

Article

Supply Chain Digitalization and Corporate Carbon Emissions: A Quasi-Natural Experiment Based on Pilot Policies for Supply Chain Innovation and Application

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Abstract

Technological progress and green, low-carbon growth are vital for sustainable economic development. Since supply chains are a major source of corporate carbon emissions and they face coordination challenges exceeding firm-level digitalization, China's SCIAPP policy emphasizing cross-organizational green collaboration for low-carbon transformation applies to them. This study, using panel data from A-share listed companies (2013–2022), employs a difference-in-differences method to analyze how supply chain digitalization influences corporate carbon emissions within the framework of the Supply Chain Innovation and Application Pilot Program (SCIAPP). The results show that supply chain digitalization significantly lowers emissions, and the findings are robust to endogeneity tests and other robustness checks. Heterogeneity analysis indicates that firms with higher governance standards and advanced digital maturity gain the most in emission reductions, especially state-owned enterprises and manufacturing companies. Mechanism tests suggest that improvements in supply chain efficiency and increased corporate innovation drive this effect. Theoretically, the research extends the digitalization–emission relationship from individual firms to entire supply chains, proposing and confirming a dual-channel framework (efficiency and innovation) that combines transaction-cost and resource-based views. Methodologically, treating the implementation of the SCIAPP as a quasi-natural experiment yields strong causal evidence beyond mere correlations. The study highlights the importance of the SCIAPP in achieving dual carbon targets and tackling global climate challenges, providing empirical insights to help enterprises reduce emissions and promote high-quality, efficient development.

Keywords: supply chain digitalization; carbon emissions; supply chain efficiency; green innovation; quasi-natural experiment



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1. Introduction

As global climate challenges intensify, carbon emissions have become a central concern for the international community. Governments and enterprises around the world are actively exploring pathways to reduce emissions and achieve green development. According to the latest ranking (2025), the top 100 listed companies in China emitted 5.134 billion

tonnes of CO₂ in 2024. This amount accounts for about 40.75% of China's total national emissions of 12.6 billion tonnes that year. This volume highlights the pivotal role of listed companies in China's carbon emissions. However, enterprises face many obstacles in pursuing low-carbon transformation, including constraints from traditional management models and limited technological capabilities. Achieving carbon reduction at the micro-production level is therefore of substantial practical significance.

Han and Wei's research indicates that the majority of corporate carbon emissions originate from supply chains [1]. As a vital link between production and consumption, supply-chain carbon emissions cannot be overlooked. How to effectively use existing technologies to reduce these emissions has therefore become a hot research topic. Rapid advances in digital technology have transformed how businesses and individuals communicate and have served as a primary driver of corporate digital transformation [2]. These developments have made supply chain digitization a new trend for promoting carbon reduction within supply chains, prompting academic research on supply chain restructuring and giving rise to the concept of a digital supply chain [3]. The idea of digital supply chains aligns with that of intelligent supply chains and Supply Chain 4.0 [4], which is the use of digital products, services, and processes that employ digital technologies to enhance supply chain efficiency. Supply chain digitalization to integrate internal and external resources has become a critical issue [5]. Moreover, traditional supply chains, which are based on an event-driven chain-like organization, have given rise to information silos between supply chain nodes, rendering them increasingly unable to meet societal development needs [6]. Consequently, collaborative, intelligent decision-making across the entire chain has become imperative. In April 2018, China's Ministry of Commerce, in collaboration with seven other departments, jointly issued the Announcement on Advancing Pilot Projects for Supply Chain Innovation and Application. That October, 266 enterprises were selected for a two-year pilot program on supply chain innovation and application, and 55 cities were designated as pilot cities for the same initiative; they are to jointly explore supply chain innovations and practical implementations. Similar pilot policies have been the subject of fairly extensive research, which has provided valuable insights into the impact of the Supply Chain Innovation and Application Pilot Program (SCIAPP) and provided methodological and perspective references for this research [7]. The SCIAPP stands apart from traditional innovation or governance policies because it requires pilot firms to digitize inter-firm processes. This requirement includes building shared data platforms and collaborative logistics with key partners. The SCIAPP focuses directly on the supply-chain layer. Firms were selected based on their status as supply-chain core enterprises. This selection caused a shock since inter-organizational digital coordination is largely separate from a firm's prior carbon or innovation path.

Digitalization is widely regarded as a crucial pathway for achieving dual carbon goals [8]. A considerable body of literature recognizes the generally positive impact of digitalization on carbon reduction, often through channels such as green innovation and regional collaboration [9–12]. However, the evidence is not unambiguous. Some studies, for instance, caution that digitalization may increase emissions due to technology bias or rebound effects [13]. Thus, a coherent theoretical framework linking digitalization to carbon mitigation, especially beyond the firm level, remains to be developed.

Digitalization is a crucial pathway for achieving the dual carbon goals [8], and its specific effects on carbon reduction have sparked extensive academic debate. The existing literature has thoroughly demonstrated the significant impact of digitalization on carbon emission reduction [9,10]. Concurrently, multiple studies indicate that digitalization significantly reduces carbon emissions through pathways such as fostering regional collaborative innovation and accelerating green technological innovation [11,12]. Gu et al. further

demonstrated that industrial digital transformation markedly enhances green efficiency via the threshold effect of regional collaborative innovation, thereby promoting carbon emission reduction [12]. However, this view differs from those of studies concerning digitalization's role in promoting carbon reduction and sustainable development at the continental level and across China's provinces. Zhang et al. argue that digitalization-driven technological progress is biased and increases carbon emissions [13]. Consequently, no unified framework has been established. Nevertheless, corporate digital transformation has already precipitated profound internal changes within enterprises. Scholars have found that such transformation provides economic benefits through several avenues: significantly enhancing corporate capital market performance [14], improving corporate social responsibility outcomes [15], and markedly increasing enterprise value levels [16]. Regarding environmental benefits, Chen et al. [17] contend that corporate digital transformation can significantly reduce carbon emissions. Digital transformation enhances corporate social responsibility fulfillment and technological advancement, exerting a positive influence on carbon reduction within manufacturing enterprises. The prevailing view holds that corporate digitalization delivers tangible benefits to businesses.

Focusing on how digitalization reduces carbon emissions in supply chains, Song et al. [18] used the business innovation cycle theory to systematically analyze the mechanisms through which digital technologies facilitate carbon reduction. They constructed a logically rigorous and falsifiable framework. Belhadi et al. [19] used survey data from 437 manufacturing companies across Asia, Europe, and Africa to demonstrate that data-driven digital transformation can help supply chains achieve greater reductions in carbon emissions. Existing research has thoroughly examined the impact of digital transformation on carbon reduction, providing ample theoretical foundations and empirical evidence for this study. However, few studies have verified the actual implications of supply chain digitalization for corporate carbon reduction in China. The primary focus of this study is to clarify the impact of supply chain digitalization on carbon reduction. It also examines and delineates the mediating effects of corporate supply chain efficiency and green innovation levels—both influenced by supply chain digitalization—on carbon emissions. This approach aims to discern the practical role supply chain digitalization plays in the carbon reduction process. Existing studies on digital transformation and green innovation have predominantly focused on single-firm adoption or regional aggregates, creating two significant gaps in the existing body of research. First, it remains empirically untested whether digitalization confined to the supply chain layer generates additional carbon savings beyond firm-level upgrades. Second, the absence of exogenous policy shocks impedes causal inference about systemic emission reductions. By exploiting the pilot-program design at the supply-chain node level, this study addresses both gaps, providing causal evidence that inter-firm digital coordination yields incremental abatement effects that would be underestimated when the supply chain perspective is ignored.

The marginal contributions of this study are as follows: First, it shifts the research focus from the financial and operational repercussions of supply chain digitalization to its hitherto unexplored environmental consequences, particularly corporate carbon emissions. Second, this paper elucidates how supply chain digitalization promotes corporate carbon reduction by enhancing supply chain efficiency and strengthening enterprises' green innovation capabilities, thereby deepening our understanding of the critical mechanisms through which digitalization enables carbon mitigation. Third, it examines the heterogeneity of supply chain digitalization's impact on corporate carbon emissions across four dimensions: corporate governance levels, property rights characteristics, digitalization intensity, and sector-specific variations. These findings assist local governments in formulating targeted policy interventions.

This paper is organized as follows: Section 2 presents the research hypotheses. Section 3 outlines the study design. Section 4 reports the empirical findings. Section 5 summarizes the main findings and presents the corresponding policy recommendations.

2. Theoretical Analysis and Hypothesis

Song et al. [18] note that digital technologies contribute to carbon reduction in supply chains by substantially lowering the costs and risks of data processing while also enabling integrated innovation opportunities for low-carbon development. Multiple studies also indicate that digitalization plays a dual role in carbon reduction by lowering transaction costs [20] and integrating key resources [21]. Drawing on resource-based theory, digital platforms significantly enhance corporate carbon efficiency by bundling data, knowledge, and green capabilities into resource packages that are difficult to imitate. This suggests the applicability of both transaction cost theory and resource-based theory in explaining the effects of digitalization on carbon reduction. Consequently, this study analyzes the impact of supply chain digitalization on corporate carbon emissions from these two perspectives.

From a transaction-cost perspective, supply chain digitalization has been shown to reduce costs through two primary means. First, enhanced information transparency and operational automation enable precise monitoring of energy use and carbon emissions while streamlining processes [22,23]. Second, supply chain digitalization can strengthen collaborative relationships among partners, thereby reducing coordination and oversight costs through technologies such as blockchain that enhance data integrity and trust [24]. This helps reduce oversight and default costs arising from distrust, ultimately promoting collaborative management of carbon emissions. Furthermore, the information spillover effects generated by corporate digital transformation significantly reduce information search and verification costs across supply chain segments, effectively mitigating the bullwhip effect [25]. Supply chain digitalization operates through two distinct layers: internal-firm mechanisms and inter-firm coordination mechanisms. The former reduces a firm's own-scope emissions by curbing overproduction and energy waste. The latter synchronizes activities across partners, reducing systemic inefficiencies such as redundant shipments and upstream emissions. Empirically, we proxy these layers with inventory turnover days (internal efficiency) and supply chain concentration (external coordination), allowing us to quantify their respective contributions to carbon reduction.

The resource-based theory holds that a firm's unique resources are the source of its competitive advantage. Supply chain digitalization gives enterprises green competitiveness by combining data, knowledge, and green capabilities into a resource package that is hard to replicate [26]. First, supply chain digitalization provides enterprises with data analytics and decision support, enabling the identification and management of carbon-emitting sources in the supply chain. This allows targeted reduction measures to be formulated, such as optimizing logistics routes through data analysis to reduce transport distances and frequencies, thereby lowering carbon emissions during transportation. Second, digitalization facilitates the flow of supply chain knowledge and its effective integration. Enterprises can continuously enhance their carbon emission management capabilities through organizational learning and knowledge management, thereby transforming experience into competitive advantage [27]. Third, as carbon trading markets continue to mature, carbon emission rights have evolved into a quantifiable and tradable corporate asset [28]. Enterprises possessing advanced digital capabilities have developed inimitable competitive advantages in carbon asset management through real-time monitoring, precise accounting, and intelligent forecasting. This advantage propagates through the supply chain, incentivizing node enterprises to accelerate digital transformation and thereby driving a low-carbon transition across the entire chain. Consequently, supply chain digitalization

enhances resource utilization efficiency and management capabilities. Building on both theoretical perspectives, these mechanisms are fundamentally linked.

Although transaction cost theory and the resource-based view offer different perspectives, both help explain how digitalizing supply chains can reduce carbon emissions. Digitalization's ability to lower transaction costs creates the operational efficiency and relational context needed for firms to integrate and use unique resources. Efficiency gains from reduced coordination friction free up managerial and financial resources, which can then be redirected toward green innovation activities. Conversely, the novel capabilities and resources developed through innovation, such as sophisticated carbon monitoring systems, further cement trust and reduce future coordination costs within the supply network. Therefore, these theoretical strands are functionally interlinked: transaction cost reduction enables resource leveraging, and resource-based advantages reinforce efficient coordination, both of which drive measurable reductions in carbon emissions. Based on this integrated theoretical foundation, we propose the following hypothesis:

H1. *Supply chain digitalization reduces corporate carbon emissions.*

The essence of supply chain inefficiency lies in the increased supply chain turnaround cycle resulting from managerial dysfunction. Supply chain digitalization addresses a range of issues stemming from management dysfunction, manifesting its impact through enhanced supply chain transparency, flexibility, and stability. Integrating cutting-edge technologies into supply chain management drives intelligent transformation of business processes, significantly improving the efficiency of data circulation among enterprises at various nodes. This process facilitates swift and seamless information sharing, effectively mitigating market information asymmetry. Consequently, it enhances the efficacy of market mechanisms and elevates supply chain transparency [29]. The utilization of smart contract technology has facilitated the execution of ownership transfers and payment processes within supply chain management, significantly enhancing supply chain transparency and overall operational efficiency [30]. Enhanced supply chain transparency within enterprises has improved information transmission efficiency and significantly increased supply chain responsiveness. By bolstering supply chain visibility, it endows the chain with greater agility, enabling flexible adaptation to market fluctuations [31]. This ensures robust operation and continuous optimization, thereby enhancing supply chain efficiency [32]. One study further demonstrated that by enhancing end-to-end visibility, supply chains can flexibly respond to market fluctuations, ensuring robust operations and continuous optimization, thereby comprehensively improving supply chain efficiency [33].

Moreover, supply chain digitalization helps reduce supply chain concentration and promotes diversification in supply chain resource allocation, thereby enhancing supply chain stability and adaptability [34]. Regarding research on enhancing supply chain efficiency through digitalization, Fu et al. [35] examined how the digital economy affects inventory turnover efficiency in energy-sector enterprises. They found that technological innovation, a key driver of the digital economy, plays a pivotal role in optimizing supply chain processes and accelerating inventory turnover. Meanwhile, Krishan et al. [36] used the inventory turnover cycle as the core metric for assessing supply chain efficiency. They found that enterprises' digital transformation significantly reduced turnaround times through real-time inventory visibility, thereby comprehensively enhancing supply chain efficiency. This further corroborates the profound transformative impact of technological innovation on supply chain management. Moreover, improvements in supply chain efficiency, accompanied by optimizations in production and logistics operations, contribute to reducing carbon emissions. Accordingly, this study proposes the research hypothesis H2:

H2. *Supply chain digitalization reduces corporate carbon emissions by enhancing supply chain efficiency.*

Resource dependency theory holds that enterprises operate within open systems, continuously drawing essential resources from their external environment through close, interactive relationships. This resource extraction underpins the effective conduct of daily operations and the achievement of strategic objectives [37]. As a key government initiative to drive corporate innovation, the SCIAPP provides selected enterprises with external resource support, injecting robust external momentum. On the one hand, the dual safeguards of government certification and oversight send positive signals to external stakeholders, significantly alleviating financing constraints. On the other hand, supply chain digitalization enhances firms' capacity to access heterogeneous information, incentivizing increased R&D investment [38], thereby elevating corporate innovation levels.

According to sustainable development theory, technological progress is the core driver of steady, robust economic growth within the constraints of finite resources [39]. Technological innovation and upgrading can enhance resource-use efficiency and stimulate endogenous growth momentum within economic systems, thereby achieving sustainable development. Green technological progress relies on concurrent advancements in non-green technology domains [40], and digital transformation supports green technology development by facilitating the linkage, integration, and reconfiguration of multidisciplinary knowledge, thereby elevating the level of green technological innovation. The circular economy theory posits that green technological innovation, by employing circular thinking, can significantly reduce corporate energy consumption and curb carbon emissions [41]. Enterprises' green technological innovation practices not only help mitigate environmental pollution but also enhance resource-use efficiency, thereby establishing a development model that equally prioritizes environmental sustainability and economic growth [42]. Supply chain digitalization, acting as a powerful driving force, actively elevates the level of green technological innovation and assists enterprises in achieving carbon reduction targets. This approach aligns with the dual demands of modern economies for environmental governance and economic growth.

In light of this, this study proposes research hypothesis H3:

H3. *Supply chain digitalization reduces corporate carbon emissions by fostering green technological innovation.*

It is important to acknowledge that the digitalization of supply chains could, in theory, trigger offsetting or rebound effects that may attenuate its net carbon reduction impact. For instance, efficiency gains and cost savings could lead to scale expansion, increasing total output and associated emissions. Similarly, enhanced supply chain visibility and flexibility might increase the frequency of logistics activities (e.g., more frequent, smaller shipments to reduce inventory) or extend supply chain networks, potentially raising transportation emissions. However, within the specific context of the SCIAPP—a policy-driven intervention aimed explicitly at green and collaborative digital transformation—it is proposed that these rebound effects are likely secondary. The program's emphasis on optimizing system-wide efficiency and fostering green innovation directs the gains toward absolute resource savings and decarbonization, rather than solely toward business growth. Furthermore, an empirical analysis, which captured the net effect, found a balance between these countervailing forces. The significantly negative net effect found suggests that the posited efficiency and innovation channels dominate in this setting (Figure 1).

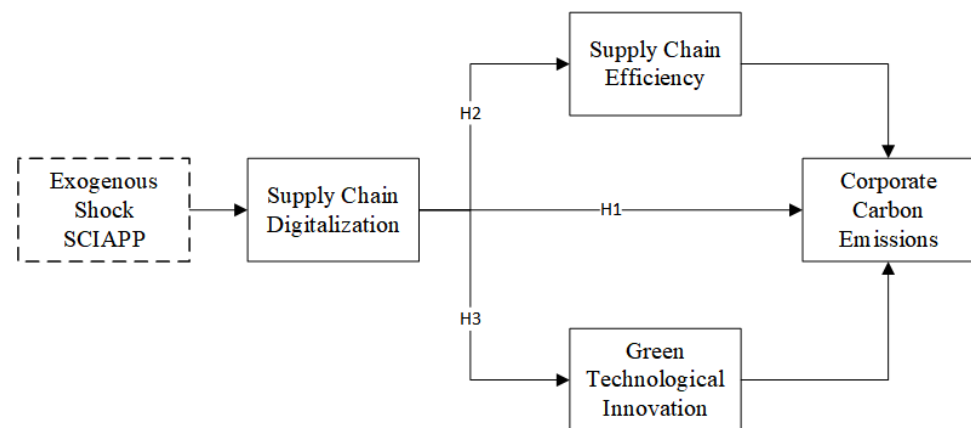


Figure 1. Theoretical framework and research hypotheses.

3. Research Design

3.1. Model Construction

3.1.1. DID Benchmark Regression Model

This study employed the implementation of the SCIAPP as a quasi-natural experiment to ascertain the causal effect of supply chain digitalization. The program was formally initiated in October 2018 by the Ministry of Commerce and seven other ministries; 266 enterprises and 55 cities were selected to participate in the pilot project consisting of a two-year exploration period (The Ministry of Commerce of China, 2018 [43]). To translate this policy into an empirical strategy, the key treatment variable was constructed as follows: The dummy variable $treat_{it}$ equals 1 if firm i is among the 266 designated pilot enterprises, and 0 otherwise. The time dummy $Policy_{it}$ equals 1 for the year 2018 and all subsequent years in the sample (i.e., the post-treatment period), and 0 for 2017 and earlier years. This coding reflects the fact that the policy was implemented starting in 2018. The interaction term $treat_{it} \times policy_{it}$ captures the differential change in outcomes for pilot firms after the policy's implementation, serving as our measure of supply chain digitalization exposure. The baseline difference-in-differences (DID) model is specified as follows:

$$CO_{2it} = \alpha_0 + \alpha_1 treat_{it} \times policy_{it} + \alpha_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

In Equation (1), CO_{2it} denotes carbon emissions and serves as the dependent variable in this study. $treat_{it} \times policy_{it}$ represents a dummy variable, where $treat_{it}$ is assigned a value of 1 for firms implementing supply chain innovation and 0 for those not implementing it. The interaction coefficient α_1 captures the net impact of supply chain digitalization on corporate carbon emissions and serves as the core estimated coefficient of interest in this study. X_{it} denotes a series of control variables designed to regulate other corporate characteristics that may simultaneously influence both digital transformation and carbon emissions, including the debt-to-equity ratio (Lev), fixed asset ratio (Ta), return on assets (ROA), and revenue growth rate ($Growth$), with α_2 representing their respective coefficients. α_0 is the model's constant term, μ_i and δ_t denote the firm-specific and time-specific fixed effects, respectively, whilst ε_{it} represents the random disturbance term.

3.1.2. Mechanism Test Model

To examine the specific mechanism through which supply chain digitalization influences carbon emissions, this study drew upon the research of Jiang Ting et al. [44] to establish the following mechanism testing model:

$$M_{it} = \beta_0 + \beta_1 treat_{it} * policy_{it} + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

M_{it} denotes the mechanism variable, β_0 represents the constant term, and β_1 signifies the effect of supply chain innovation on the mechanism variable. The remaining explanatory variables in the equation retain the same meanings as in Equation (1). Mechanism testing procedure: First, verify whether supply chain digitalization has a significant impact on supply chain efficiency and corporate green technological innovation. If the effect is substantial, proceed to the second step and, drawing on the existing literature, discuss the influence of the aforementioned mediating variables on corporate carbon emissions.

3.2. Sample Selection and Data Sources

This study selected A-share listed companies in Shanghai and Shenzhen from 2013 to 2022 as the initial sample. The focus on A-share listed companies was driven by three key considerations. First, these companies represent the core of China's formal economy and account for a dominant share of corporate carbon emissions, making them primary targets for national policies such as the SCIAPP. Second, their mandatory disclosure of standardized financial and environmental data enables the construction of the consistent, longitudinal panel required for rigorous quasi-experimental analysis. Third, although listed firms constitute a selected group, our difference-in-differences design with firm fixed effects and propensity-score matching controls for time-invariant heterogeneity improves comparability, thereby mitigating concerns about observable selection bias. The selection of pilot enterprises for the SCIAPP was carried out jointly by the Ministry of Commerce and other relevant ministries. According to official policy documents, the selection was not random but based on articulated criteria designed to identify suitable candidates for leading supply-chain innovation. The key criteria included the following: (1) the firm is a core enterprise within a key industrial supply chain; (2) the firm has demonstrated willingness and the foundational capability to undertake and lead digital transformation; (3) the firm is representative of an industry, with the aim of covering a broad spectrum of strategic sectors; and (4) the firm has a commitment to collaborative, open innovation with upstream and downstream partners. This selection process aimed to create a cohort of "lead firms" capable of experimenting with and diffusing digital supply-chain practices. The sample period ended in 2022 primarily due to data availability constraints for our key dependent variable. Corporate carbon emissions data are manually collected from corporate sustainability reports, which typically entail a publication lag of one to two years. To ensure data completeness, reliability, and consistency across all variables in the panel dataset—and to maintain a sufficient time window for a robust quasi-experimental analysis of the 2017 policy implementation—the sample was confined to the 2013–2022 period. To ensure data reliability, we applied the following exclusions: (1) We removed firms under special treatment (ST or *ST) by stock exchanges to avoid financial anomalies. (2) Financial industry samples were excluded to ensure the research findings are accurate. (3) Observations missing core variables were dropped to guarantee full data coverage. (4) Samples of companies with liabilities exceeding assets were excluded to mitigate potential financial risks. The final sample included 11,143 firm-year observations. Firms' innovation patents were retrieved from the National Intellectual Property Administration's public patent archive, and financial indicators were extracted from the China Stock Market and Accounting Research (CSMAR) database. Additionally, all continuous variables were winsorized at the 1% level to address potential outliers.

3.3. Variable Settings

Carbon emissions (CO_2). This study manually collected carbon emission data from enterprises' annually published corporate social responsibility, sustainability, and environmental reports. These figures were subsequently estimated in accordance with the

calculation methodology issued by the National Development and Reform Commission, ultimately yielding enterprise-level carbon emission data [45].

To ensure consistency and comparability across firms with divergent reporting standards, a standardized, multi-step procedure was implemented.

- (1) Source and metric prioritization. The initial step was to source figures explicitly labeled as carbon dioxide (CO₂) emissions or greenhouse gas (GHG) emissions, covering both Scope 1 and Scope 2. When a report provided GHG emissions in CO₂-equivalents (CO₂e), those values were used.
- (2) Calculation harmonization. For firms reporting only energy consumption (e.g., in tons of coal equivalent or gigajoules) without direct emission figures, official emission factor coefficients from the Guidelines for Corporate Greenhouse Gas Emission Accounting and Reporting, issued by China's National Development and Reform Commission (NDRC), were used to estimate CO₂ emissions.
- (3) Boundary consistency. The focus was on operational emissions (Scope 1 and 2) to maintain a consistent organizational boundary. Reports focusing only on Scope 3 (value chain) emissions were not used as the primary source for this variable.
- (4) Cross-verification. For firm-years with multiple reports, a cross-check was performed on the figures. In cases of minor discrepancies, the figure from the more detailed or comprehensive report was used; in cases of major unresolved discrepancies, the observation was treated as missing. This process yielded a panel of firm-year carbon emissions. The final variable used in regressions was the natural logarithm of these emission figures (in tonnes).

Supply Chain Digitalization ($treat_{it} \times policy_{it}$). This study employed an instrumental variable representing pilot enterprises: firms designated as Supply Chain Innovation and Application Pilot Enterprises were assigned to the treatment group and assigned a value of 1; otherwise, they were treated as control group samples and assigned a value of 0.

Supply chain efficiency. To ensure the comprehensiveness of the research, this study conducted an in-depth examination of supply chain efficiency from two dimensions: internal management efficiency and external coordination efficiency. Drawing on the research of Krishan et al. [36], the logarithm of inventory turnover days (*Inventory*) was used as a proxy for internal supply chain management efficiency. The shorter the inventory turnover days, the faster the turnover rate and the higher the operational efficiency within the enterprise. This metric effectively mitigates errors arising from safety stock when using non-finished goods inventory as a proxy variable while fully accounting for supply chain responsiveness. Supply chain external coordination efficiency was measured using supply chain concentration (*supply*). According to Patatoukas [46], the average of a firm's combined procurement and sales shares with its top five suppliers and customers can be used as an indicator of external coordination efficiency. A higher value indicates greater transaction frequency between upstream and downstream enterprises within the supply chain, alongside enhanced efficiency in logistics, information flow, and capital flow. Green Technological Innovation (*GTI*). The logarithm of the annual total of green patent applications plus one served as a proxy for measuring corporate green technological innovation [47]. This reflects substantive innovation (*GTI_inv*) and strategic innovation levels (*GTI_uti*).

To exclude potential influences beyond supply chain digitalization and avoid omitted variable bias, this study selected the following micro-enterprise-level control variables:

Asset-liability ratio (*Lev*): the ratio of total liabilities to total assets;

Fixed Asset Ratio (*Ta*): the ratio of fixed assets to total assets;

Return on Assets (*ROA*): net profit divided by average total assets;

Revenue Growth Rate (*Growth*): the revenue growth amount divided by total revenue from the previous year.

3.4. Descriptive Statistics

Table 1 presents the summary statistics for all variables. Based on 11,143 firm-year observations from 2013 to 2022, the average CO₂ emissions value was 12.701, with a standard deviation of 1.444, indicating considerable variation across the sampled firms. This substantial variability reflects significant disparities in carbon dioxide emissions across enterprises. The values of the other variables fell within acceptable ranges. A diagnostic check for multicollinearity, conducted prior to regression analysis, revealed that all variance inflation factor (VIF) values were below 1.2 (mean VIF = 1.06), allowing us to rule out multicollinearity as a substantive concern.

Table 1. Descriptive statistics of main variables.

Variable	N	Mean	SD	Min	Max
CO ₂	11,143	12.70	1.44	2.40	19.85
$treat_{it} \times policy_{it}$	11,143	0.24	0.43	0.00	1.00
<i>lev</i>	11,143	0.45	0.20	0.01	1.00
<i>Ta</i>	11,143	0.23	0.15	0.00	0.88
<i>ROA</i>	11,143	0.03	0.07	−1.86	0.79
<i>Growth</i>	11,143	0.58	10.48	−11.92	865.91
<i>Inventory</i>	11,143	4.63	1.27	−7.78	17.85
<i>supply</i>	11,143	29.82	17.73	−161.85	314.26
<i>GTI_inv</i>	11,143	0.51	0.98	0.00	6.91
<i>GTI_util</i>	11,143	0.32	0.72	0.00	5.79

Note: This table reports descriptive statistics.

4. Results

4.1. Baseline Regression Analysis

This study employed a difference-in-differences (DID) model to examine the impact of supply chain digitalization on corporate carbon emissions, with the results presented in Table 2. Column (1) reports the univariate test results. Building on Column (1), Columns (2) to (5) progressively add control variables while controlling for time and individual fixed effects. Across all scenarios, supply chain digitalization showed a statistically significant negative association with carbon emissions at the 1% level. This indicates that enterprises implementing digital practices exhibited markedly lower carbon emission intensities than those not undertaking supply chain innovation and application. The economic magnitude of this effect was substantial. The estimated coefficient of −0.113 implies that SCIAPP pilot firms reduced their carbon emissions by approximately 10.7% relative to the control group. To contextualize this effect, for the average pilot firm in our sample, this percentage reduction translates to an annual decrease of tens of thousands of tonnes of CO₂. Furthermore, this represents a meaningful decline in carbon emission intensity (CO₂ per unit of output), indicating a decoupling of emissions from economic activity for the treated firms. Thus, supply chain digitalization had a significant mitigating effect on carbon emissions, preliminarily validating Hypothesis H1 (supply chain digitalization can reduce carbon emissions).

Table 2. The results of the benchmark regression analysis.

Variable	(1)	(2)	(3)	(4)	(5)
	CO ₂	CO ₂	CO ₂	CO ₂	CO ₂
$treat_{it} \times policy_{it}$	−0.1151 *** (−3.0317)	−0.1128 *** (−2.9710)	−0.1123 *** (−2.9484)	−0.1131 *** (−2.9681)	−0.1132 *** (−2.9695)
<i>lev</i>		−0.1305 ** (−2.0114)	−0.1307 ** (−2.0146)	−0.1419 ** (−2.0950)	−0.1453 ** (−2.1448)

Table 2. Cont.

Variable	(1)	(2)	(3)	(4)	(5)
	CO ₂	CO ₂	CO ₂	CO ₂	CO ₂
<i>Ta</i>			0.0138 (0.1666)	0.0122 (0.1464)	0.0155 (0.1869)
<i>ROA</i>				−0.1066 (−0.5755)	−0.1121 (−0.6052)
<i>Growth</i>					0.0024 ** (1.9959)
Constant	12.7279 *** (815.3453)	12.7857 *** (391.1070)	12.7825 *** (338.0616)	12.7916 *** (312.0510)	12.7911 *** (312.0763)
Firm/Year Effects	Control		Control		
Sample size	11,143	11,143	11,143	11,143	11,143
With R ²	0.0008	0.0012	0.0012	0.0012	0.0016

Note: **, and *** represent significance at the 5%, and 1% levels, respectively, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

4.2. Robustness Test

4.2.1. Parallel Trends Test

The use of the DID model is contingent on the data passing the parallel trends test. To eliminate pre-treatment trend effects and obtain a more robust causal relationship, this study specified the following equation to conduct a parallel trends test:

$$CO_{2it} = \gamma_0 + \gamma_1 \sum_k policy_{i,t+k} + \gamma_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Among them, *k* is the year dummy variable, γ_0 denotes the constant term, and γ_1 represents the effect of supply chain innovation on carbon emissions. The other explanatory variables in the equation retain the same meaning as in Equation (1). In the parallel trends test, we examined a window spanning four years before to three years after policy implementation, defining the year immediately preceding the policy implementation as the baseline period. The regression coefficient γ_1 reflects the difference in carbon emission levels between the pilot firms and the control group in the *k*th year after policy implementation. The results of the parallel trends test are shown in Figure 2. As the figure shows, before the pilot began, the regression coefficients for each period were not significant, indicating no significant difference in carbon emission levels between the treatment and control groups. In the post-implementation period, the estimated coefficients became statistically significant and positive, confirming a divergent trend between the treatment and control groups and thereby validating the parallel trends assumption.

4.2.2. Placebo Test

This study employs a counterfactual approach to examine the potential omitted-variable issue by advancing the policy's implementation by three years. The statistically insignificant result for this placebo treatment, reported in Column (1) of Table 3, supports the parallel trends assumption. This allowed us to more confidently ascribe the subsequent reduction in corporate carbon emissions to the SCIAPP.

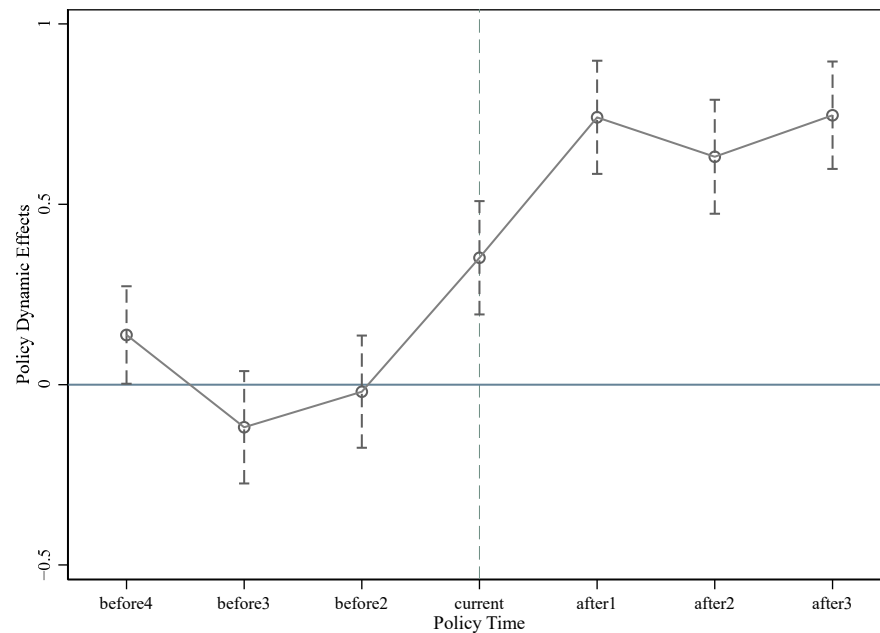


Figure 2. Parallel trend test results.

Table 3. Robustness test.

Variable	Placebo Test	PSM-DID	Exclude Data from the Year of Policy Implementation	Incorporate Additional Control Variables	Consider Pilot Cities
	(1)	(2)	(3)	(4)	(5)
	CO ₂	CO ₂	CO ₂	CO ₂	CO ₂
$treat_{it} \times policy_{it}$	−0.0000 *** (−2.6122)	−0.0992 *** (−2.6103)	−0.1740 *** (−4.0408)	−0.1133 *** (−2.9734)	
$TreatCityY$					−0.1132 *** (−2.9695)
$TreatCityN$					0.0000 (.)
$ConPos$				−0.0097 (−0.3181)	
Mng				0.0024 *** (2.9150)	
Constant	12.7745 *** (65.5934)	12.7648 *** (112.5272)	12.7496 *** (294.9702)	12.7375 *** (277.3465)	12.7911 *** (312.0763)
Firm/Year Effects	Control Control	Control Control	Control Control	Control Control	Control Control
Sample size	11,143	11,138	9951	11,143	11,143
R ²	0.0014	0.4414	0.0009	0.0009	0.0003

Note: *** represent significance at the 1% level, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

4.2.3. PSM-DID

The fundamental identification challenge in estimating the policy's causal effect is the impossibility of observing the same firm's carbon emissions with and without the treatment. To address the ensuing sample selection bias and approximate a valid counterfactual approach, we employed Propensity Score Matching combined with a DID design to re-evaluate our baseline conclusions. Figure 3 shows the kernel density distributions of the propensity scores before and after 1:1 nearest-neighbor matching, using firm characteristics

(*Lev*, *Ta*, *ROA*, and *Growth*) as covariates. The markedly reduced difference in distributions post-matching confirmed a substantial reduction in sample bias. A DID regression on this matched sample continued to yield a significantly negative estimate for the treatment effect, as shown in Column (2) of Table 3.

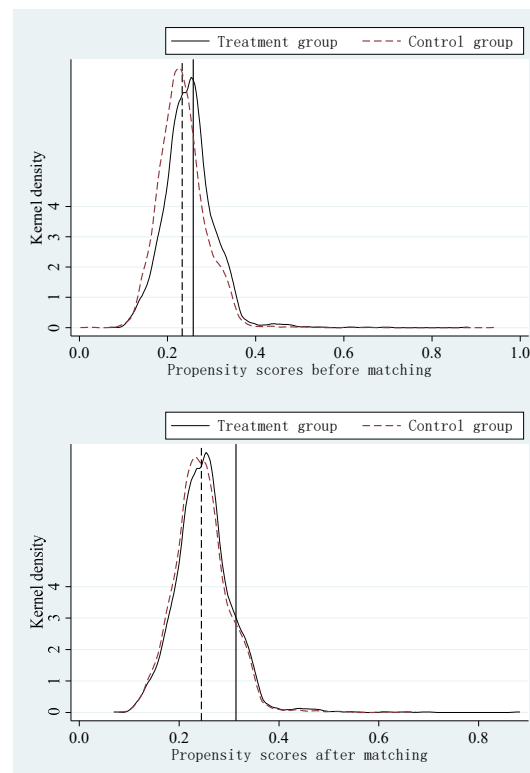


Figure 3. Comparison of kernel density distributions of propensity scores before and after matching.

4.2.4. Excluding Data from the Year of Policy Implementation

To isolate the policy's effect from its concurrent and potential lagged impacts, we re-estimated our difference-in-differences model using a sample that excluded the year of the policy's implementation. The regression results, shown in Column (3) of Table 3, remained significant after excluding the 2018 data, suggesting the robustness of the research conclusions.

4.2.5. Addressing Omitted Variable Issues

To address omitted variable problems, this study included additional variables that may affect the results, such as CEO duality (*ConPos*) and the management ownership ratio (*Mng*), and reran the regression analysis. The regression results, as presented in Column (4) of Table 3, remained robust after fully accounting for omitted variable issues.

4.2.6. Considering the Impact of Supply Chain Innovation and Application Pilot Cities

The Supply Chain Innovation and Application Pilot initiative was implemented at both the enterprise and city levels, with 266 enterprises and 55 cities included in the pilot project. Pilot cities can support the digitalization of supply chains for enterprises. To probe the role of pilot cities, we disaggregated the sample by distinguishing pilot firms located within pilot cities from all others. This classification was incorporated into the DID framework via the interaction term specified in Equation (4).

$$CO_{2it} = \beta_0 + \beta_1 \text{TreatCity}Y_{it} + \beta_2 \text{TreatCity}N_{it} + \beta_3 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

TreatcityY and *TreatcityN* represent enterprises located in pilot cities and other enterprises. β_1 and β_2 are the coefficients of interest, capturing the differential effects of carbon reduction for pilot firms with and without city-level policy support, respectively. β_0 and β_3 denote the coefficients of the constant term and control variables, respectively, with the remaining variables retaining the same meanings as in Equation (1). The regression results are shown in Column (5) of Table 3. The marked contrast between the significantly negative coefficient for *TreatcityY* and the lack of a statistically significant effect for *TreatcityN* suggests that the supportive effect of pilot cities was concentrated among local pilot enterprises. This finding further strengthens the robustness of our primary results.

4.3. Heterogeneity Test

The degree of digitalization within a company's supply chain is influenced by its inherent capabilities. At the same time, carbon emission intensity varies with factors such as enterprise scale, industry sector, and ownership structure. Consequently, this study examined enterprise heterogeneity across four dimensions: corporate governance standards, property rights characteristics, digitalization levels, and industry sector.

4.3.1. Corporate Governance Level

Following the methodology of Zhou Qian et al. [45], principal component analysis was used to measure corporate governance across three dimensions: incentives, oversight, and decision-making. The sample was split annually into high- and low-governance groups based on the median governance level to measure the heterogeneity in the impact of supply chain digitalization on carbon emissions across firms with different governance levels. As shown in columns (1) and (2) of Table 4, the carbon reduction effect in the high-governance group was negative at the 5% significance level. Compared with the low-governance group, this effect was more statistically significant and had a larger absolute coefficient, indicating that firms with higher governance levels experienced a stronger carbon reduction effect from supply chain digitalization policies. The enhanced efficacy observed in firms with superior governance can be attributed to two interwoven economic principles: firstly, effective oversight and aligned incentives, which are hallmarks of robust governance, show the efficacy of policy implementation. This enhances the translation of the strategic mandate for supply chain digitalization into operational changes and resource commitments. Secondly, enhanced governance fosters efficiency in resource allocation. Better-governed firms demonstrate greater proficiency in identifying and allocating the financial and managerial resources facilitated by digitalization (e.g., cost savings from efficiency gains) toward further green investments and innovation rather than diverting them for other purposes. This amplifies the returns on carbon reduction.

Table 4. Heterogeneity test A.

Variable	High Governance Level	Low Governance Level	State-Owned Enterprises	Non-State-Owned Enterprises
	(1)	(2)	(3)	(4)
	CO ₂	CO ₂	CO ₂	CO ₂
$treat_{it} \times policy_{it}$			−0.1391 ** (−2.2809)	−0.0734 (−1.4870)
<i>TreatGovH</i>	−0.1714 *** (−3.8799)			
<i>TreatGovL</i>		0.0182 (0.4241)		

Table 4. Cont.

Variable	High Governance Level	Low Governance Level	State-Owned Enterprises	Non-State-Owned Enterprises
	(1)	(2)	(3)	(4)
	CO ₂	CO ₂	CO ₂	CO ₂
Control Variables	Control	Control	Control	Control
Constant	12.7654 *** (321.5416)	12.7564 *** (310.8769)	12.7493 *** (165.9658)	12.7810 *** (245.0493)
Firm/Year Effects	Control Control	Control Control	Control Control	Control Control
Sample size	5045	6098	4256	6887

Note: **, and *** represent significance at the 5%, and 1% levels, respectively, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

4.3.2. Property Rights

State-owned enterprises (SOEs) and non-state-owned enterprises differ significantly in ownership structure, capital contribution ratios, social functions, and profit allocation. Consequently, this study divided the sample into state-owned and non-state-owned enterprises to examine the differential impact of corporate property rights on the role of supply chain digitalization in carbon emissions. The regression results in Table 4, columns (3) and (4), indicate that the carbon reduction effect was significant for the state-owned enterprise sample, whereas the regression results for the non-state-owned enterprise sample were not significant. A possible explanation is that state-owned enterprises bear the social responsibility of implementing national policies and possess a more robust industrial foundation. As policy conduits, SOEs receive stronger implementation incentives, thereby achieving larger emission reductions. The pronounced effect for state-owned enterprises stems from their unique institutional role and resource profile. First, as policy conduits, SOEs face stronger implicit mandates to align with national strategic objectives, such as the “dual-carbon” goals, leading to more vigorous and faithful execution of the SCIAPP’s directives. Second, their resource advantage in terms of capital access and scale allows them to undertake the substantial upfront investments required for cross-organizational digital infrastructure. Third, their position as “chain leaders” in many critical industries grants them greater leverage to coordinate and impose digital standards on their often numerous and smaller suppliers, enabling systemic change that extends beyond their own boundaries.

4.3.3. Enterprise Digitalization Level

Based on the method of Zhao [48], we constructed a firm-level Digitalization Index (*DIGI*) through text analysis of annual reports. Using Python 3.13, we extracted management discussion text, identified keywords across four dimensions (e.g., Digital Technology Application and Intelligent Manufacturing), and counted frequencies with the Jieba tool. The raw counts were standardized and weighted using the entropy method, and the final *DIGI* was computed as a weighted composite score for each firm-year. The complete list of keywords used for this text analysis is provided in Appendix A for transparency.

Firms were categorized into two distinct groups, designated as “High” and “Low” digitalization groups, on an annual basis. This classification was determined using the annual median of the specified index. The index served as a metric that reflects a firm’s inherent digital capability and engagement, which was measured prior to or independently of the SCIAPP policy implementation. Consequently, this enabled us to test whether pre-existing digital maturity moderates the policy’s effect.

As shown in Table 5, columns (1) and (2), the regression coefficients for highly digitalized enterprises were statistically significant at the 1% level, whereas those for low-digitalization enterprises were not. This indicates that highly digitalized enterprises are better positioned to amplify the emission-reduction effects of policy interventions.

Table 5. Heterogeneity test B.

Variable	High Level of Digitalization	Low Level of Digitalization	Manufacturing Industry	Non-Manufacturing Industry
	(1)	(2)	(3)	(4)
	CO ₂	CO ₂	CO ₂	CO ₂
$treat_{it} \times policy_{it}$	−0.1149 *** (−2.7344)	0.4167 (0.6842)	−0.1998 ** (−2.2528)	−0.0774 * (−1.8086)
Control Variables	Control	Control	Control	Control
Constant	13.1265 *** (210.9568)	12.3738 *** (232.7280)	12.6343 *** (121.1877)	12.7459 *** (152.2842)
Firm/Year Effects	Control Control	Control Control	Control Control	Control Control
Sample size	6271	4872	2188	8955

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

The evidence suggests that firms with higher pre-existing digital maturity benefit more from the policy, underscoring the role of absorptive capacity. Firms with advanced digital infrastructure and skilled personnel have a stronger baseline capability to integrate, adapt, and deploy new supply chain-specific digital tools introduced by the policy. This reduces learning costs and implementation lags, allowing them to leverage the policy implementation more rapidly and fully. In essence, digital maturity lowers the marginal cost of adopting additional digital solutions, enabling these firms to obtain efficiency and innovation gains at a larger scale and at a faster rate.

4.3.4. Industry Heterogeneity

Manufacturing is the primary battleground for the development of the real economy. Compared with non-manufacturing enterprises, manufacturing enterprises have more complex supply chains, closer collaborative relationships with upstream and downstream partners, and more intricate production processes, leading to higher carbon emissions. Therefore, it is necessary to compare manufacturing and non-manufacturing enterprises. Columns (3) and (4) of Table 5 present the regression results for these sub-samples. Compared with non-manufacturing enterprises, manufacturing enterprises showed larger-magnitude regression coefficients. Manufacturing enterprises focus on enhancing supply chain coordination, reducing inventory, and optimizing logistics through supply chain management innovation. They also place a greater emphasis on advancing production technologies and optimizing production processes. Consequently, they are better positioned to demonstrate the carbon reduction effects of policy interventions. The most significant effect observed in the manufacturing sector was rooted in the physical and systemic nature of its production and logistics. Manufacturing supply chains involve tangible flows of materials, components, and finished goods, where inefficiencies (e.g., excess inventory, unoptimized routing, and energy-intensive processes) directly translate into higher carbon emissions. Therefore, digitalization that improves coordination and visibility yields immediate and significant physical savings. In contrast, many non-manufacturing sectors (e.g., services)

have less material-intensive operations, so the same degree of digital coordination might yield smaller marginal gains in direct emission reduction.

4.4. Mechanism Test

This study proposed that supply chain digitalization can reduce corporate carbon emissions by improving supply chain efficiency and strengthening enterprise innovation capabilities. To validate these mechanisms, a two-step testing approach was employed to examine transmission channels, thereby achieving “cleaner causal identification”.

- (1) Supply chain efficiency. Supply chain digitalization enhances corporate supply chain efficiency. On the one hand, it applies digital technologies across all supply chain segments, achieving process informatization and intelligent decision-making. This resolves issues of overinvestment or underinvestment while improving internal management efficiency [49]. On the other hand, supply chain digitalization facilitates information connectivity across the entire supply chain, enabling enterprises to respond swiftly and collaborate efficiently. This ensures the stability of the supply chain network and enhances overall collaborative efficiency. Column (2) of Table 6 shows a significantly negative coefficient, indicating that implementing supply chain digitalization markedly reduced a firm’s inventory turnover days, thereby enhancing internal management efficiency. Column (3) of Table 6 shows a significantly positive coefficient, demonstrating that supply chain digitalization increased supply chain concentration. Consequently, supply chain digitalization enhanced the overall supply chain efficiency. This systemic optimization—where improved coordination within a system leads to greater efficiency and emission reductions—is also observed at the regional level. Research shows that the coupling coordination between industrial structure optimization and ecosystem services not only curbs local carbon emissions but also generates positive spatial spillover effects [50], underscoring the universal importance of integrated, coordinated approaches for achieving sustainability goals. Existing research indicates that enhancing corporate efficiency can promote carbon reduction [51]. Specifically, improvements in supply chain efficiency can reduce energy consumption and lower corporate carbon emissions by increasing resource utilization efficiency and strengthening supply chain synergies. Therefore, Hypothesis 2 (supply chain digitalization reduces corporate carbon emissions by enhancing supply chain efficiency) was validated.
- (2) Green technological innovation. The SCIAPP provides enterprises with a clear innovation pathway and strategic direction. Furthermore, through preferential policies such as tax incentives, financial subsidies, and technical support, the government reduces the costs and risks associated with green innovation for enterprises. This incentivizes companies to increase investment in green innovation, thereby capturing the policy’s critical externalities. Moreover, the pilot enterprises themselves possess robust innovation capabilities. Their selection sends a positive signal to the external world. Government endorsement boosts the confidence of other enterprises in investing in them, thereby reducing the screening costs associated with adverse selection and moral hazard issues for investors. The coefficients in columns (4) and (5) of Table 6 are significantly positive, indicating that the implementation of supply chain digitalization can markedly enhance a company’s level of green technological innovation. Jiang et al. [52] found that corporate green technological innovation significantly reduces carbon emission reduction costs, thereby achieving carbon emission reductions. The existing research also generally recognizes that green technological innovation is a crucial channel for realizing carbon emission reduction effects [52].

Thus, Hypothesis 3 (supply chain digitalization reduces corporate carbon emissions by enhancing green technological innovation within the supply chain) was validated.

Table 6. Conduction mechanism test results.

Variable	(1)	(2)	(3)	(4)	(5)
	CO ₂	<i>Inventory</i>	<i>Supply</i>	<i>GTI_inv</i>	<i>GTI_utili</i>
	Supply Chain Efficiency			Green Technology Innovation	
$treat_{it} \times policy_{it}$	−0.1132 *** (−2.9695)	−0.0637 ** (−2.0131)	0.7392 * (1.6817)	0.1839 *** (6.7234)	0.0974 *** (4.8695)
Control Variables	Control	Control	Control	Control	Control
Constant	12.7911 *** (312.0763)	5.3693 *** (157.7180)	33.5212 *** (70.9174)	0.0318 (1.0808)	−0.0104 (−0.4849)
Firm/Year Effects	Control	Control	Control	Control	Control
Sample size	11,143	11,143	11,143	11,143	11,143
R ²	0.0003	0.1560	0.0337	0.0299	0.0244

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

To address concerns about reverse causality in our mechanism analysis (i.e., current carbon emissions may influence our mediator variables), we performed a test using lagged mediators. Specifically, we examined whether mediators from the previous period ($t - 1$) are associated with carbon emissions in the current period (t). This temporal ordering reinforces the causal argument that changes in the mediators precede and may induce changes in emissions.

The results, presented in Table 7, offer nuanced insights. For the green technological innovation channel, the results remained robust: both substantive GTI_inv_{t-1} and strategic GTI_uti_{t-1} innovation retained highly significant positive associations with current-period emission reductions. This reinforces the causal argument that innovation is a persistent driver of carbon mitigation.

Table 7. Robustness Tests for the Mechanism Analysis.

Variable	(1)	(2)	(3)	(4)	(5)
	CO ₂	<i>Inventory</i>	<i>Supply</i>	<i>GTI_inv</i>	<i>GTI_utili</i>
	Supply Chain Efficiency			Green Technology Innovation	
$treat_{it} \times policy_{it}$	−0.1132 *** (−2.9695)	−0.0526 * (−1.6580)	0.5848 (1.3115)	0.1962 *** (7.0937)	0.1138 *** (5.6190)
Control Variables	Control	Control	Control	Control	Control
Constant	4.8529 *** (102.9405)	5.3571 *** (146.2715)	32.9751 *** (63.9943)	0.0096 (0.3010)	−0.0354 (−1.5148)
Firm/Year Effects	Control	Control	Control	Control	Control
Sample size	11,143	9525	9525	9525	9525
R ²	0.0003	0.1623	0.0311	0.0316	0.0274

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively, and the values in parentheses are *t* statistics based on robust standard errors clustered at the urban level.

For the supply chain efficiency channel, the results were mixed. The coefficient on lagged internal management efficiency, using inventory turnover ($Inventory_{t-1}$) as a proxy, remained negative and significant ($p < 0.1$), providing support for this dimension of the efficiency pathway. However, the coefficient on lagged external coordination efficiency,

measured as supply chain concentration (supplyt-1), was not statistically significant. This suggests that the carbon reduction effect associated with supply chain concentration may be more contemporaneous or more susceptible to unobserved time-varying confounders. Therefore, the primary efficiency mechanism appears to be more robustly driven by improvements in internal operational efficiency (inventory management) rather than changes in the external supply network structure in the prior period.

These robustness checks affirmed the central role of green innovation and internal supply chain efficiency as causal pathways. They also provide a more refined understanding of the efficiency mechanism, highlighting the dimension that shows more persistent effects over time.

4.5. Discussion and Comparison with Literature

The empirical results showed that the Supply Chain Innovation and Application Pilot Program (SCIAPP), which targets inter-organizational digitalization, significantly reduced corporate carbon emissions. This core finding, together with supporting evidence on the dual-channel mechanism and heterogeneous effects, invites a direct comparison with existing research to clarify its contributions.

First, our finding that supply chain-level digital integration reduces emissions aligns with the broader consensus on the positive environmental effect of digitalization and refines its scope. Prior studies primarily documented this relationship at the firm level, focusing on internal digital transformation's impact on operational efficiency and innovation [17,23] or at the regional/macro level, examining the digital economy's aggregate effects [11,53]. By exploiting a policy that explicitly mandates cross-firm digital coordination, we provide causal evidence that digitalization's carbon abatement potential extends beyond a firm's boundaries. The incremental effect captured by our DID design suggests that the systemic benefits of reducing inter-organizational friction and enabling chain-wide optimization are substantial and may be overlooked in analyses confined to a single entity.

Second, the validation of a dual-channel mechanism involving supply chain efficiency and green innovation integrated and tested theoretical pathways that have often been examined in isolation. Previous research has highlighted either the efficiency gains from digitalization, such as improved inventory management [35,36], or its role in fostering innovation [12,17]. Our study bridges these perspectives, showing they are not mutually exclusive but complementary in the context of supply chain digitalization. This supports and operationalizes the theoretical integration of transaction-cost economics and the resource-based view [20,21], suggesting that efficiency savings (reduced transaction costs) create the resources and stability necessary for investing in green innovation, which in turn reinforces long-term systemic efficiency.

Third, the heterogeneity analysis offers nuanced insights that resonate with and specify the contingent value of digitalization policies. The stronger effects observed in state-owned enterprises (SOEs) corroborate their unique role as policy implementers and "chain leaders" in China's institutional context, a finding that aligns with research on the differential behavior between SOEs and non-SOEs in environmental governance. The more pronounced results in the manufacturing sector underscore the tangible, physical nature of its supply chains, where digital coordination can directly curb emissions from material, energy, and logistics flows. These results contrast with those from less emission-intensive sectors. This is a point that is not sufficiently emphasized in the extant literature on the digital economy. Furthermore, the greater carbon reduction in firms with higher pre-existing digital maturity underscores the role of absorptive capacity, indicating that digital infrastructure and skills are critical complements to policy shocks for achieving environmental goals.

In summary, this study confirmed the carbon mitigation potential of digitalization while delineating its specific operation at the supply-chain level. It advances the literature by providing causal evidence for systemic, inter-firm effects, empirically unifying efficiency and innovation pathways, and identifying the firm- and sector-level conditions under which such policies are most effective.

5. Conclusions, Policy Implications, and Future Research

5.1. Conclusions

This study makes several key contributions to the literature on digitalization and environmental governance. Theoretically, it advances the field by integrating transaction-cost economics and the resource-based view to develop and test a novel dual-channel framework (efficiency and innovation) that explains how supply chain-level digitalization reduces emissions. This approach moves beyond firm-centric analyses. Methodologically, it demonstrated the value of using the implementation of the SCIAPP as a quasi-natural experiment, providing robust causal evidence at the firm level and offering a blueprint for leveraging policy shocks to study the systemic impacts of digital transformation. Empirically, it not only confirmed a carbon mitigation effect but also uncovered critical heterogeneous effects across different forms of governance, ownership, and different industries, thereby providing nuanced evidence for targeted policy design.

The key findings are as follows:

- (1) The SCIAPP significantly reduced corporate carbon emissions. This conclusion remained robust after controlling for endogeneity and conducting robustness tests.
- (2) The carbon emission reduction effect of supply chain digitalization varies across firms differing in governance level, digitalization level, industry, and ownership type. Horizontally, supply chain digitalization facilitates sustained carbon emission reductions in firms with higher governance levels and deeper digitalization. Vertically, the policy's effects are more pronounced in state-owned enterprises and manufacturing firms.
- (3) The mechanism analysis indicates that enhancing supply chain efficiency and strengthening corporate innovation capacity are the two primary pathways through which supply chain digitalization enables corporate carbon emission reduction.

This study, using the quasi-natural experimental context of the implementation of the SCIAPP, demonstrated that supply chain digitalization significantly mitigates corporate carbon emissions. It further revealed a dual-channel mechanism involving efficiency gains and green innovation. This conclusion complements and extends the existing literature in three key aspects:

- (1) At the micro level, this study validated and deepens our understanding of the primary effect of digitalization on carbon reduction. Li et al., using data from 269 prefecture-level cities in China, found that the digital economy can reduce regional carbon emissions through green technological innovation [54]. However, their research was performed at the macro city level, making it difficult to identify corporate heterogeneity. This study lowered the research granularity to the firm level. Using panel data from A-share listed companies between 2013 and 2022, it confirmed that the carbon emission-suppressing effect of supply chain digitalization is more pronounced in firms with high governance levels and high digital maturity, providing micro-level evidence for macro-level conclusions.
- (2) Regarding mechanisms, the existing literature examined the pathways through which digitalization affects carbon emissions either by examining green technological innovation mechanisms [17] or supply chain efficiency mechanisms [35]. This study constructed a dual-mechanism framework for carbon reduction through efficiency

enhancement and green innovation. The empirical findings reveal that supply chain digitalization reduces carbon emissions through two pathways: by improving supply chain efficiency and by strengthening enterprises' green technological innovation capabilities. This expands the theoretical boundaries of digital carbon reduction mechanisms.

- (3) In terms of its institutional context, this study used the implementation of the SCIAPP as a quasi-experimental setting. It pioneers the analysis of the effects of policy shocks on corporate supply chain digitalization processes to verify the carbon reduction effects driven by policy interventions. This adds to the discussion raised by Song et al. [18] on whether institutional arrangements influence digitalization-driven emissions reductions, providing micro-level evidence on the policy–firm–carbon emissions relationship within China's institutional framework.

5.2. Policy Implications

- (1) The coverage of the SCIAPP should be gradually expanded. Given the significant effectiveness of the pilot policies in reducing corporate carbon emissions, the government should seize this opportunity. On the one hand, it should guide enterprises in undertaking supply chain digitalization, foster modern supply chain management concepts among businesses, and incentivize the application of cutting-edge digital technologies such as the Internet of Things, blockchain, and big data at critical junctures within supply chains. This will comprehensively enhance supply chain efficiency and innovation capabilities. Moreover, the carbon emissions regulatory framework should be improved by strengthening monitoring, reporting, and verification of corporate emissions. The carbon emissions trading market should be refined to incentivize voluntary reductions through market mechanisms, and tax incentives should be offered to enterprises demonstrating outstanding performance to create positive reinforcement. While prudently expanding the scope of the SCIAPP, the guiding and exemplary effects of the pilot policies should be fully leveraged. Core enterprises should be guided to actively assume leadership responsibilities within supply chains and coordinate digital resources and technological R&D, and enterprises along the chain should be encouraged to break down information silos. Through collaborative operations, management efficiency and resource utilization should be improved, thereby reducing carbon emissions and providing crucial support for driving economic growth with enhanced quality.
- (2) Tiered and targeted policies should be formulated considering heterogeneous effects. The findings reveal that the carbon reduction effect varied significantly across firms with different characteristics. Therefore, policy design should move beyond a “one-size-fits-all” approach and align with these heterogeneities to maximize impact. For SOEs and manufacturing firms, which demonstrate the most significant effects, policy should empower them as “chain leaders”. Integrating supply chain digitalization and emission-reduction targets into SOE executive performance evaluations is recommended, along with concentrated R&D support for manufacturing firms to develop sector-specific digital solutions. For enterprises with higher governance standards and deeper digital maturity, the other groups that benefit the most, policy should recognize them as “transmission hubs”. Providing priority incentives to drive digital and low-carbon standards through their supply networks, creating positive spillovers, is also recommended. For enterprises with lower governance standards or those who embark on digitalization later, greater guidance and support should be provided to facilitate their gradual transition toward low-carbon, high-efficiency operations. This includes public technical assistance, subsidized consulting for digital roadmaps,

and capacity-building programs to prevent a widening “digital divide”. Enterprises should be encouraged to strengthen internal governance, establish oversight and evaluation mechanisms, and enhance their focus on social responsibility and sustainable development to lay the groundwork for supply chain digitalization. Concurrently, support for enterprises’ supply chain digitalization should be intensified, including through technical training, financial assistance, and tax incentives, to help them elevate their digital capabilities.

- (3) Synergy and efficiency within the supply chain should be promoted. On the one hand, information sharing and collaboration among upstream and downstream partners should be fostered, and digital technologies should be used to optimize resource allocation and enhance overall supply-chain efficiency. Public platforms should be established to connect all supply-chain segments, reduce transaction costs, and accelerate the diffusion of green and low-carbon technologies. This is especially important in the manufacturing sector, where the effects are most pronounced. It is therefore recommended that initiatives for the development of industry-specific digital platforms for logistics and inventory synchronization be given priority. On the other hand, firms should be provided help in integrating inventory management with digital technologies to advance supply chain digitalization and enhance resilience and stability.
- (4) Corporate innovation capabilities should be enhanced. Internally, firms should be encouraged to increase R&D spending, especially in green and low-carbon technologies, intelligent manufacturing, and big data analytics. This will help reduce supply-chain carbon emissions. The evidence shows that firms with higher digital maturity exhibit more robust innovation responses. Consequently, policy can target R&D grants and tax credits to encourage digital and green innovation. The disclosure of innovation activities should be improved to reduce information asymmetry between external investors and supply-chain partners and to strengthen mutual trust. Externally, governments and capital markets should support corporate innovation. To accelerate the commercialization of research outputs, governments should establish dedicated R&D funds and strengthen university–industry collaboration. They should also act as neutral facilitators, sending positive signals to capital markets to ensure that firms can access external financing for innovation.

5.3. Limitations and Future Research

This study has two main limitations. First, in terms of research design, the sample focused on A-share listed companies in China from 2013 to 2022. Their higher governance standards and resource endowments may limit the generalizability of the findings to non-listed SMEs, which form a substantial part of the industrial ecosystem. Furthermore, the measurement of core variables—employing a policy dummy for digitalization and manually collected, self-reported carbon data—may not fully capture the intensity of digital transformation and could introduce measurement errors. Second, regarding the temporal scope, the sample period precedes recent technological advances like generative AI in supply chains, potentially limiting insights into the policy’s long-term dynamics. The analysis also did not explicitly account for interactions between digitalization and external shocks, which could moderate the estimated effects.

Future research could proceed in two key directions. Firstly, the scope could be extended and the methodology refined. This could involve expanding the sample to include non-listed firms or conducting cross-country comparisons to test the external validity of the findings. Secondly, the measurement of constructs could be enhanced by developing a multidimensional index of supply chain digitalization and by incorporating

objective emission data from environmental agencies. Alternatively, the investigation into mechanisms and systemic effects could be deepened. Researchers could examine more complex pathways, such as chain-mediation models, and include moderators like policy intensity or market competition. As longer time-series data become available, analyzing the time-varying nature of carbon-reduction effects and investigating inter-firm spillovers would offer a more comprehensive understanding of systemic impacts.

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Abbreviations

The following abbreviations are used in this manuscript:

SCIAPP	Supply Chain Innovation and Application Pilot Program
DIGI	Digitalization Index
SOEs	state-owned enterprises

Appendix A. Keyword List for Digitalization Index (DIGI) Construction

This appendix provides the complete keyword list used to construct the firm-level Digitalization Index (*DIGI*), which measures a firm's inherent digital maturity and was employed in the heterogeneity analysis (Section 4.3.3). The construction method follows the text-analysis approach established in prior literature [48].

Index Construction Method:

The index was created by analyzing the “Management Discussion and Analysis” sections of corporate annual reports. Using textual analysis in Python (with the Jieba toolkit for word segmentation), we identified and counted the frequency of keywords related to digitalization. The final composite DIGI score for each firm-year is a weighted sum of standardized keyword frequencies across four dimensions, with the weights determined using the entropy method.

Keyword List by Dimension:

1. Digital Technology Application

Core Concepts: Data, Digitalization, Big Data

Keywords: Cloud Computing, Cloud IT, Cloud Ecosystem, Cloud Services, Cloud Platform, Blockchain, Internet of Things (IoT), Machine Learning, Data Management, Data Mining, Data Network, Data Platform, Data Center, Data Science, Digital Control, Digital Technology, Digital Communication, Digital Network, Digital Intelligence, Digital Terminal, Digital Marketing.

2. Internet Business Model

Core Concepts: Internet, E-commerce

Keywords: Mobile Internet, Industrial Internet, Internet Solutions, Internet Technology, Internet Thinking, Internet Action, Internet Business, Internet Mobile, Internet Application, Internet Marketing, Internet Strategy, Internet Platform, Internet Model, Internet Business Model, Internet Ecosystem, E-commerce, Internet+, Online-to-Offline (O2O), B2B, C2C, B2C, C2B.

3. Intelligent Manufacturing

Core Concepts: Intelligent, Automation, CNC, Integration

Keywords: Artificial Intelligence (AI), Advanced Intelligence, Industrial Intelligence, Mobile Intelligence, Intelligent Control, Intelligent Terminal, Intelligent Mobility, Intelligent Management, Smart Factory, Intelligent Logistics, Intelligent Manufacturing, Intelligent Warehousing, Intelligent Technology, Intelligent Equipment, Intelligent Production, Intelligent Connected Systems, Automatic Control, Automatic Monitoring, Automatic Detection, Automatic Production, Integrated Solutions, Industrial Cloud, Future Factory, Intelligent Fault Diagnosis, Lifecycle Management, Manufacturing Execution System (MES), Virtualization, Virtual Manufacturing.

4. Informatization

Core Concepts: Information, Informatization, Networking

Keywords: Information Sharing, Information Management, Information Integration, Information Software, Information System, Information Network, Information Terminal, Information Center, Industrial Information, Industrial Communication.

Source Reference:

The selection and categorization of keywords are adapted from the methodology established by Zhao [48] for measuring corporate digital development.

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