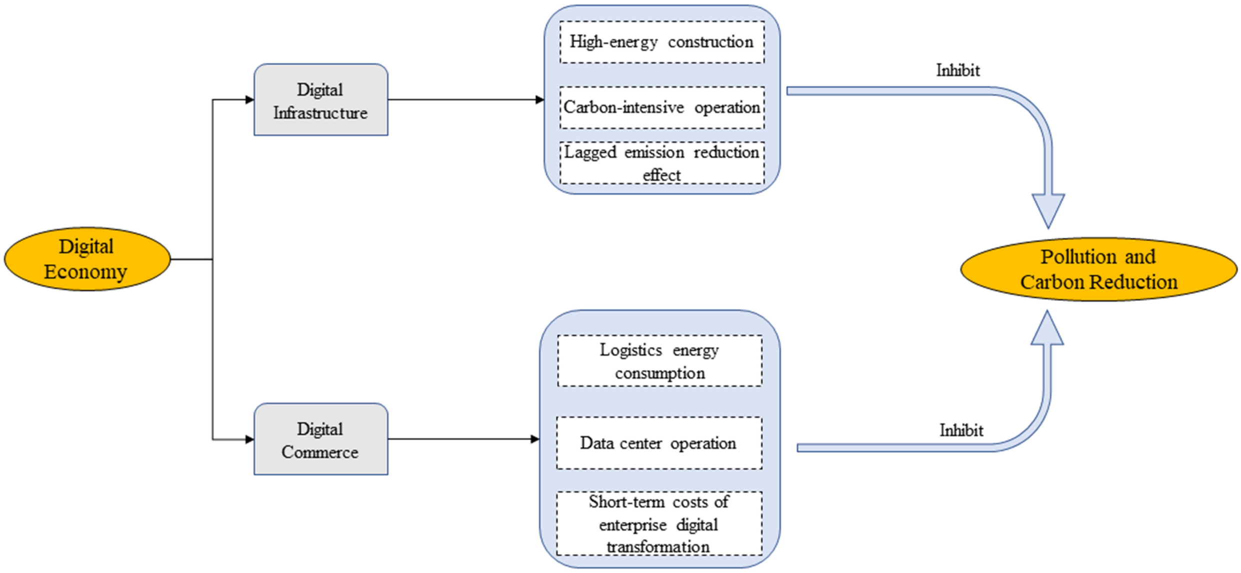

Figure 1. Research Framework Diagram.

2. Current State of Domestic and International Research and Literature Review

Researchers around the world have undertaken numerous investigations of problems associated with the digital economy, environmental governance, pollution and carbon reduction and have drawn some significant conclusions in the sphere of theoretical research, empirical investigation, and policy recommendations.

2.1. Current State of International Research

The study of the digital economy, environmental regulation and pollution as well as carbon reduction through international studies started early and it has mostly concentrated on two aspects namely the effects of the environment on application of digital technologies and the influence of digital technologies on energy transition [3, 4]. Initial researchers were more focused on the level of the internet effect on the relationship between energy and the environment and the development of digital technologies [5, 6]. They believe that the introduction of the internet and the adoption of digital technologies can also be applied in enhancing the approach to production, the best utilization of resources, and altering the way energy is managed, thus decreasing industrial pollution and carbon dioxide emissions [7, 8]. Their work focused specifically on the effects of reduced emissions of conventional industrial pollutants like sulfur dioxide and nitrogen oxides and substitution of fossil fuels with other fuel types [9]. Since the next stage of development of the digital economy, scientists have shifted their attention to particular applications of digital technology, studying how the consumption of energy by different industries is affected by e-commerce and other forms of electronic transactions [10, 11]. They believe that digital commerce and logistics will minimize losses incurred in intermediary processes and lead companies to make use of clean energy sources [12]. However, there are some counter arguments that say that to build a digital infrastructure and operate a data center massive volumes of electricity are needed, which can counteract the energy-saving and emission reduction advantages of digitalization at least in the short term; besides, the emission reduction advantages of digitalization are also reduced [13, 14]. On the whole, the environmental effects and their causes concerning the digital economy were explored by foreign investigators primarily on the ground of the empirical approach, and there is extremely little literature on the study of pollution reduction/carbon reduction synergism or cross-level of the digital economy. Moreover, many of the assessments use developing countries as examples which do not meet the particular circumstances of China.

2.2. Current State of Domestic Research

The domestic research is rapidly increasing and is in line with the double-carbon goals and creating the digital economy where the results are increasingly fruitful every time. One group of researchers thinks that the digital economy will not only minimize emissions but carbon emissions as well [15]. According to some scholars, the digital economy may be measured through the population of those accessing the internet, the extent of infrastructure digitalization, and the size of the digital economy sector or certain application indicators, including the amount of transactions conducted on e-commerce platforms or the proportion of businesses that are digitized [16, 17]. The environmental indicators are carbon emissions, particular pollutants or an overall pollution index. The correct data to examine has been chosen in this paper since the paper is largely focused on investigating the relationship between pollutants and energy. Nevertheless, integrated analyses that consider the three types of pollutants, sulfur dioxide, nitrogen oxides, and particulates, as well as the three measures of energy use, raw coal, natural gas, and coke, are relatively rare. Both theoretically and pragmatically, Chinese academics appear to concur with the idea that digital infrastructure is the backbone of digital empowerment. It can minimize the energy consumption patterns with the assistance of technology penetration and may also minimize the carbon emissions and e-commerce and other digital business transactions would have the potential to reduce the emissions even further. But when the overall situation of the digital economy is discussed, there are not so many articles that touch upon both the aspects of the digital infrastructure and e-commerce-based digital applications. Moreover, the majority of the research works concentrate solely on carbon emissions and do not pay enough attention to the synergy between the pollution and carbon emissions or do not transmit the connection between the two indicators correctly.

2.3. Literature Review

Numerous studies have investigated the relationship between the digital economy and environmental governance. However, a critical examination reveals three major gaps in the existing literature.

First, most studies treat the digital economy as a monolithic phenomenon, relying on a single composite index or a few simple proxies to measure its development level. This approach implicitly assumes that all components of the digital economy exert identical environmental effects. In reality, digital infrastructure (e.g., data centers and 5G base stations) and digital commerce applications (e.g., e-commerce and enterprise digitalization) differ fundamentally in their energy consumption patterns, emission intensities, and environmental impact pathways. By aggregating these distinct sub-sectors, existing studies may obscure or even reverse the true direction of their respective effects.

Second, the measurement of environmental outcomes is often incomplete. A substantial body of literature focuses exclusively on carbon emissions, while another strand concentrates on a single air pollutant such as sulfur dioxide or PM2.5. Few studies have integrated both pollution and carbon emissions into a unified analytical framework, despite the fact that pollution reduction and carbon reduction are inherently synergistic and are jointly pursued in China's policy agenda. This fragmented approach fails to capture the full environmental consequences of the digital economy.

Third, methodological concerns remain unresolved. Many studies employ a limited set of control variables, overlook endogeneity issues, or lack sufficient robustness checks. Moreover, most existing empirical work relies on data before 2020, which predates the rapid expansion of 5G networks, the surge in e-commerce, and the widespread digital transformation of enterprises in China. These recent developments may have qualitatively different environmental implications than earlier stages of digitalization, and thus warrant re-evaluation with up-to-date data.

To address these gaps, this paper makes three specific contributions. It disaggregates the digital economy into digital infrastructure and digital commerce application, allowing for a nuanced comparison of their distinct environmental effects. It constructs a comprehensive dependent variable that simultaneously captures sulfur dioxide, nitrogen oxides, particulate matter, and carbon dioxide emissions, reflecting the synergistic nature of pollution and carbon reduction. It employs a two-way fixed effects model with cluster-robust standard errors on the most recent panel data of 31 Chinese provinces from 2015 to 2024, accompanied by a battery of robustness tests including the Hausman test and multicollinearity diagnostics, thereby improving the credibility of the empirical findings.

2.4. Theoretical Framework and Research Hypotheses

Based on the above critical review, the following section develops the theoretical framework. This study decomposes the digital economy into digital infrastructure and digital commerce application.

Digital infrastructure affects emissions through two channels: energy-intensive construction and high electricity consumption during operation. Given China's coal-dominant energy mix, increased electricity demand raises CO_2 and pollutant emissions. This study hypothesizes that digital infrastructure development hinders pollution and carbon reduction.

Digital commerce application affects emissions through logistics fuel consumption, packaging production and disposal, and additional energy demand from data centers and IT upgrades. These benefits are currently outweighed by emissions from rapid expansion. This study hypothesizes that digital commerce application development hinders pollution and carbon reduction.

Digital infrastructure involves rigid energy demand, whereas digital commerce application has greater flexibility for green optimization. This study hypothesizes that the inhibiting effect of digital infrastructure is stronger than that of digital commerce application.

3. Research Design and Model Specification

3.1. Data Sources and Variable Descriptions

The given research has been carried out through the panel data of 31 provinces, autonomous regions and municipalities of China (except Hong Kong, Macao and Taiwan) in 2015–2024 as a sample. The sample period 2015–2024 is selected for two reasons. First, 2015 marks the launch of China's "Internet+" action plan, which accelerated the development of the digital economy, and the full implementation of the new Environmental Protection Law, which strengthened environmental governance. Second, provincial-level statistics for key variables have been consistently and completely available since 2015, and 2024 is the most recent year with complete data at the time of this study. All data analyzed in this paper were obtained from publicly available statistical reports, including the China Statistical Yearbook, the China Environmental Statistics Yearbook, and the China Energy Statistical Yearbook. The 2024 provincial data are the latest official releases as of the time of this study and are fully available for all 31 provinces. These sources are widely used in peer-reviewed research and ensure accuracy, credibility, and comparability. The description of the variables is shown in Table 1.

In particular, the emissions of sulfur dioxide, nitrogen oxide, and particulate matter are based on the China Environmental Statistics Yearbook; carbon dioxide emissions on the EDGAR (Emissions Database for Global Atmospheric Research) database; and all other variables are based on the China Statistical Yearbook (2015–2024).

Table 1. Variable descriptions.

Variable Name	Variable Description
Sulfur dioxide emissions	As one of the most significant pollutants in the air released when industrial production takes place, it is used to measure the effectiveness of the pollution control measures
Nitrogen Oxide Emissions	Air pollutants generated by industrial and mobile sources, contributing to complex pollution
Particulate Matter Emissions	The amount of fine particulate matter emitted (dust in industries and construction dust)
Carbon dioxide emissions	A key indicator of a region's level of low-carbon development
Number of broadband internet access ports	Reflects the scale of a region's network infrastructure development
Number of mobile internet users	Reflects the penetration rate of mobile networks
Mobile Internet Access Traffic	Reflects the actual level of activity on digital networks
Number of Internet Broadband Subscribers	Reflects the penetration rate of fixed broadband networks among the general public
Number of Internet Domains	Reflects the vitality of a region's digital economy
Online retail sales	Reflect the scale of digital consumption
Number of enterprises engaged in e-commerce transactions	Reflect the scope of corporate digital transformation
Corporate e-commerce sales	Reflect the scale of a company's digital sales
Corporate e-commerce procurement	Reflect a company's level of digital procurement and supply chain optimization
Per capita regional GDP	A measure of economic development; the data is log-transformed after regression
Urbanization rate	The proportion of the urban population in the total population
Share of the secondary sector	Secondary sector value added in GDP as a share of the total GDP is an indicator of industrial structure
Total imports and exports of goods by foreign-invested enterprises	A measure of the degree of openness to the outside world

3.2. Calculation of the Composite Index using the Entropy Method

To derive the weights of the indicators objectively and eliminate the subjective bias, this paper will utilize the entropy method that will be used to build the composite indices of digital infrastructure and the application of digital commerce. The first data matrix was produced using the panel data of 31 Chinese provinces with a period of 2015–2024:

$$W = (x_{ij})_{n*m},\ i = 1, 2 \dots n;\ j = 1, 2 \dots m \tag{1}$$

where, *n* denotes the number of observations and *m* represents the number of indicators.

Before index construction, all original indicators are normalized to eliminate scale effects. For negative indicators (pollution and carbon emission variables), we apply Equation (2); for positive indicators (digital infrastructure and digital commerce variables), we apply Equation (3). After min–max normalization, all values are shifted uniformly by adding 0.001 to avoid meaningless logarithmic calculations in subsequent entropy weight computation.

In this paper, the pollution reduction and carbon reduction variables are negative indicators, so:

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \tag{2}$$

The digital infrastructure and digital commerce application variables are positive indicators, so:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{3}$$

To avoid rendering subsequent logarithmic operations meaningless, a uniform shift is applied after standardization:

$$z_{ij} = x'_{ij} + 0.001 \tag{4}$$

Calculate the proportion of the ith sample under the jth indicator:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{5}$$

Calculate the entropy of the jth indicator:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{6}$$

Calculate the coefficient of variation:

$$g_j = 1 - e_j \tag{7}$$

Calculate the indicator weight:

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j} \tag{8}$$

Calculate the composite index:

$$S_i = \sum_{j=1}^{m} w_j * z_{ij}. \tag{9}$$

3.3. Specification of Regression Models

This paper provides the development of two two-way fixed-effects panel data analysis models in order to examine the contribution of digital infrastructure and digital commerce applications to the mitigation of pollution and carbon emissions:

Model 1: The Impact of Digital Infrastructure on Pollution and Carbon Reduction

$$env_{it} = \alpha_0 + \beta_1 infra_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_t \tag{10}$$

Model 2: The Impact of Digital Commerce Applications on Pollution and Carbon Reduction

$$env_{it} = \alpha_0 + \beta_2 digital_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_t \tag{11}$$

The mean pollution and carbon reduction index as well as the mean indices of digital infrastructure and digital commerce applications, respectively, are the following control variables (per capita GDP logarithm, urbanization rate, percentage of secondary industry, and total import and export volume of foreign-invested enterprises): provincial fixed effect: year fixed effect: and random error term. The estimation is done using cluster-robust standard errors at the provincial level.

4. Research on the Effects of the Digital Economy on Pollution and Carbon Reduction

4.1. Analysis of the Impact of Digital Infrastructure on Pollution and Carbon Reduction

4.1.1. Descriptive Statistical Analysis

As it is presented in Table 2, in the years 2015–2024, there was a significant disparity of pollution and carbon reduction indicator values and digital infrastructure indicators of the 31 provinces in China.

In regard to pollution and carbon reduction, the overall rate of sulfur dioxide (SO_2) emission was 180,500 metric tons, but the rates per province were very different, where the lowest was 1100 metric tons and the highest 1,525,700 metric tons, standard deviation 214,400 metric tons; the average level of nitrogen oxide emissions is 394,300 metric tons and the maximum is 1,422,400 metric tons, or about 42-fold higher than the minimum value of 34,100 metric tons, which means that the levels in the regions are significantly different; the average level of particulate matter emissions was 299,200 metric tons, the highest level was 1,575,400 metric tons and the lowest level was 4100 metric tons, which also points to the diversity in regional variation. The mean carbon dioxide emission was 361 million tons, the highest was 1.172 billion tons and the lowest was 25 tons. It is evident that the scale of low-carbon development is not the same in the regions and especially in those provinces that are highly industrialized and carbon emissions are also of great importance.

The average number of internet broadband access ports was 29.748 million, but the highest number of internet broadband access ports was 106.642 million and the lowest number was 510,000 (or more than 200 times smaller), which could be explained by the fact that the digital infrastructure has not been developed evenly across the regions; The average number of mobile internet users is 42.696 million, the maximum is 165.729 million, and the minimum is 1.624 million, and it can be seen that the differences in mobile network coverage of areas are very big; meanwhile, the standard deviation of mobile internet access traffic (579,700 GB) is much higher than its mean (490,400 GB), and this suggests that certain parts of the globe are much keener to use digital technologies compared to other parts of the world; the average number of Internet broadband access users is 15.087 million, with great regional differences. Internet domain names volume average (1.17 million) and the gap between the maximum (8.825 million) and the minimum (10,000) are important because they show spatial disparities in the state of digital economic development.

As it is illustrated in Figure 2, it can be stated that from 2015–2024, the average levels of sulfur dioxide, nitrogen oxides, particulate matter and carbon dioxide in 31 provinces and autonomous regions of China have been on a declining trend annually. In particular, the average sulfur dioxide was reduced by 12, approximately 75 to 66; the average nitrogen oxides were reduced by 35, approximately 94 to 61; the average particulate matter by 29, approximately 93 to 66; the average carbon dioxide increased by 33% points, or 3000 to 4000. On the whole, the results of the first three pollutants emissions reduction are positive, however, there are still rising carbon dioxide emissions, hence, the requirement to lower them to reduce emissions.

Before conducting the empirical analysis section, we first plotted a bin-scatter plot of digital infrastructure and pollution reduction and carbon emission reduction, as a line-fit graph, as shown in Figure 3. From the graph, it can be seen that there is a clear positive relationship between digital infrastructure and pollution reduction and carbon emission reduction. This initially indicates that digital infrastructure is likely to inhibit pollution reduction and carbon emission reduction.

Table 2. Descriptive statistics.

Variable	Mean	Standard Deviation	Minimum	Maximum
Sulfur Dioxide (tons)	180,484.9	214,415.3	1063	1,525,670
Nitrogen Oxides (tons)	394,279.9	281,494.5	34,095	1,423,884
Particulate Matter (tons)	299,179.4	279,389.0	4124	1,575,417
Carbon Dioxide (tons)	3.61×10^8	2.62×10^8	2.49×10^7	1.17×10^9
Internet Broadband Access Ports (10,000 ports)	2974.8	2127.8	51.0	10,664.2
Mobile Internet Users (10,000 users)	4269.6	3016.2	162.4	16,572.9
Mobile Internet Traffic (10,000 GB)	490,366.6	579,712.2	738.2	3,710,384
Internet Broadband Access Users (10,000 users)	1508.7	1152.8	29.6	5049.5
Number of Internet Domain Names (10,000 names)	117.0	154.0	1.0	882.5

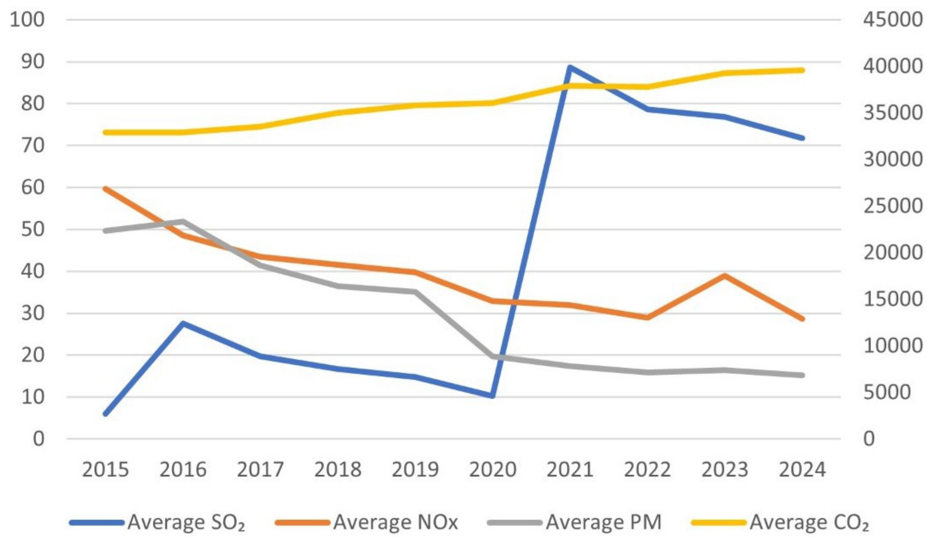

Figure 2. Trends in Average Pollutant Emissions (2015–2024).

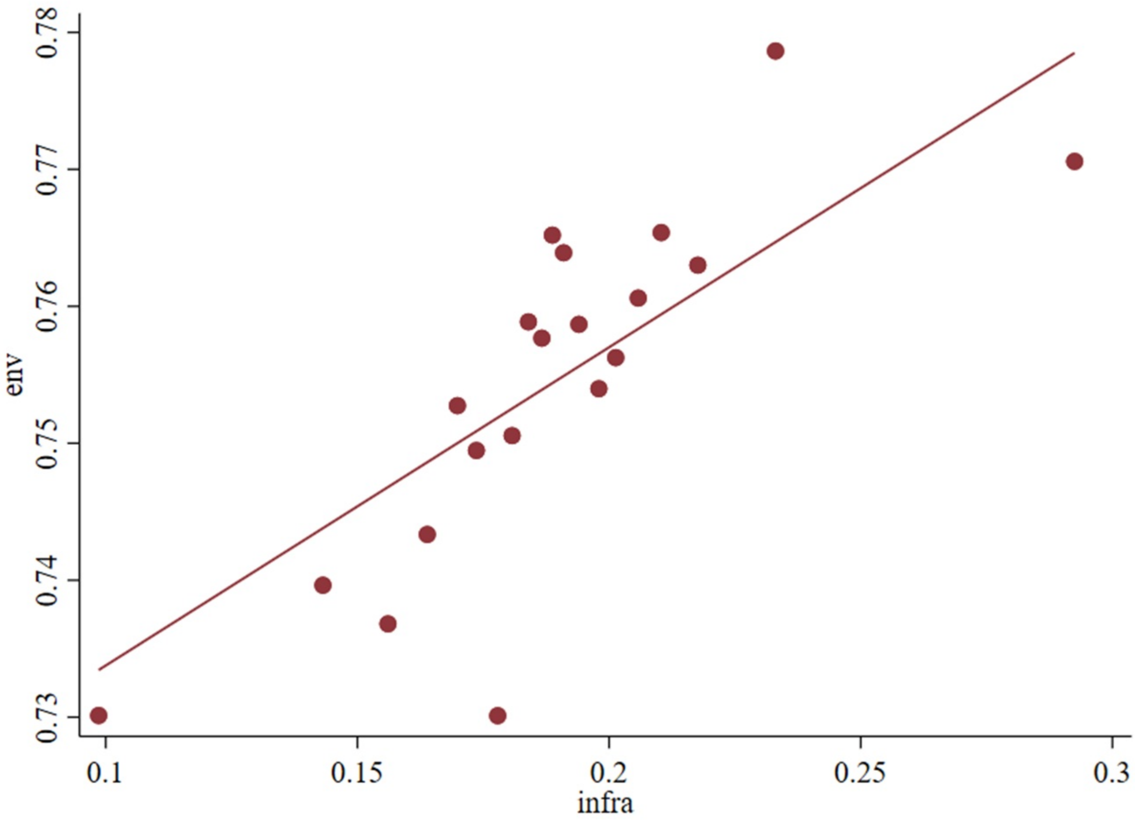

Figure 3. The fitting curve between digital infrastructure and pollution reduction and carbon emission reduction.

4.1.2. Baseline Regression

Two-way fixed-effects model was used as the base regression to explore the effect of digital infrastructure on the mitigating pollution and carbon emissions. We held province fixed effects, year fixed effects, and province-level cluster-robust standard errors in the regression. Table 3 shows the baseline regression results.

The baseline regression results in Table 3 show the effect of digital infrastructure on the reduction of pollution and carbon emissions. The outcome of a mixed OLS regression without fixed effects control is presented in Column (1), in Column (2) there are annual fixed effects to the model in Column (1), and in Column (3) there is the main model of the paper that also has provincial fixed effects and annual fixed effects and the cluster-robust standard errors at the provincial level are used.

The composite index of digital infrastructure has a negative coefficient and is statistically significant at 1% in columns (1) and (2), which means that the correlation between digital infrastructure and the composite index of pollution reduction and carbon emission reduction is negative assuming that there are no interprovincial differences. Nevertheless, in Column (3) it is shown that even with both provincial and year fixed effects, the coefficient of the digital infrastructure composite index is 0.232 and significant at 5% statistically. The total index of pollution reduction and carbon emission reduction is an inverse indicator (the lower the values of this index are more desirable in terms of reducing the amount of pollution and carbon emissions), and since the coefficient of the index of comprehensive digital infrastructure is positive, this means that the development of digital infrastructure in fact leads to an increase in the total index of pollution reduction and carbon emission reduction, that is, it has a negative impact on the process of pollution reduction and carbon emission reduction. This contradicts the findings in Columns (1) and (2) where it is demonstrated that the results presented are biased as the provincial fixed effects were not taken into account (geography, natural resources and industrial base). The two-way fixed effects in column (3) remove those interprovincial differences and therefore are more credible.

It is possible to identify several factors that could limit pollution and carbon emission as they are caused by the digital infrastructure: to begin with, the erection and functioning of digital infrastructure (data centers, 5G base stations, and broadband networks) take massive volumes of electricity. As most of the energy mix in China is still dominated by coal, most of the extra electricity will be generated using thermal power, leading to increased CO_2 and pollution levels in the atmosphere; Secondly, digital infrastructure will not yield an immediate emission reduction benefit. It is possible that during that period the sector was undergoing a construction stage that consumed a lot of energy and more emissions were recorded than the reduction achieved.

Table 3. Benchmark regression.

Variable	(1)	(2)	(3)
Digital Infrastructure Composite Index	−0.542***	−0.608***	0.232**
	(−7.85)	(−8.40)	(2.28)
Log of GDP per Capita	0.177***	0.117***	−0.092**
	(4.59)	(2.71)	(−2.60)
Urbanization Rate	−0.004***	−0.003**	0.007**
	(−2.92)	(−1.99)	(2.50)
Share of Secondary Industry	−0.010***	−0.009***	0.002
	(−9.14)	(−7.87)	(0.87)
Total Import and Export Volume of Foreign-invested Enterprises	−0.000	0.000	0.000
	(−0.43)	(0.37)	(0.96)
R-squared	0.3	0.42	0.664
Number of obs	310	310	310

Please note that: ****p* value is less than 0.01, ***p* value is less than 0.05, **p* value is less than 0.1 (all in the same table as the one below). Column (1) reports mixed OLS results without fixed effects; Column (2) adds year fixed effects; Column (3) includes both province and year fixed effects with cluster-robust standard errors.

Regarding controlled variables, an additional unit of per capita GDP would imply a decrease of around 0.092% points in pollution and carbon reduction. This is statistically significant at the 5% confidence level and thus it can be inferred that such economically well-developed areas do not have many results on pollution and carbon reduction. The reason behind this could be the existence of higher environmental technology, stricter environmental laws as well as the smarter industrial systems in developed countries; for each additional percentage point of urbanization rate, there is a decrease in pollution and carbon emissions by about 0.007% points (statistically significant at 5% confidence level). It is evident that the present trend of urbanization in China also has some constraints regarding energy use and pollutant emissions; at every 1% point increase of the secondary sector share the resulting pollution and carbon reduction are reduced by 0.002% points. Nonetheless, the link is positive (the larger the share of the industry, the higher the pressure to pollute), yet it is not statistically significant; 1% growth in the overall trade volume of imports and exports of foreign invested firms causes an insignificant change in pollution and carbon reduction, suggesting that open trade is not an essential factor in pollution and carbon reduction.

4.1.3. Robustness Tests

(1) Hausman test

Hausman test is applied in identifying whether to use fixed-effects model or random-effects model. As the number of degrees of freedom in the chi-squared statistic (chi2(4)), the number, which is 4, represents the number of degrees of freedom and the chi-squared value is indicated by chi2. There are four main variables that are being compared and therefore four degrees of freedom are present. Large chi-squared values with small *p*-values indicate higher chances of null hypothesis rejection.

The null hypothesis of the Hausman test is that the random-effects model is the best. You can observe in Table 4 that the chi-square value is 21.84 and the *p*-value is 0.0002. The null hypothesis is rejected at a 1% level of significance. Therefore, it implies that coefficients are not the same in fixed effect models and random effects models and there is no equality in variance of the random effects models. And consequently, this paper will employ fixed effects model to estimate which was selected previously.

(2) Multicollinearity test

The Variance Inflation Factor (VIF) is a statistical instrument used to determine multicollinearity. The common perception is that severe multicollinearity problems cannot exist when the value of VIF is less than 10 and should be below 5 on average.

As shown in Table 5, the VIF of each variable is under 10. In particular, the per capita GDP VIF is 5.33, the urbanization rate VIF is 4.31, the overall volume of imports and exports of the foreign-invested enterprises VIF is 2.25, the composite digital infrastructure index VIF is 1.98, and the secondary industry portion VIF is 1.23. Mean VIF of these variables is 2.37, which is relatively low compared to the empirical threshold of 10. It means that the regression equation derived in the present paper is not affected by too much multicollinearity such that the associations among the independent variables in the model would not introduce significant bias in our estimates.

Table 4. Hausman test.

Test Item	Statistic	*P*-Value
chi2(4)	21.84	0.0002

Table 5. Multicollinearity test.

Variable	VIF
Log of GDP per Capita	5.33
Urbanization Rate	4.31
Digital Infrastructure Composite Index	1.98
Share of Secondary Industry	1.23
Total Import and Export Volume of Foreign-invested Enterprises	2.25

4.2. Analysis of How Application Variables of Digital Commerce Can Be Used to Reduce Pollution and Carbon Emissions Effects

4.2.1. Descriptive Statistical Analysis

According to Table 6 and Figure 4, it can be seen that during the period between 2015–2024 there was a major difference in the level of digital commerce use in 31 Chinese provinces, autonomous regions, and municipalities.

The average value of online retailing sales amounted to 335.36 billion yuan on average, although the largest volume of online retailing sales was 3148.41 billion yuan and the least amount of sales was 420 million yuan with a standard deviation of 529.97. There are solid indications that the extent of the use of e-commerce differs significantly across various locations; on average, there were 4208 companies involved in e-commerce activities and the highest number of companies was 28,076 and the lowest number was only 76, which is more than 370 times higher, which means that there is a considerable difference between these levels of digitalization of the company; the mean value of e-commerce purchases and enterprise supply were 684.13 billion yuan and 364.81 billion yuan respectively, where there were differences in values in the regions. Both the standard deviations are also much larger than the means which suggests that in some regions the growth of electronic commerce is much more pronounced as compared to others.

The use of Regional GDP per capita as a control variable was applied and its mean was 72,200 yuan whereby the highest value of 228,300 yuan is 8.5 times larger than the lowest value of 26,900 yuan, indicating a great difference in the level of economic development across the regions; urbanization rates were 62.66, 89.85 (the highest) and 28.87 (the lowest), a difference of more than 61% points, meaning that levels of urbanization vary throughout the country; mean secondary sector share was 38.88, maximum was 54 and minimum was 14.5, a difference of 39.5% points, which indicates that there are disparities in industrial structure across regions; the imports and exports volume of foreign-owned companies has a standard deviation of (7.26×10^7) which is much greater than the mean (3.76×10^7) suggesting a large regional variability in the extent of openness.

In general, all indicators are region-specific, which enables doing additional studies based on different effects of implementing the tools of digital commerce on reducing pollution and carbon emissions.

Before conducting the empirical analysis section, we first plotted a bin-scatter plot of digital commerce and pollution reduction and carbon emission reduction, as a line-fit graph, as shown in Figure 5. From the graph, it can be seen that there is a clear positive relationship between digital commerce and pollution reduction and carbon emission reduction. This initially indicates that digital commerce is likely to inhibit pollution reduction and carbon emission reduction.

Table 6. Descriptive statistics.

Variable	Mean	Standard Deviation	Minimum	Maximum
Online Retail Sales (100 million yuan)	3353.6	5299.7	4.2	31,484.1
Number of Enterprises with E-commerce Transaction Activities	4208.1	4824.3	76	28,076
Enterprise E-commerce Sales (100 million yuan)	6841.3	9793.8	31.4	53,706.6
Enterprise E-commerce Procurement (100 million yuan)	3648.1	5605.2	2.8	38,057.2
Gross Regional Product per Capita (10,000 yuan)	7.22	3.47	2.69	22.83
Urbanization Rate (%)	62.66	11.55	28.87	89.85
Share of Secondary Industry (%)	38.88	7.70	14.50	54.00

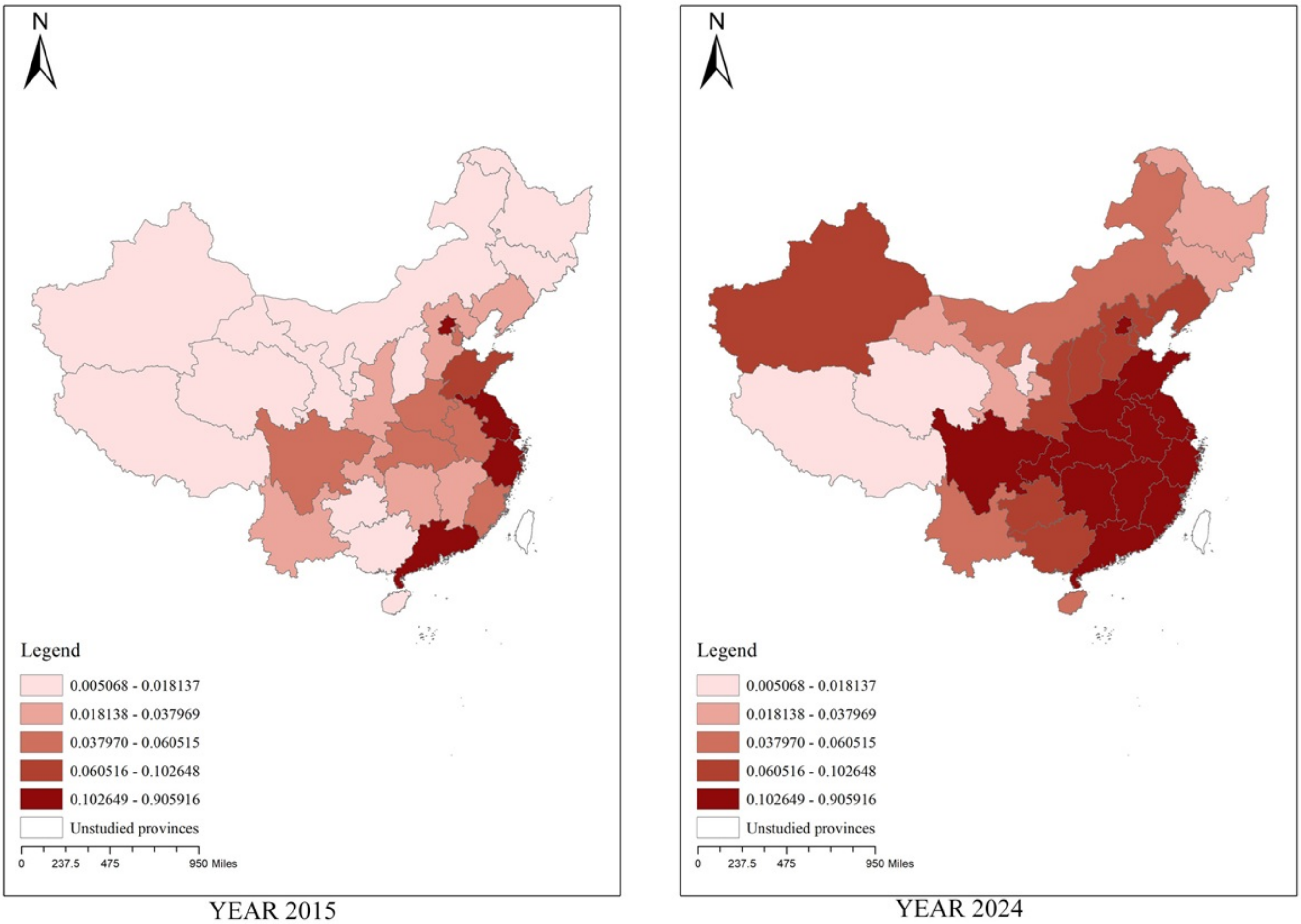

Figure 4. Distribution map of digital commerce application spaces in China in 2015 and 2024.

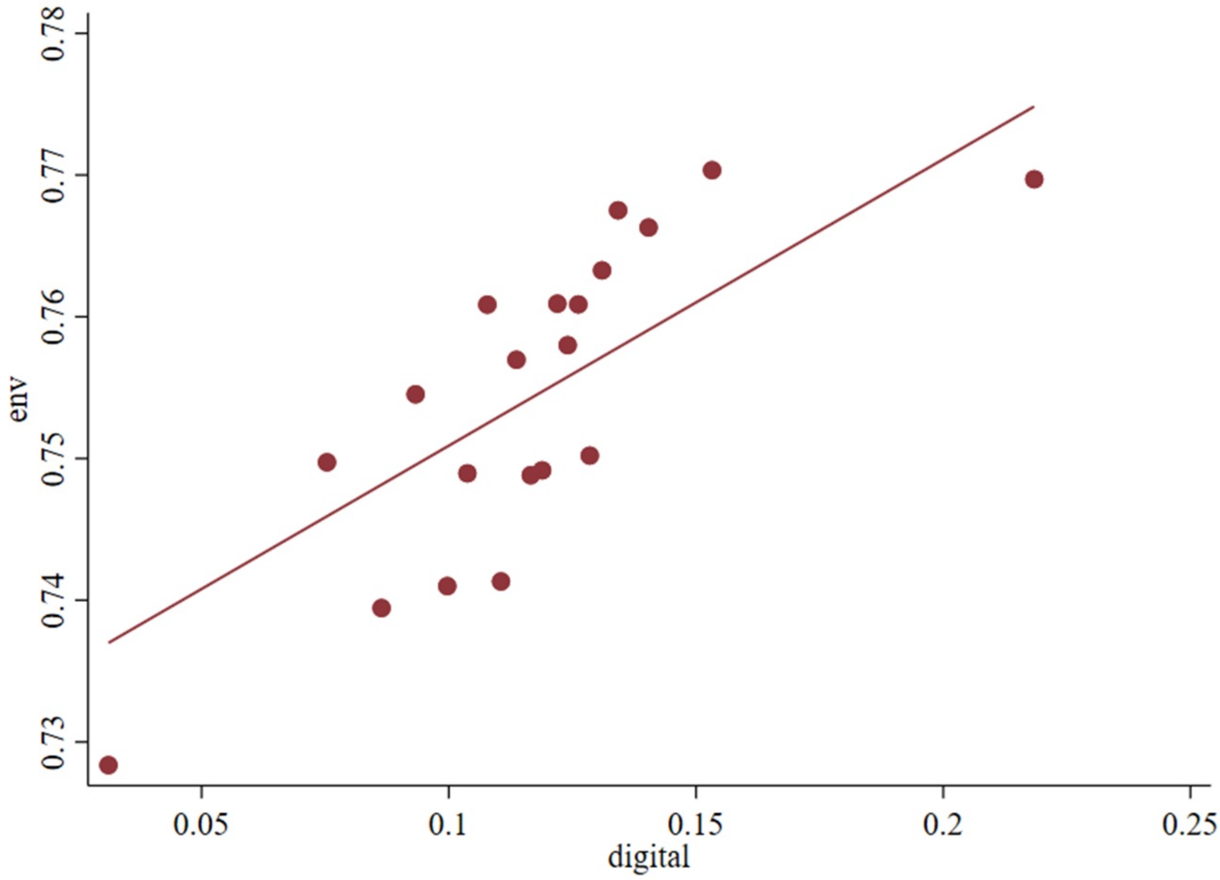

Figure 5. The fitting curve between digital commerce and pollution reduction and carbon emission reduction.

4.2.2. Regression Analysis

As shown in Table 7, the outcome of the baseline regression analysis is provided, which quantifies the influence of digital commerce applications on reducing pollution and carbon emissions. The first column is a mixed OLS regression without fixed effects; the second column is an extension of the first column with fixed effects of years; and the third column is the focal model of this paper, which also includes fixed effects of provinces and years as well as uses provincial clustered standard errors.

In relation to the major explanatory variables, the coefficients of the overall indicators of digital commerce applications are negative and statistically significant (1% level) in Columns (1) and (2) (-0.464 and -0.451 respectively). It indicates that, in the absence of the provincial fixed effects, the adoption of digital commerce is highly negatively correlated with the total index of pollution reduction and carbon emission reduction. Because the total index of pollution reduction and carbon reduction is an inverse indicator (the lower the value, the better the performance regarding pollution and carbon emission reduction), this negative coefficient suggests that the adoption of digital commerce will decrease the total index, which is positive; but in Column (3), after controlling on provincial and annual fixed effects, the coefficient of the total index of digital commerce application is 0.181 and significant at 5% level. It appears that taking into account the long-term and steady factors peculiar to every province (including geographical location, state of natural resources, and industrial potential), digital commerce implementation leads to the reduction of the pollution and carbon reduction. To put it another way, the greater the implementation of digital commerce is, the more detrimental it is to the overall pollution and carbon reduction index and the failure to reduce the pollution and carbon emissions.

The output is distinct because of the findings recorded in columns (1) and (2), which indicates that inherent disparities among provinces should be omitted because they could have resulted in a biased outcome. To address these constant inter-provincial changes the two-way fixed effects (which are in the column 3) are being eliminated so that it can make the results more credible. It is obvious that digital commerce is much more limiting in nature in terms of pollution and carbon reduction since it is more energy intensive and carbon intensive (such as e-commerce logistics, data center operations, and express delivery packaging); second, digitization can be linked to additional acquisition of equipment and system installation by companies, which will boost energy use of these companies, and this will not be able to produce environmental advantage in the near future.

Table 7. Benchmark regression.

Variable	(1)	(2)	(3)
Digital Commerce Application Composite Index	−0.464***	−0.451***	0.181**
	(−4.65)	(−4.35)	(2.53)
Log of GDP per Capita	0.167***	0.143***	−0.115***
	(3.94)	(2.98)	(−2.97)
Urbanization Rate	−0.003*	−0.002	0.014***
	(−1.92)	(−1.50)	(4.13)
Share of Secondary Industry	−0.011***	−0.011***	0.002
	(−9.80)	(−9.17)	(0.79)
Total Import and Export Volume of Foreign-invested Enterprises	−0.000	−0.000	0.000
	(−0.23)	(−0.28)	(1.07)
R-squared	0.315	0.325	0.652
Number of obs	310	310	310

According to the control variables, the coefficient of the logarithm of per capita GDP is −0.115, which is statistically significant at 1% level, indicating that the most economically developed regions are more effective in reducing the pollution and carbon emission rates. This can be seen in association with the findings of the regression of the digital infrastructure. The coefficient of the urbanization rate is 0.014, and is statistically significant at 1% which indicates that urbanization is linked to higher energy consumption as well as pollutants production. The coefficient of the share of secondary industry is as expected, positive but insignificant. Import and export volumes of foreign-invested enterprises do not significantly influence the coefficient either, which means that import and export volumes of foreign-invested enterprises hardly have any effect on emissions reduction of companies.

Alternatively, in contrast to the findings of the digital infrastructure regression, the core model shows 0.232 as the coefficient of the comprehensive digital infrastructure index (significant at 5%) and 0.181 as the coefficient of the comprehensive digital commerce application index (significant at 5%). Each exerts an inhibitory influence but the digital infrastructure has more inhibition, and the digital commerce applications have less inhibition. It implies that the problem of excessive energy consumption and excessive pollution caused by digital infrastructure is much larger both in terms of construction and the use, whereas the negative effects of digital commerce applications are small by comparison.

4.2.3. Robustness Tests

(1) Hausman test

The null hypothesis of the Hausman test suggests that the random-effects model should be applied. As shown in Table 8, the value of the chi-square is 105.07 and the probability of significance is 0.000. Our null hypothesis is rejected at the level of 1%, implying that the coefficients of the fixed-effects model and the random-effects model differ. The fixed-effects model will be estimated because the random-effects model does not satisfy the consistency condition. The findings are in line with what was found as per the regression analysis of digital infrastructure.

(2) Multicollinearity test

As illustrated in Table 9, there are no variables with VIFs exceeding 10. To be even more precise, the VIF of per capita GDP is 5.76, and the VIF of urbanization is 4.31, the VIF of overall index of digital commerce applications is 3.75, and total import and export value of foreign-invested enterprises is 3.15, and the share of the secondary sector is 1.23. Mean VIF of all variables is 2.58 that is much lower than the empirical value of 10.

This implies that the multiple regression model developed in the present research is not significantly affected by multicollinearity and the interaction among the explanatory variables is not a significant factor in the reliability and stability of the estimations obtained.

Table 8. Hausman test.

Test Item	Statistic	*P*-Value
chi2(4)	105.07	0.000

Table 9. Multicollinearity test.

Variable	VIF
Log of GDP per Capita	5.76
Urbanization Rate	4.31
Digital Commerce Application Composite Index	3.75
Total Import and Export Volume of Foreign-invested Enterprises	3.15
Share of Secondary Industry	1.23

5. Research Findings and Policy Recommendations

5.1. Research Findings

Based on the panel data of 31 Chinese provinces from 2015 to 2024, this paper constructs composite indices for digital infrastructure and digital commerce application using the entropy method, and employs a two-way fixed effects model to examine their impacts on pollution and carbon reduction. The main findings are as follows.

First, digital infrastructure significantly hinders pollution and carbon reduction. The coefficient of the digital infrastructure composite index is 0.232 ($p < 0.05$). Since the dependent variable is a reverse indicator, this positive coefficient indicates an inhibiting effect. This result is robust, as confirmed by the Hausman test and VIF diagnostics. The likely reason is the high electricity consumption of data centers and 5G base stations, which, under China's coal-dominant energy mix, leads to substantial CO_2 and pollutant emissions.

Second, digital commerce application also significantly hinders pollution and carbon reduction, with a coefficient of 0.181 ($p < 0.05$). This inhibiting effect is primarily attributed to the energy demands of e-commerce logistics, express delivery packaging, data center operations, and enterprise IT system upgrades.

Third, the inhibiting effect of digital infrastructure (0.232) is stronger than that of digital commerce application (0.181), reflecting the more rigid and energy-intensive nature of infrastructure investments.

Regarding control variables, per capita GDP is negatively associated with the composite index, indicating better environmental performance in more developed regions. Urbanization shows a significant positive coefficient, suggesting increased energy consumption and emissions during the urbanization process. The share of secondary industry and foreign-invested enterprise trade volumes are not statistically significant.

5.2. Policy Recommendations

Based on the above research findings, this paper proposes the following policy recommendations:

To begin with, accelerate the green and low-carbon transformation of digital infrastructure. Since digital infrastructure exhibits a stronger inhibiting effect on pollution and carbon reduction than digital commerce application, targeted measures should focus on its most energy-intensive components, namely data centers, 5G base stations, and cloud computing facilities. Specifically, the adoption of energy-efficient technologies such as liquid cooling systems and high-voltage direct current power supply should be promoted to reduce the power usage effectiveness of data centers. The share of renewable electricity (wind and solar) in powering digital facilities should be increased, and the "Eastern Data, Western Computing" national layout should be further optimized to locate large-scale data centers in western regions with abundant renewable energy resources, thereby reducing reliance on coal-fired power. In addition, mandatory energy efficiency standards and carbon emission intensity limits should be established for the construction and operation of digital infrastructure, and these indicators should be incorporated into project approval and performance assessment systems. By implementing these measures, the negative environmental impact of digital infrastructure can be mitigated while maintaining its role in supporting economic digitalization.

Finally, encourage the migration of digital commerce applications to green and low-carbon. The negative effects of digital commerce applications are much less compared to the negative effects of digital infrastructure, but they are not insignificant. Freight forwarders and e-commerce sites should be motivated to reduce the amount of carbon produced by packaging and shipping them with the help of environmentally friendly packaging materials, minimizing delivery distances and setting up reverse logistics. Nonetheless, the role of energy-saving and emission-lowering technologies must be considered within the framework of the digital economy as the excessive growth in the energy consumption rate due to the improper promotion of the idea of digitization may result in the uncontrolled growth in energy consumption. There could be an advantage to consider the findings of reduced emissions and carbon sequestration as important measures of performance of digital commerce businesses and offer tax cuts or positive policy to the highly performing companies under such a strategy.

Finally, a particular group of low-carbon digital policies must be created based on the situation at the moment. It is evident that areas have significant disparities in terms of the extent of digitization of the economy and the level of emission reduction and carbon reduction. Eastern regions, which are economically relatively more developed, will take the lead in piloting the green transformation of the digital infrastructure and serve as a model, whereas the development of the central and western regions will not adopt the eastern path of constructing before management, but rather incorporate green and low-carbon interests during the implementation of early phases of building the digital infrastructure. Meanwhile, the other regions that have been undergoing the digital commerce application should receive additional assistance to reduce the digital gap in their territories and developed territories, and therefore, bring about the more equal distribution of green forces of the digital economy across all territories.

Finally, improve the integrated governance of the digital economy and reduce carbon emissions and pollution. The proper agencies must develop and enhance interdepartmental working relations so that they can incorporate the growth of the digital economy in their carbon objectives as well as protection of the environment. Environmental impact assessments are needed when developing the policies of the digital economy and incorporating the benefits of digital technologies in the countermeasures proposals to mitigate pollution and carbon footprint. Moreover, the study of the environmental effects of the digital economy needs to be enhanced since this will help adjust and improve the relevant measures and policies at the right time.

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Conflicts of Interest

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Use of AI and AI-Assisted Technologies

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