

Article

Bridging Digitalization and Greening: The Effect of Supply Chain Innovation Policies on Firms

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Abstract

Promoting the coordinated development of digitalization and greening has become an important pathway for firms to achieve high-quality growth. Using panel data for A-share listed firms in China's Yangtze River Basin from 2010 to 2022, this study examines the effect of supply chain innovation policy on firms' digital-green development. We measure the synergy between digitalization and greening using a composite system synergy approach and identify the policy effect through a quasi-natural experiment based on the supply chain innovation policy, combined with a synthetic difference-in-differences model. The results show that the policy significantly improves the coordinated development of firm digitalization and greening, and the findings remain robust across a series of tests. Mechanism analysis indicates that this effect operates through three channels: easing financing constraints, increasing supply chain diversification, and promoting industrial chain modernization. Moderating effect tests further show that supply chain efficiency, supply chain resilience, and entrepreneurship strengthen the policy's positive effect on digital-green development. Heterogeneity analysis suggests that the policy effect varies systematically with firm size, market competitiveness, and information asymmetry. This study provides micro-level evidence on how supply chain innovation policy can promote firms' digital-green transformation and offers useful implications for policies aimed at improving firm competitiveness and supporting sustainable development.

Keywords: supply chain innovation policy; collaborative development of digitalization and greening among enterprises; supply chain diversification; industry chain modernization; supply chain resilience; composite system synergy algorithm; SDID

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1. Introduction

Countries worldwide are seeking to strengthen supply chain development, albeit with differing policy priorities. The United Kingdom emphasizes collaboration and resilience, the United States prioritizes resilience and security, and Germany focuses on digitalization and sustainability. Against this backdrop, China's Supply Chain Innovation and Application Demonstration City Policy (SCIN) represents a distinctive, integrated approach to fostering supply chain innovation. As a bridge between supply and demand, the supply chain is central to economic stability, and its security and reliability are critical to performance at both national and firm levels [1]. With the rapid diffusion of the Internet

of Things, big data, and artificial intelligence, supply chain innovation has become increasingly important not only for enhancing firm competitiveness but also for advancing sustainable development [2]. This raises an important question: can supply chain innovation policy also promote the coordinated development of enterprise digitalization and greening?

This question is particularly important in China, where traditional supply chain models have become increasingly inadequate for supporting high-quality enterprise development. In response, the Ministry of Commerce, together with eight other government agencies, launched the SCIN policy in 2018. The policy acts as a coordinated government intervention, providing financial subsidies for technology adoption, regulatory guidance on green production, and digital infrastructure support to pilot cities. By aligning fiscal, regulatory, and technological measures, the government reduces transformation risks, facilitates inter-firm collaboration, and promotes the integration of digitalization and greening along supply chains. Since then, supply chain innovation has attracted growing scholarly and managerial attention in business-to-business marketing and production research [3]. Existing studies suggest that supply chain innovation can improve coordination across supply chain links, facilitate resource integration, optimize business processes, and enhance information and knowledge sharing [4,5]. It can also improve firms' innovation efficiency [6] and ease the resource pressures associated with transformation by supporting R&D investment and access to finance [7]. At the same time, however, supply chain innovation is costly, risky, and investment intensive [8]. Firms undertaking supply chain digitalization must invest heavily in process redesign, operating model upgrading, product intelligence, and service innovation [9]. Such transformation requires firms to redesign existing processes and improve operational precision [10] while also upgrading products and services to strengthen market competitiveness and customer value [11,12]. These investments are essential for long-term transformation, but they do not necessarily translate automatically into the joint advancement of digitalization and greening [13]. Whether and how supply chain innovation policy promotes this dual transformation therefore remains an open empirical question.

This issue is further amplified by the growing strategic importance of digitalization and greening in enterprise development. Digital technologies are increasingly regarded as a key driver of productivity improvement and industrial upgrading [14,15], whereas greening addresses environmental pressures through low-carbon, energy-efficient, and environmentally responsible practices [16]. Prior studies demonstrate that digitalization can facilitate more sustainable industrial development [17], while green transformation has become an important trend in the information era [18]. At the firm level, however, the two processes differ in orientation. Digital transformation often emphasizes responsiveness, efficiency, and short-term competitiveness, whereas greening places greater weight on environmental stewardship, social responsibility, and long-term sustainability [19,20]. Precisely because these two logics differ, understanding how they can be developed in a coordinated manner has become increasingly important. The integration of digital intelligence and green development is now widely regarded as a key pathway toward modern industrial transformation and sustainable firm growth [21,22].

Despite this growing interest, the existing literature leaves several important gaps. First, although prior research has examined the effect of digitalization on greening, limited attention has been paid to the coordinated development of their at the firm level. Second, few studies have examined whether SCIN policy can serve as an external institutional driver of digital–green synergy. Third, the mechanisms through which such policy effects operate remain poorly understood. These gaps are theoretically and practically important, as firms often face simultaneous pressures to improve efficiency, strengthen resilience, and meet sustainability expectations. Against this background, the SCIN policy provides

a useful quasi-natural experiment for identifying whether it promotes the coordinated development of enterprise digitalization and greening, and through which channels this effect occurs.

This study makes several significant and distinct contributions to the existing literature, which are elaborated as follows: 1. Comprehensive Assessment of Synergistic Transformation: Unlike prior studies that mainly examine the influence of digitalization on greening in isolation, our research provides a systematic and quantitative evaluation of the synergy between enterprise digital transformation and greening. By employing a composite system synergy algorithm, we accurately measure the collaborative development of these two subsystems, filling a gap in the empirical analysis of digital–green integration at the enterprise level. This approach extends beyond conventional analyses focused solely on policy effectiveness or individual factors. 2. Systems Theory Perspective on Enterprise Digital–Green Fusion: We conceptualize digital transformation and greening as interdependent subsystems within a composite system, applying systems theory to explore their interaction dynamics. This perspective allows for a deeper understanding of how the interplay between digital and green initiatives affects enterprise evolution, providing methodological novelty over existing literature that predominantly uses linear or single-dimensional approaches. 3. Identification of Policy Mechanisms via Digital Ecology Lens: While earlier studies typically focus on the self-effectiveness of supply chain policies, our study investigates how SCIN policies promote synergistic development through specific mechanisms such as alleviating financing constraints, enhancing supply chain diversification, and modernizing industrial chains. By integrating a digital ecology framework, we uncover previously unexplored pathways through which policy influences enterprise outcomes. 4. Expanded Multidimensional Heterogeneity Analysis: Our research further differentiates itself by examining heterogeneity across enterprise size, competitive capability, and information asymmetry. This multi-angle analysis highlights how the impact of SCIN policies on digital–green synergy varies across firm types, offering actionable insights for policymakers and managers. This contrasts with prior studies that often limit heterogeneity analysis to a single dimension or neglect it entirely. 5. Empirical Evidence from a Quasi-Natural Experiment: By leveraging the SCIN policy implementation in China as a quasi-natural experiment and applying a synthetic double difference (SDID) model, we provide robust causal evidence of the policy’s effect on the collaborative development of digitalization and greening. This methodological contribution strengthens the validity and replicability of our findings compared to prior observational studies lacking such exogenous shock designs. These enhancements ensure that each contribution is explicitly connected to novel methods, data, or theoretical insights, distinguishing our study from the existing body of research.

2. Literature Review

2.1. Supply Chain Innovation Policy for Collaborative Development of Enterprise Digitalization and Greening

In conventional supply chain systems, enterprises often grapple with insufficient information governance mechanisms, which hinder their ability to track product distribution in real time. This challenge leads to delayed decision-making, inefficient resource allocation, and significantly impedes improvements in production efficiency within organizations [1]. Although enterprises often maintain highly inventory levels to overcome the continuous problems of instability and volatility in market demand for smooth supply, this intensifies capital strain and storage costs, thereby reducing production efficiency as reiterated by Saberi, Kouhizadeh et al. in 2019 [23]. In addressing these persistent issues, supply chain innovation policy, or SCIN, proves instrumental. This policy is now in a

place where it can promote the deep integration of the next generation of digital technologies and advanced information systems, enabling real-time monitoring, intelligent decision-making, and effective collaboration in each component of the supply chain. This transformative change enhances flexibility enterprises in responding to external fluctuation and improves the accuracy of production planning and inventory control [24]. Consequently, enterprises can effectively reduce risks associated with overcapacity while adeptly managing potential disruptions supply chain [25], thereby laying a solid foundation for sustainable growth. From the resource-based view, innovations in supply chain management enhance organizations' capacity to integrate resources, particularly with respect to supply chain dynamics. This, in turn, enhances resource allocation and coordination capabilities, thereby improving efficiency, as noted by Nandi, Sarkis et al. (2021) [26], and supporting the collaborative development of digitalization and greening. Dynamic capability theory further explains that SCIN enhances flexibility, responsiveness, and synergy between upstream and downstream operations, as noted by Gupta, Kumar et al. (2021) [27]. These innovations address the inherent challenges of high costs, inefficiencies, and excessive resource wastage prevail in traditional supply chain structures. With real-time monitoring, smart decision-making systems, and a culture of collaborative effectiveness, these innovations help to significantly save on unnecessary expense and improve efficiency in operations, utilizing resources optimally [28]. In this way, the synergy between digital transformation and an enterprise's efforts toward sustainability is strengthened. According to transaction cost theory, innovation in the supply chain is crucial for alleviating information asymmetries while enhancing transparency and communication efficiency [29,30]. By enabling comprehensive and effective information sharing, these innovations can lower transaction costs, optimize resource allocation, and mitigate financial challenges faced by businesses [31]. Moreover, enhancements in supply chain processes accelerate the external dissemination of enterprises knowledge resources, providing essential financial and resource support for both digital transformation and green upgrades [32], thereby fostering the development of sustainable corporate strategies and business models. SCIN policy does not merely promote digitalization and greening in parallel: digitalization focuses on short-term efficiency and returns, while greening emphasizes long-term emissions reduction and compliance. Under resource constraints such as funding and manpower, these two objectives compete with one another. The policy alleviates this conflict by expanding resource supply, optimizing supply chain networks, and reducing coordination costs, thereby shifting digitalization and greening from competing for resources to complementary collaboration. Organizational capability theory posits that supply chain innovations enhance collaborative practices within enterprises [27] while also achieving optimal energy allocation, which significantly boosts green production efficiency. Additionally, these innovations improve the capacity to manage pollution and carbon emissions and enhance the effectiveness of green initiatives [33]. Internally, SCIN promotes the thorough sharing and integration of innovative resources [7]. Externally, the integration of digital technologies enhances engagement with suppliers, government entities, and customers, addressing their innovation needs [34] and supporting the "digital-green convergence" within enterprises. Collectively, these advancements steering organizations toward a contemporary industrial paradigm characterized by dual synergistic growth. Therefore, we propose the following hypothesis:

Hypothesis 1: *SCIN policy improves enterprises DGS.*

2.2. Supply Chain Innovation Policy Promote Collaborative Development of Enterprise Digitalization and Greening by Financing Constraints

Sufficient access to capital is critical for enterprises transformation. However, the process of transformation and upgrading necessitates substantial long-term investment and is often characterized by risk and uncertainty, leading to heightened external financing constraints for enterprises [35]. Such constraints limit organizations' ability to pursue transformation initiatives. The challenge is exacerbated by information asymmetry, which prevents external stakeholders from accurately evaluating the future benefits of these transformations. Consequently, companies engaging in innovative practices may be undervalued [36], resulting in adverse selection among creditors and investors and subsequently dampening enterprises' motivation to embrace digital and sustainable practices [37]. The transition to digital platforms within supply chains is facilitated by the adoption of intelligent supply chain systems, which enhance contractual frameworks [38]. These innovations considerably reduce costs associated with information search, negotiation processes, and transaction monitoring. A notable feature of SCIN is its networked structure, which significantly lowers transaction conversion costs [39]. This structural advantage is especially crucial for SMEs, enabling them to access precisely the amount of information required by financial institutions. In this respect, it plays the role of making capital allocation more effective and helps in securing internally generated finances for specialized production activities [40]. As a result, both the risk premiums anticipated by investors and the recovery risks associated with creditor debts are decreased, enhancing the capacity of enterprises to secure external funding [41]. Improved external financing conditions provide companies with stable and reliable access to capital [42]. This influx of financial resources promotes knowledge spillovers within organizations, offering essential support for initiatives centered on the collaborative development of digitalization and greening. Therefore, from the perspective of the resource-based view, financing constraints represent a key obstacle to firms' acquisition of strategic resources, directly hindering the simultaneous advancement of both digital and green transitions. By alleviating financing constraints, SCIN policy effectively injects incremental capital into firms' "resource pools" from external sources, thereby transforming what was originally a zero-sum resource competition into a scenario where coexistence becomes possible. In summary, supply chain innovation serves as a vital catalyst for the integrated advancement of enterprise digitalization and sustainability by alleviating financing constraints.

Building upon this analytical foundation, the following assumption is formulated:

Hypothesis 2: *SCIN policy improves enterprises DGS by mitigating SA.*

2.3. Supply Chain Innovation Policy Promotes Collaborative Development of Enterprise Digitalization and Greening by Increasing Supply Chain Diversity

The extent of diversification in a supply chain reflects the degree to which a firm's connections with suppliers and customers are concentrated within a limited set of entities. Several critical factors determine whether a centralized or diversified structure is more suitable for a firm's supply chain. These include the dependence on a small number of suppliers for procurement and the concentration of sales among a few key customers [43]. This study employs the concentration of supply and demand as a quantitative measure to assess the diversification profile of enterprises' supply chains. To evaluate demand-side diversification, the research calculates the ratio of sales revenue derived from the top five customers relative to the firm's total operating revenue. Supply-side diversification is simultaneously measured by the ratio of acquisitions made from the enterprise's five largest suppliers in comparison to its overall operating revenue [44]. After standardization, an

arithmetic mean is then computed for an index summarizing general supply chain diversification. This holistic metric serves as a basis for identifying the diversification status of enterprises [45].

It serves as a key factor that influences the diversified development of an enterprise supply chain. The first point of pilot work for SCIN is to accelerate digital transformation and convert an enterprise supply chain into an intelligent system using big data platforms to share information with networks and intelligent, collaborative operation [24]. Such systems enable enterprises to overcome the “gravitational effect” that traditional supply chains often have, which normally impedes the influence of geographical boundaries. This innovation expands the geographical scope of the supply chain and boosts initiatives towards diversification [29]. A diversified supply chain enhances enterprises market exposure while reducing related market risks. It will enhance the flow and cooperation of different products or services by creating greater integration in all aspects of the supply chain network. This approach will lower the transaction costs from outside partners with regard to both upstream and downstream transactions effectively [31]. Such integration not only improves the efficiency of supply chain management [32] but also forms the basis for the experimental and application of different business models. Furthermore, a diversified supply chain framework reduces the dependence of an enterprise on any one constituent in the supply chain [46]. This diversification, which is strategic to the production and operational activities, thus reduces the possible impacts of risks on it, such as supply interruption and price volatility [47]. Consequently, firms enhance their resilience and agility, which increases their overall supply chain robustness. In such strong environments, diversification of sources of procurement and expansion of sales targets gives the firms flexibility and less dependency on any given link [48]. Such stabilization of supply chain relationship translates into more stable cash flows, which are essential for sustaining the current operations and financing expansion into new markets [49]. According to transaction cost theory, the SCIN policy reduces the costs of searching for, negotiating with, and monitoring new partners through a smart platform; meanwhile, resource dependence theory posits that firms proactively alter their dependency structures to reduce uncertainty. The integration of these two theories explains why the policy promotes diversification: lower costs enable firms to break away from centralized networks, while diversification mitigates the risks associated with reliance on a single path to digital transformation. In summary, SCIN creates favorable conditions for the coordinated development of digitalization and greening within enterprises, enhancing supply chain diversification that drives continuous innovation and facilitates high-quality growth.

Hypothesis 3: *SCIN policy improves enterprises DGS through SCD.*

2.4. Supply Chain Innovation Policy Promotes Collaborative Development of Enterprise Digitalization and Greening by Improving the Modernization of the Industrial Chain

This is underlined by the study by Zhang Hu et al. (2022) [50], which underscores the need to evaluate the modernization level of industrial chains in China. Modernization, in this case, entails optimizing and upgrading traditional structures using advanced technologies, effective management strategies, and innovative business models. The bottom line is to establish the competitive edge and collaborative scope of these industrial chains in that specific context in China [51]. Big data exploitation facilitates SCIN in designing smarter supply chain infrastructure that encourages data exchange and coordination [52]. This digital transformation constitutes a foundational element for the evolution and expansion of industrial chains, enhancing production, supply, and sales processes [49] while significantly reducing costs associated with labor, logistics, and information exchange.

Moreover, this transformation shifts industrial production models toward intelligent paradigms, thus markedly improving the efficiency of the entire industrial chain [53]. Within this framework, SCIN serves as a critical link across different tiers of the industrial chain [54], optimizing resource allocation, enhancing information interoperability, and fostering collaborative interactions. This synergistic approach substantially enhances industrial cooperation and drives the modernization of industrial chains [55]. On one hand, the modernization of industrial chains improves resource utilization, reduces energy consumption, minimizes waste, and promotes the recycling of limited resources, thus providing a strong foundation for sustainable industrial development [56]. The increased efficiency in resource use not only generates cost savings but also aligns with the collaborative development of digitalization and greening within enterprises [57]. On the other hand, industrial chains modernization enhances the transformative processes that make the industries sensitive to current market demands and, consequently, more competitive. Waldron, Brown et al., 2010 [58] add that SCIN also promotes the integration of digital technologies with traditional sectors, hence allowing for technological cooperation and innovation among enterprises along the industrial chain. This drives the adoption of green and low-carbon technologies [59] and advances the digitalization and sustainability of companies. From the perspective of innovation ecosystem theory, the modernization of industrial chains does not involve directly providing resources to enterprises but rather involves building public platforms that integrate digital and green technologies, enabling enterprises to achieve collaborative upgrades at lower cost. This mechanism embodies the logic of empowerment at the ecosystem level. In summary, SCIN not only optimizes resource allocation and enhances industrial chain efficiency but also fosters collaboration and stimulates green technology innovation. This dynamic supports the establishment of a smart, sustainable, and environmentally friendly industrial ecosystem. Looking ahead, as technologies for SCIN evolve and gain traction, the modernization of industrial chains in China will accelerate, paving the way for synergistic advancements in both enterprise digitalization and sustainability.

Hypothesis 4: *SCIN policy improves corporate DGS through ICM.*

2.5. Supply Chain Efficiency Plays a Positive Moderating Role in Supply Chain Innovation Policy to Promote Collaborative Development of Enterprise Digitalization and Greening

Fu-Ling Zhang (2024) [60] suggests that SCIN can improve supply chain efficiency by reducing costs and enhancing collaborative relationship among enterprises in the chain, thereby reinforcing the marginal benefits of digital inputs. Furthermore, big data-driven demand forecasting and route optimization significantly shorten logistics response cycle, cloud computing-supported virtual trading platforms reduce coordination friction among node enterprises, and AI-enabled smart warehousing systems enhance resource turnover efficiency. This chain-wide efficiency improvement not only buffers the operational uncertainty during digital transformation but also facilitates the visualization of environmental footprints through real-time data sharing mechanisms, thereby providing a precise entry point for green process innovation. Based on this, this paper argues that supply chain efficiency positively moderates the effect of SCIN policies on enterprise digital and green transformation, and therefore proposes the following hypothesis:

Hypothesis 5: *Stock plays a positive moderating role in the mechanism of action of SCIN policy on increasing firms' DGS.*

2.6. Supply Chain Resilience Plays a Positive Moderating Role in Supply Chain Innovation Policy to Promote Collaborative Development of Enterprise Digitalization and Greening

Digital technology reconfigures the supply chain network topology by optimizing information flows, while the resilience mechanism forms a dynamic buffer layer, effectively alleviating the organizational inertia and path dependence in the process of technology diffusion. A highly resilient supply chain can transform technological spillovers generated by digital transformation into cross-organizational learning kinetic energy by enhancing collaborative response capabilities among nodes [61], and this knowledge transfer mechanism breaks through the traditional linear transmission mode to form a networked innovation ecosystem. In the dimension of green transformation, the elastic buffer capacity of resilient supply chains [62] provides enterprises with the space for trial and error, enabling environmental technology innovation to be iteratively upgraded under controllable risk conditions. Therefore, the following hypothesis is proposed:

Hypothesis 6: *Resilience plays a positive moderating role in the mechanism of action of SCIN policy on increasing firms' DGS.*

2.7. Entrepreneurship Plays a Positive Moderating Role in Supply Chain Innovation Policy to Promote Collaborative Development of Enterprise Digitalization and Greening

Established studies demonstrate that entrepreneurship is a key driver of economic development [63] and significantly affects the effectiveness of enterprise digital transformation [64]. Supply chain digital integration is not just a transformation of the original system, but also an innovative process of resource integration and reorganization, which fits with the core innovative dimension of entrepreneurship. Driven by entrepreneurship, enterprises actively use digital technology to deepen cooperation with supply chain partners, overcome digital supply chain integration challenges, enhance cooperation efficiency, and promote performance growth. Simultaneously, the diffusion of entrepreneurship enhances the awareness of risk taking, helps enterprises consolidate the accumulation of supply chain integration, accelerates the internalization of external knowledge and information, and realizes the knowledge spillover effect. Therefore, we propose the following hypothesis:

Hypothesis 7: *Entrepreneurship plays a positive moderating role in the mechanism of SCIN policy's effect on improving enterprise DGS.*

2.8. Integrated Theoretical Framework

Digital and green transformation generate resource competition and logical tensions within enterprises. SCIN policies facilitate synergy between the two by resolving this tension through three parallel pathways grounded in distinct theoretical foundations. First, the resource supply pathway, based on the resource-based view, operates through alleviating financing constraints—equivalent to injecting external resources—thereby breaking the zero-sum competition between digitalization and greening. Second, the structural restructuring pathway, integrating transaction cost theory and resource dependence theory, operates through reducing transaction costs and alter dependency structures, thereby promoting diversification to disperse transformation risks and integrate heterogeneous resources; Third, the ecosystem empowerment pathway, grounded in innovation ecosystem theory, involves building public platforms for digital–green convergence, enabling enterprises to achieve low-cost co-evolution. Additionally, supply chain efficiency, supply chain resilience, and entrepreneurship exert positive moderating effects on the main effect from the perspectives of operational absorption, risk buffering, and strategic leadership, respectively. Figure 1 clearly illustrates the mechanism framework described in the article.

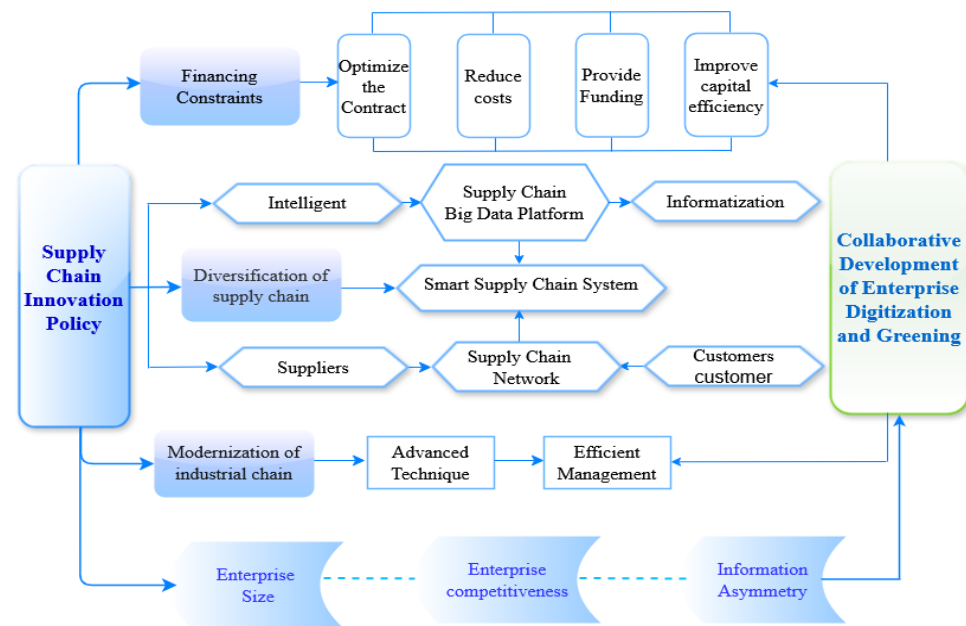


Figure 1. Mechanism diagram.

3. Research Design

3.1. Sample Selection and Data Sources

This study utilizes panel data from 320 publicly listed A-share companies, representing 11 provinces in the Yangtze River Basin, and covers the timeframe from 2010 to 2022. The dataset encompasses essential information for evaluating the degree of synergy between the collaborative development of digitalization and greening, in addition to various control variables, all extracted from the Cathay Pacific database. Following the methodologies outlined in prior research, the data screening procedure excluded financial institutions, as well as firms designated as ST (special treatment) or PT (special transfer) throughout the study period, along with any entities exhibiting significant data gaps. This careful vetting resulted in a total of 4160 valid observations. To address potential biases from outliers, the primary continuous variables were truncated at the 1st and 99th percentiles.

The year 2018 is significant as it marks the commencement of supply chain innovation and development, coinciding with the release of the Notice on Pilot Supply Chain Innovation and Application. Accordingly, the timeframe from 2010 to 2017 has been designated as the pre-policy implementation phase, while the period from 2018 to 2022 is recognized as the subsequent control phase following the policy's enactment.

3.2. Models and Methods

3.2.1. Composite System Synergy Algorithm

Building on the work of Wu Caixia (2021) [65], we conceptualize the enterprise digitalization and greening systems as interconnected components that together form a composite system representing the level of synergistic development of digitalization and greening within enterprises. In exploring the key determinants of the system's evolution rate, we introduce a sequential parameter, which serves as a significant indicator for measuring this evolution rate. Importantly, the sequential parameter exerts dual influences on the system: while it can facilitate system evolution, it may impose an inhibitory effect. These opposing effects interact within the system, collectively shaping the overall evolution of the composite system of digitalization and greening in enterprises. The specific methodology for calculating these effects is outlined as follows:

Define the composite synergistic system $S = (S_1, S_2, S_3, \dots, S_i)$, where S is the i subsystem; there are two subsystems in this study, namely S_1 and S_2 . S_1 is the enterprise digitalization system and S_2 is the enterprise greening system. Let the subsystem S_i , $i \in [1, k]$; the order parameter of the system is $y_i = (y_{i,1}, y_{i,2}, \dots, y_{i,n})$, where $n \geq 1, \beta_{i,j} \leq y_{i,j} \leq \alpha_{i,j}, j \in [1, n]$. Generally speaking, the system ordering degree reflects the degree of ordering of the system, with two types of positive and negative, defined when $j \in [1, m]$, $y_{i,j}$ is a positive indicator, its value has a positive impact on the system ordering degree; when $j \in [m+1, n]$, $y_{i,j}$ is a negative indicator, its value size has a negative impact on the system ordering degree; $\mu_i(y_{i,j}) \in [0, 1]$ represents the contribution value of the indicator to the ordering degree of the subsystem, and the larger the value, the greater indication that $y_{i,j}$ contributes to the ordering degree of the subsystem. $\mu_i(y_i)$ denotes the contribution value of all indicators of the subsystem to the orderliness of the composite system.

Based on the servitude principle, the system ordering degree is calculated as follows:

$$\mu_i(y_{i,j}) = \begin{cases} \frac{y_{i,j} - \beta_{i,j}}{\alpha_{i,j} - \beta_{i,j}}, j \in [1, m] \\ \frac{y_{i,j} - \beta_{i,j}}{\alpha_{i,j} - \beta_{i,j}}, j \in [m+1, n] \end{cases} \quad (1)$$

Using the geometric mean method, the subsystem ordering degree is calculated as:

$$\mu_i(y_i) = \sqrt[n]{\prod_{j=1}^n \mu_i(y_{i,j})} \quad (2)$$

Finally, in order to assess the stability of the system during the observation period, the time dimension is also introduced. Setting the value of the subsystem's order change at the initial moment t_0 as $\mu_i^0(y_i)$, and the value of the order change at any t_n moment as $\mu_i^n(y_i)$, the geometric mean method is used to calculate the degree of synergy of the composite system of enterprise digitalization and greening development, which is recorded as cor , and the direction and intensity of the subsystem's role in the development trend of the composite system as a whole is expressed through ω . The operating state of the composite system is not only profoundly affected by the interactions among the subsystems but also by the complex effects of the interconnections among the indicators within the subsystems. Therefore, when calculating the synergy degree of composite systems, that is, when measuring the degree of composite synergy between enterprise digitalization and green development, we use a more refined mathematical model, which comprehensively considers all the above factors to ensure the accuracy and reliability of the evaluation results. We use the following formula to calculate the degree of synergy of the composite system, that is, the degree of synergy between enterprise digitalization and green development:

$$cor = \omega \sqrt[n]{\prod_{i=1}^n [\mu_i^1(y_i) - \mu_i^0(y_i)]} \quad (3)$$

Of these, $\omega = \min [\mu_{i1}(y_i) - \mu_{i0}(y_i)] / |\min [\mu_{i1}(y_i) - \mu_{i0}(y_i)]|$. For mathematical rigor, the geometric mean is computed on the absolute value of the product of differences $\left| \prod_{i=1}^n [\mu_i^1(y_i) - \mu_i^0(y_i)] \right|$, ensuring that the inputs for the root operation are non-negative. The coefficient ω serves solely as a sign function to indicate the direction of the change in synergy, allowing the final *cor* to range from -1 to 1 while keeping intermediate calculations valid.

In summary, the synergy degree of the composite system is obtained; this is used to measure the level of enterprise digitalization and greening synergistic development, where, the larger its value, the higher the level of enterprise digitalization and greening synergistic development.

3.2.2. Synthetic Double Difference Model

It was expected that combining the principles of synthetic control with those of the double difference approach in what is called an SDID would yield more robust coefficient estimates. This approach overcomes the challenge of unequal intensity in the implementation of policy across the pilot regions by forming a unique treatment group for each experimental cohort, based on specific individual and temporal characteristics. Following the synthetic difference-in-differences framework, for each publicly listed enterprises, a “policy-neutral” control group is created. Enterprises located in the pilot cities are put into the treatment group, with the rest being put into the control group. Then, the analysis calculates DT between treatment and control groups to determine how the policy affected the collaborative development of digitalization and greening initiatives within enterprises. The following model is set:

$$(\hat{\tau}^{sdid}, \hat{\mu}, \hat{\alpha}, \hat{\beta}) = \arg \min_{\tau, \mu, \alpha, \beta} \left\{ \sum_{i=1}^N \sum_{t=1}^T (Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau)^2 \hat{\omega}_t^{sdid} \hat{\lambda}_t^{sdid} \right\} \quad (4)$$

Among them, N signifies the count of participants within the sample, T indicates the time dimension of the sample, Y_{it} represents the DGS of company i in the t -th period, and the dummy variable W_{it} is used to represent whether SCIN is carried out. μ , α_i , and β_t represent constant term, individual fixed effect, and year fixed effect, respectively. τ is the processing effect, ω_i and λ_t represent individual weight and time weight, respectively, and $\hat{\cdot}$ represents the estimated value.

3.3. Model Setting

In 2018, an initiative involving eight divisions of the Ministry of Commerce and various other government agencies launched a nationwide pilot program aimed at the innovation and application of supply chains (SCIN). This SCIN policy functions as an exogenous shock for analytical purposes. To evaluate the effects of this pilot program on SCIN, the study adopts the difference-in-differences (DID) methodology. Accordingly, the following model has been formulated to guide the analysis:

$$DGS_{it} = \beta_0 + \beta_1 Treat_i + \beta_2 Post_t + \beta_3 Treat_i \times Post_t + \gamma X_{it-1} + \delta_i + \mu_t + \varepsilon_{it} \quad (5)$$

The explanatory variable DGS_{it} is the composite synergy of enterprise digitalization and greening of enterprise i in year t . $Treat_i$ is a dummy variable that distinguishes the experimental group from the control group and is assigned a value of 1 if the city where the enterprise is registered is a pilot city for SCIN and application, and 0 vice versa. $Post_t$ is the point in time when the “Supply Chain Innovation and Application City Pilot” policy is implemented, assigned a value of 1 in 2018 and beyond, and 0 before

2018. The interaction term, $DID = Treat_i \times Post_t$, serves as the core explanatory variable; X_{im-1} is the control variable, denoted by δ_i individual fixed effects; μ_t denotes time fixed effects; and ε_{it} is the random error term.

3.4. Definition of Variables

3.4.1. Explained Variable

In order to objectively evaluate the synergistic development of digitalization and greening of listed companies in China, a composite synergistic system of enterprise digitalization and greening is constructed based on the principles of scientific principles and data availability. Referring to Zhou Weihua (2023) [66], the index system of enterprise digitalization and greening composite system synergistic development is constructed as shown in Table 1. Specifically, on the input side of the digitalization system, we use smart investment, while on the output side, we select per capita labor productivity and revenue growth rate. Although these two indicators are operational metrics, existing literature has used them as proxy variables for the effectiveness of digitalization. The rationale is that the application of digital technologies should ultimately manifest as improvements in labor efficiency and business growth. The greening system employs the proportion of green R&D, carbon emissions, and ESG performance—all of which are core indicators in current environmental management research. Furthermore, the composite system synergy algorithm, through multidimensional aggregation and standardization, can to some extent reduce the noise associated with individual indicators.

Table 1. Collaborative development of enterprise digitalization and greening indicator system.

System Type	Level 1 Indicators	Calculation Method
Digitize the system	Intelligent Investment Level	By examining the specific designations of fixed assets and intangible assets, along with their respective values as detailed in the notes accompanying the financial statements of publicly listed companies, we compile a comprehensive total of the investments made in intangible assets and fixed assets pertinent to intelligence
	Labor Productivity Per Capita	Operating income/number of employees
	Operating Income Growth Rate	(Amount of operating income for the current year—Amount of operating income for the same period of the previous year)/(Amount of operating income for the same period of the previous year)
Green system	Green Innovation R&D Percentage	R&D expenses/operating income
	Carbon Emission	Sum of carbon emissions from combustion and fugitive carbon emissions, carbon emissions from production processes, carbon emissions from waste, and carbon emissions from land-use change (conversion of forests to industrial land) of listed companies
	ESG	CSI ESG ratings, which are categorized into nine grades from AAA to C, are assigned a 9-1 score from highest to lowest. Since the ratings are assigned quarterly, and the time unit of this paper is year; the average of four quarters in a year is selected

The digital investment level is derived from firms' disclosures in the notes to financial statements regarding fixed and intangible assets. We manually extracted investments related to artificial intelligence by identifying specific asset items and their corresponding amounts. The total AI-related investment is then divided by the firm's total annual assets to obtain the proportion that represents the digital investment level.

Specifically, intangible assets related to digital transformation are identified based on account names containing keywords such as "intelligent", "software", "system", "information platform", and "data". Corresponding fixed assets include items with names containing "electronic equipment", "computer", and "data equipment". The sum of these items' values, divided by total assets, forms the firm-level digital investment index.

3.4.2. Key Explanatory Variable: DID = Treat × Post

The experimental variable (treat) was chosen to represent the city of business registration for which the SCIN policy is intended; the experimental period variable (post) represents whether or not the SCIN policy has been initiated, with the data defined as before the policy was implemented in 2018 and after the policy was implemented in 2018.

3.4.3. Control Variables

Other economic characteristics affecting the composite synergistic system of digitalization and greening of firms were chosen as control variables, including two jobs (Dual), equity concentration (TOP1) [67], total asset turnover (ATO), Tobin's Q (Q) [68], gearing ratio (Lev) [69], return on equity (ROE), and board size (Board) [70], which are defined in Table 2.

Table 2. The definitions of the variables in the study.

Variable Type	Variable Name	Variable Symbol	Variable Measurement
Explained variable	DGS	Composite Synergy Index of Enterprise Digitalization and Greening	Calculated by the entropy method, it consists of financial performance, environmental performance, and production performance.
Explanatory variable	Treat	Dummy Variable	The experimental group is defined as firms located in supply chain innovation policy pilot cities, defined as 1, and the control group is defined as firms located in non-pilot cities, defined as 0.
	Post	Dummy Variable	0 before 2018, otherwise 1
	SCIN	Net Effect of Policy	Treat × Post
Control variables	Dual	Integration of Two Positions	Assigned a value of 1 if the two positions are combined, otherwise 0
	TOP1	Equity Concentration	Shareholding ratio of the first largest shareholder
	ATO	Total Asset Turnover	Ratio of operating income to average total assets
	Q	Tobin's Q	Market capitalization/total assets
	Lev	Gearing Ratio	Total liabilities/total assets
	ROE	Return on Net Assets	Net profit/average total assets
	Board	Board Size	Ratio of operating income to average total assets
Intermediary variable	SA	Financing Constraints	SA index
	SCD	Supply Chain Diversification	Mean value of the sum of supplier concentration and customer concentration.

Moderator variables	ICM	Industry Chain Modernization	Industry chain modernization index
	Stock	Supply Chain Efficiency	ln(365/inventory turnover rate)
	Resil	Supply Chain Resilience	Composite indicator of supply chain resistance and resilience
	Entre	Entrepreneurship	Composite indicator of entrepreneurship

3.4.4. Intermediary Variable

Financing constraints (SA), supply chain diversification (SCD) [71] and industry chain modernization (ICM) are selected as mediating variables.

3.4.5. Moderator Variables

Supply chain efficiency (Stock), supply chain resilience (Resil), and entrepreneurship (Entre) are moderating variables. The definitions of the specific variables are shown in Table 2.

For the moderating variables, supply chain resilience (Resil) and entrepreneurship (Entre) are constructed in accordance with prior literature. Supply chain resilience is measured along two dimensions: resistance ability and recovery ability. Specifically, it includes the ratio of accounts receivable to revenue, the proportion of stable top-five customers, supply–demand deviation, and performance deviation. The comprehensive index is calculated using the entropy weight method.

Entrepreneurship is measured using five indicators: patent applications, per capita fixed assets, per capita income, per capita intangible assets, and board independence. The final comprehensive index is computed using the entropy weight method.

All control variables are selected based on theoretical relevance and mainstream literature. In particular, board size reflects corporate governance capacity, which influence firms' strategic decisions on digital investment and green innovation, thereby affecting digital–green synergy (DGS). All control variables are consistent with previous studies on digital transformation and green development.

4. Empirical Analysis

4.1. Descriptive Statistics

Table 3 summarizes the descriptive statistics for the companies included in the sample. Notably, there is a considerable gap between the maximum and minimum values of the DGS composite synergy among enterprises in the Yangtze River Basin. This variation highlights the different levels of synergistic progress achieved by these firms, revealing significant potential for enhancement. The difference-in-differences (DID) analysis yielded an average outcome of 0.191, indicating that the policies implemented in the pilot region have a direct impact on 19.1% of the enterprises situated in the Yangtze River Basin. Additionally, the values associated with control variables fall within acceptable limits, meeting standard criteria.

Table 3. Descriptive statistical analysis.

Variables	Obs	Mean	Std. Dev.	Min	Max
DGS	4160	1.326	24.21	−72.89	65.60
DID	4160	0.191	0.393	0	1
Dual	4160	0.177	0.381	0	1
Top1	4160	34.02	13.61	8.260	73.13
ATO	4160	0.715	0.444	0.105	2.775
Q	4160	1.874	1.183	0	7.219
Lev	4160	0.471	0.189	0.0880	0.883

ROE	4160	0.0730	0.0960	−0.405	0.319
Board	4160	7.112	3.790	0	14

4.2. Benchmark Regression Analysis

In this research, model (1) is employed to conduct a regression analysis aimed at assessing the effects of supply chain innovation (SCIN) policy on the synergy between the collaborative development of digitalization and greening among enterprises. The findings from this analysis are detailed in Table 4. The initial regression, which excludes control variables, indicates a significant positive relationship between the synergy levels in the digitalization and greening composite system and the SCIN policy, as illustrated in column (1). Furthermore, as shown in column (2), the results demonstrate that SCIN markedly boosts the synergy between digitalization and greening initiatives, with a correlation coefficient of 4.239, significant at the 5% level. These empirical findings support hypothesis H1.

Table 4. Benchmark regression results.

Variables	(1) DGS	(2) DGS
DID	4.232 * (1.949)	4.239 ** (2.22)
Dual		−1.583 (−1.29)
Top1		0.0910 (1.16)
ATO		−10.23 *** (−4.19)
Q		−0.0136 (−0.03)
Lev		−9.538 ** (−2.05)
ROE		2.779 (0.64)
Board		0.561 (0.99)
Constant	−0.792 (0.831)	57.787 *** (30.036)
Number of id	4160	4160
Company FE	YES	YES
Year FE	YES	YES
R-squared	0.735	0.621

***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively.

4.3. Robustness Test

4.3.1. Parallel Trend Test

A fundamental requirement for the application of the double-difference model is that both the experimental and control groups conform to the parallel trend hypothesis. This condition indicates that, before the implementation of the supply chain innovation policy, the trends in digitalization–greening synergy among enterprises should exhibit close similarities in both pilot and non-pilot cities. Specifically, these trends must either align or be comparable, with no statistically significant differences before the policy’s implementation. As illustrated in Figure 2, there are no significant differences in the synergy related

to the collaborative development of digitalization and greening between the pilot and non-pilot cities before policy implementation, evidenced by the parallel trend test yielding non-significant results. However, post-2018, a stark contrast emerges between the experimental and control groups regarding their synergy levels in this collaborative development, with the parallel trend test indicating statistical significance. This observation offers crucial evidence affirming the validity of the parallel trend hypothesis.

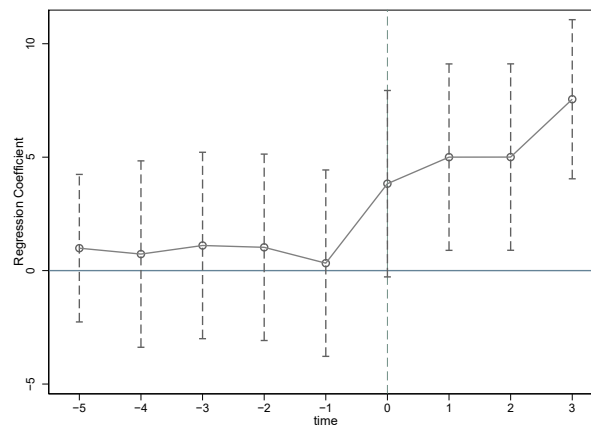


Figure 2. Parallel trend hypothesis test.

4.3.2. Placebo Test

To address the potential bias in estimation results stemming from unobservable variables, a placebo test was performed utilizing a method that randomly selects treatment groups. By ensuring a uniform timing for the policy shocks, a pseudo treatment group was generated from the original dataset. Subsequently, model (1) was assessed with the double difference method, repeating the procedure 500 times to determine the effects of the dummy policy shocks [72]. The outcomes of this analysis are depicted in Figure 3. The results indicate that the regression coefficients for the explanatory variable (DGS) and the key explanatory dummy variable predominantly cluster near zero, contrasting sharply with the baseline regression coefficient of 4.239. Furthermore, the majority of these coefficients do not reach statistical significance at the 10% level within the randomly created treatment groups. Overall, the insights gained from the placebo test imply that the impact of other unobservable factors has been appropriately controlled for, thereby reinforcing the assertion that SCIN plays a significant role in advancing the collaborative development of digitalization and greening within enterprises.

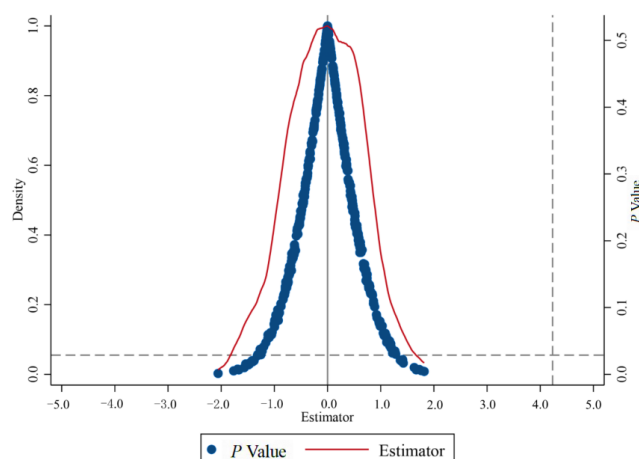
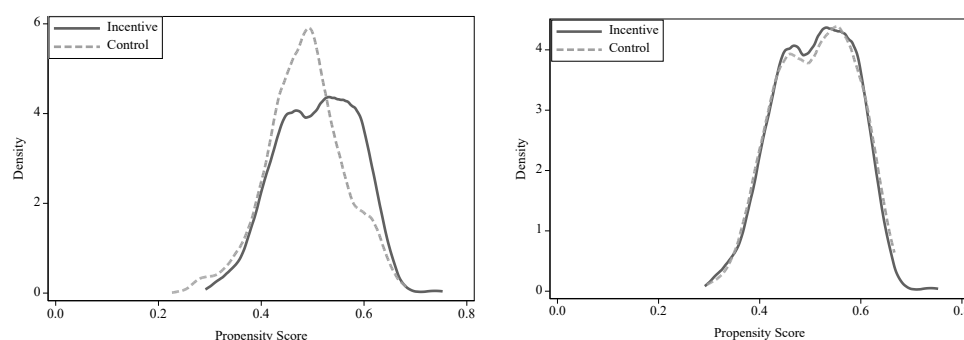


Figure 3. Placebo test results.

4.3.3. PSM-DID

To address the challenge of partial endogeneity in the empirical analysis and to bolster the credibility of the findings, propensity score matching (PSM) has been employed as a methodological approach to mitigate these endogeneity issues. When combined with the difference-in-differences (DID) technique, PSM effectively reduces differences between samples, thereby enhancing the model's robustness [73]. In this study, enterprises located in pilot cities are designated as the treatment group, while other A-share listed companies function as the control group. All control variables included in the regression analysis will serve as covariates for the propensity score matching process [74].

The density plot of propensity score values serves as a valuable visual representation for evaluating the effectiveness of the matching procedure. Figure 4 displays the density distributions of propensity scores both before and after the matching process. This comparative analysis illustrates that the probability density distributions of the treatment and control groups exhibit greater similarity following matching, indicating a significant enhancement in the quality of the matching outcome.

**Figure 4.** Kernel density distribution of propensity score.

To mitigate sample selection bias due to the non-random selection of SCIN pilot cities, we conducted a balance test between the treatment and control groups prior to the PSM-DID regression. As shown in Table 5, after matching, there were no significant differences between the two groups in key characteristics such as firm size, age, debt-to-asset ratio, Top1, ROE, and Tobin's Q. Standardized deviations were all less than 10%, effectively eliminating the confounding effects of firm-specific characteristics. This indicates that PSM effectively mitigated the endogeneity issues arising from the non-random allocation of pilot cities.

Table 5. PSM balance test.

Variable	Mean			t-test	
	Treated	Control	%Bias	t	p > t
Dual	0.164	0.171	−2.0	−0.660	0.512
Top1	35.061	35.346	−2.1	−0.680	0.498
ATO	0.688	0.684	1.1	0.380	0.706
Q	1.771	1.798	−2.2	−0.780	0.437
Lev	0.495	0.495	0.0	−0.010	0.993
ROE	0.069	0.072	−3.9	−1.250	0.213
Board	7.074	7.148	−2.0	−0.640	0.522

Building upon the preceding analysis, a selection of variables—encompassing the dual functions of enterprises, equity concentration, total asset turnover, Tobin's Q, and the gearing ratio—has been identified for model estimation through propensity score matching. To empirically evaluate the effects of the supply chain innovation (SCIN) policy on the digitalization and greening of enterprises (DGS), the double difference (DID) methodology has been utilized.

The regression outcomes from the difference-in-differences (DID) model, after propensity score matching, are displayed in column (1) of Table 6. Notably, the coefficients of the interaction terms (DID) are statistically significant at the 10% level, indicating that enterprises located in pilot cities are substantially impacted by the SCIN policy. Furthermore, these results remain consistent even after conducting the PSM-DID test, thereby bolstering the robustness of the empirical findings.

Table 6. PSM-DID test and time-placebo test results.

	PSM-DID	Policy Three Years Ahead
Treat × Post	5.045 *	2.232
	(1.847)	(1.564)
Constant	70.683 **	60.073 ***
	(30.393)	(30.099)
Control	YES	YES
Observations	4160	4160
Number of id	320	320
R-squared	0.641	0.592
Industry FE	YES	YES
Year FE	YES	YES

***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively.

4.3.4. Virtual Policy Implementation Time

This analysis purposefully accelerates the implementation timeline of the supply chain innovation (SCIN) policy to 2015—three years ahead of the original schedule—while concentrating on the period from 2012 to 2016, prior to the initiation of the SCIN policy pilot zones, which officially began in 2018. The aim is to examine whether the creation of these pilot areas has influenced the simultaneous digitalization and greening efforts of enterprises. In this context, the hypothesis posits that the *p*-value for the interaction term of the policy dummy lacks statistical significance. Confirmation of this hypothesis would support the contention that the potential impacts of other variables on the collaborative development of digitalization and greening (DGS) can be disregarded [75]. The findings presented in column (2) of Table 6 substantiate this claim, indicating no significant differences in the explanatory variables of the sample when the effects of the SCIN policy are excluded.

4.3.5. Synthesizing Double Differences (SDID)

Figure 5 presents dynamic trends from the synthetic double difference method, showing that both groups have a similar trend before implementing the supply chain innovation policy and thus support the parallel trend assumption.

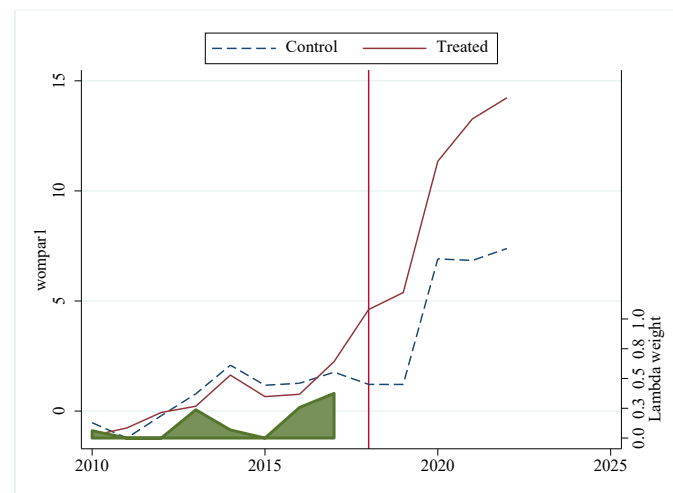


Figure 5. Synthetic double difference test.

Additionally, employing the bootstrap method for statistical inference provides us with the results of the synthetic double difference analysis, detailed in Table 7. The regression coefficient for the interaction term remains significantly positive, reinforcing the notion that the introduction of the supply chain innovation policy enhances the synergy between digital transformation and greening efforts within enterprises.

Table 7. Estimation of the Policy Treatment Effect.

	ATT	T Value
Treat × post	4.438 **	2.32
Observations		4121

** indicate significance at the 5% statistical levels, respectively.

4.4. Heterogeneity Analysis

The empirical analysis indicates that the supply chain innovation (SCIN) policy significantly contributes to the enhancement of synergy between digitalization and greening (DGS) within enterprises. However, to fully understand this impact, it is crucial to account for additional influencing factors. For instance, local governments often create tailored implementation plans that reflect regional characteristics, resulting in disparate policy effects across various areas. In addition, the inherent attributes of enterprises, such as their size, operational efficiency, and information asymmetry, may also affect policy implementation and its consequent effects. Based on the resource-based view, dynamic capabilities theory, and information asymmetry theory, firm characteristics influence the efficiency with which policy benefits are absorbed and transformed, thereby altering the extent to which SCIN policy promotes synergy between digitalization and greening. Therefore, it is relevant to explore whether the effectiveness of the SCIN policy in promoting the collaborative development of digitalization and greening differs across contexts, especially in terms of enterprise size, operational capabilities, and information asymmetry.

4.4.1. Heterogeneity Test Based on Firm Size

The effectiveness of policy implementation is significantly influenced by variations in enterprise size [76]. From a resource-based perspective, scale determines a company's resource endowment and absorption capacity; large enterprises are better positioned to translate policy incentives into actual investments in transformation, thereby strengthening the synergies between digital and green. Specifically, the ability of policies to promote the synergistic integration of digitalization and greening initiatives is closely tied to the

scale of the enterprise. For categorization purposes, we use the median of the natural logarithm of employee counts as a threshold: firms with employee numbers above this median are classified as large enterprises, while those below it are identified as non-large enterprises. The regression results, organized by firm size, are displayed in columns (1) and (2) of Table 8. The findings reveal that the SCIN policy exhibits a more substantial positive effect on the integrated development of digitalization and greening within larger firms compared to their smaller counterparts. This discrepancy may stem from larger enterprises being better positioned to develop comprehensive digital infrastructures and optimize their information management systems, supported by a skilled workforce and superior technological assets [77]. Generally, these larger entities enjoy enhanced access to both resources and innovative technologies, which allows them to effectively leverage emerging external technologies to tackle existing technological challenges. Furthermore, the expansion of big data creates a favorable environment for enterprises and increases their likelihood of securing digital subsidies [78]. As a result, this environment fosters significant incremental progress in the collaborative development of digitalization and greening efforts within enterprises.

Table 8. Heterogeneity test results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Large Firms	Non-Large Firms	High Competitiveness	Low Competitiveness	Low Information Asymmetry	High Information Asymmetry
Treat × Post	5.248 *** (3.48)	1.727 (1.13)	6.739 *** (4.51)	1.695 (1.16)	4.996 *** (3.35)	3.030 * (1.88)
Control	YES	YES	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	2050	2046	1963	2158	2061	2041
R2	0.656	0.605	0.618	0.581	0.625	0.638

*** and * indicate significance at the 1% and 10% statistical levels, respectively.

4.4.2. Heterogeneity Test Based on Firms' Competitiveness

According to the research framework by Uberti and Figini (2010) [79], the Herfindahl Index is a measure of the enterprise's market competitiveness. The smaller the HHI value, the more competitive the market is. According to the theory of dynamic capabilities, highly competitive enterprises possess greater market influence and risk tolerance, enabling them to capitalize on policy benefits and amplify the synergies between the digital and green sectors. This index can be calculated using the following formula: $HHI = \sum [(X_i/X)^2]$, where X_i is the year-end main business revenue of the enterprise and X is the year-end main business revenue of the industry in which the enterprise is located. Based on the results of the calculations, firms above the median are classified as having low market competitiveness, while those below are categorized as high market competitiveness. The estimation results, presented in columns (3) and (4) of Table 8, reflect outcomes after firms have been grouped by their market competitiveness. The analysis reveals that the SCIN policy significantly promotes the collaborative development of digitalization and greening in both low and high competitiveness enterprises, with a particularly pronounced effect observed among those with high competitiveness. This phenomenon can be attributed to the fact that firms which are highly competitive normally possess more financial resources and exercise significant power in their markets, which enables them to gain better market penetration and a stronger market presence [80].

As a result, these firms are in a strong position to capitalize on the new technologies and resource benefits from the SCIN policy [81]. Such capabilities not only accelerate their progress to more effective digitalization and environmental responsibility but also become instrumental for them in better aligning their production framework with regional industrial ecosystems. In addition, this alignment enhances their innovative capabilities, further integrating digitalization and sustainability to contribute to the high-quality development of these enterprises.

4.4.3. Heterogeneity Test Based on Firms' Information Asymmetry

This includes significant information asymmetry as a determinant of financial resource allocation inefficiencies in China [82]. Based on the theory of information asymmetry, low information transparency hinders the identification of policy signals and the acquisition of resources, thereby weakening the positive impact of SCIN policy on the synergy between digital and green synergy. Resource allocation patterns will be instrumental in determining the style of high-quality enterprise development. Also, more socially responsible to stakeholders is positioned firms that have lower information asymmetry levels [83]. This improved image not only enhances market recognition [84] but also helps these enterprises minimize decision-making costs [85]. To assess information asymmetry among firms, we formulate three indicators related to stock liquidity: the liquidity ratio, the illiquidity ratio, and the yield reversal indicator. The first principal component derived from these indicators is used as a proxy for information asymmetry, labeled as ASY, with higher values indicating elevated levels of information asymmetry among enterprises.

As shown in columns (5) and (6) of Table 8, firms characterized by lower information asymmetry experience a more pronounced positive effect from SCIN policies on the collaborative development of digitalization and greening, in contrast to those with higher information asymmetry levels.

5. Mechanism Analysis

In order to effectively address endogeneity concerns, this study utilizes existing literature to investigate the roles of corporate financing constraints (SA), supply chain diversification (SCD), and industrial chain modernization (ICM) as mediating variables in the relationship between SCIN policies and the efforts of enterprises toward digitalization, greening, and sustainability (DGS).

5.1. Mediation Effect Test

5.1.1. Financing Constraints (SA)

The SCIN policy facilitates collaboration between banks and enterprises, thereby alleviating financing constraints faced by businesses. This alleviation, in turn, enhances the digitalization, greening, and sustainability (DGS) initiatives of those enterprises. Following the research conducted by Hadlock C. J. and Pierce J. R. (2010) [86], the absolute value of the SA index is proposed as an indicator of financing constraints; a greater absolute value signifies more significant financing limitations for firms. This index is constructed from two robust exogenous factors—company size and age—which effectively minimizes the risk of endogenous bias. The formula is presented as follows:

$$SAindex_{it} = -0.737 \times C_size_{it} + 0.043 \times C_size_{it}^2 - 0.04 \times Age_{it} \quad (6)$$

where C_size is firm scale, and $Ln(\text{Total business assets}/1 \text{ million})$ is firm age. In column (1) of Table 9 are the baseline regression results, and in column (2) are the esti-

mated coefficients of the mediating variable financing constraints (SA) and the core explanatory variable ($Treat \times Post$), which are -0.0156 and are tested for significance at the 5% level, which suggests that the SCIN policy improves the DGS of enterprises by alleviating the financing constraints of enterprises. Accordingly, hypothesis H2 is supported by empirical evidence.

Table 9. The estimation results of action mechanism test.

Variables	(1) DGS	(2) SA	(3) SCD	(4) ICM
Treat $\times$ Post	4.239 ** (2.22)	-0.0156 ** (-1.98)	2.149 *** (3.70)	0.0104 *** (9.45)
Constant	57.787 *** (30.036)	-4.333 *** (-22.64)	4.330 * (1.67)	0.180 *** (3.78)
Control	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	4160	4160	4160	4160
R2	0.6211	0.907	0.6212	0.947

***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively.

5.1.2. Supply Chain Diversification (SCD)

This indicator is an inverse indicator, and the larger its value, the lower the degree of supply chain diversification of the firm. In column (3) of Table 9, the estimated coefficients of the mediating variable supply chain diversification (SCD) and the core explanatory variable (DID) are negative and pass the significance test at the 5% level, indicating that the SCIN policy improves the DGS of enterprises by promoting supply chain diversification. Therefore, hypothesis H3 is verified.

5.1.3. Industry Chain Modernization (ICM)

In column (4) of Table 9, the estimated coefficients of the mediating variable Industry Chain Modernization (ICM) and the core explanatory variable ($Treat \times Post$) are 0.0104 and pass the test of significance at the 1% level, which indicates that suggests that the SCIN policy improves the DGS of enterprises by increasing the chain modernization of the industry chain. Therefore, hypothesis H4 is verified.

5.2. Moderating Effects Test

5.2.1. Supply Chain Efficiency (Stock)

Supply chain efficiency emphasizes increasing the frequency of communication and trade between upstream and downstream enterprises, which is manifested in the smooth flow of product and services. Existing studies have used the inventory of work-in-process as the indicator of supply chain efficiency; however, only using the inventory level to characterize the supply chain efficiency will ignore factor mobility among the node enterprises of the supply chain. Therefore, the inventory turnover days are used to characterize the supply chain efficiency, which is calculated as $\ln(365/\text{inventory turnover})$ [87]. The index is a negative indicator, i.e., the larger the value indicates that the enterprise's supply chain is less efficient; the smaller the value of stock, the higher the efficiency of the enterprise's supply chain. As shown in column (1) of Table 9, the coefficient of the interaction term $DID \times Stock$ is significantly negative, indicating that a positive moderating effect on supply chain efficiency, which verifies hypothesis H5.

5.2.2. Supply Chain Resilience (Resil)

According to the existing research results on supply chain resilience, supply chain resilience has two dimensions supply chain resistance and resilience [88], and supply chain resilience is measured by a composite index. The natural logarithm of accounts receivable to revenue ratio is utilized to measure capital utilization and the percentage of firms' number of stable customers with their top five customers in consecutive years to measure firms' supply chain resistance, and supply chain resilience is measured by supply and demand deviation and firm performance deviation. As can be seen in column (2) of Table 9, the interaction term DID $\times$ Resil coefficient is significantly positive, indicating the existence of a positive moderating effect of supply chain efficiency, which verifies hypothesis H6.

5.2.3. Entrepreneurship (Entre)

Drawing on prior studies, the number of patent applications, fixed assets per capita, income per capita, intangible assets per capita, and board of directors' independence are chosen to measure entrepreneurship comprehensively [89]. Finally, the weights of the above indicators are obtained by the entropy weighting method and then calculated to get the comprehensive result, and the natural logarithm of this result is used to measure entrepreneurship. From column (3) of Table 10, the coefficient of the interaction term DID $\times$ Entre is significantly positive, indicating the existence of a positive moderating effect of entrepreneurship, which verifies hypothesis H7.

Table 10. Moderating effect test results.

Variables	(1) Stock	(2) Resil	(3) Entre
DID	4.485 ** (2.41)	4.660 ** (2.46)	6.084 *** (3.26)
Stock	0.467 (0.58)		
DID $\times$ Stock	−2.378 *** (−2.73)		
Resil		−1.218 (−0.51)	
DID $\times$ Resil		7.141 * (1.82)	
Entre			13.971 (0.20)
DID $\times$ Entre			22.604 ** (2.01)
Constant	4.379 ** (2.63)	7.413 *** (3.02)	4.677 *** (2.78)
Control	YES	YES	YES

***, **, and * indicate significance at the 1%, 5%, and 10% statistical levels, respectively.

6. Discussion

This study aims to analyze how supply chain innovation policies can promote the coordinated development of digitalization and greening in enterprises from multiple perspectives. Innovation in supply chain policies provides a new view through which one can consider the interaction of digital strategies with the collaborative development of greening and digitalization in enterprises. By fostering intelligent supply chains and harnessing advanced technologies such as big data analytics, the Internet of Things (IoT), and

artificial intelligence [90], enterprises can improve their understanding of technology adoption and optimize resource allocation. This integration of technology not only boosts operational efficiency but also supports the execution of sustainable development initiatives [91], significantly raising enterprises' environmental consciousness and reducing emissions [92].

Firstly, the supply chain innovation (SCIN) policy enhances the capabilities of enterprises, thereby facilitating the collaborative development of digitalization and greening (DGS). The establishment of systems for real-time monitoring, intelligent decision-making frameworks, and efficient models of collaboration-based operation by the policy provides enterprises with increased flexibility and responsiveness, thus better equipping them to achieve success in the face of changes within their external environment. This facilitates internal innovation and sustainability while creating synergies with upstream and downstream partners [93] in the pursuit of DGS. This study thus examines the relationship between DGS and the sustainable innovation efforts of firms to expand current knowledge and to articulate what unique role SCIN policies play in innovation. Additionally, SCIN policies trigger digital supply chain transformation, enabling companies to gain insights into operational status across all links and to monitor and optimize operations in real time. By harnessing advanced technologies, businesses can swiftly identify and address supply chain bottlenecks, enhance operational efficiency, reduce costs, and bolster market competitiveness. In an increasingly complex market landscape, this digital transformation equips enterprises to more effectively respond to risks and to achieve their sustainable development objectives.

Secondly, the SCIN policy equips enterprises with a strong technological platform that allows them to accelerate collaborative development of DGS by investing more in innovation. Continuous innovation is a key requirement for the sustainable growth of enterprises. The policy encourages technological innovation and green transformation [94], thereby fulfilling social responsibilities, enhancing corporate image, and gaining public trust, all of which establish a strong basis for long-term success. Digital supply chain management plays a crucial role in cost reduction [95]. By automating processes and integrating intelligent systems, enterprises can minimize manual tasks and reliance on paper documentation, thereby enhancing operational efficiency while cutting labor and time expenditures. This synergistic approach not only fosters stronger partnerships but also reduces transaction costs and improves access to financing [96].

Additionally, the supply chain innovation (SCIN) policy fosters the collaborative development of digitalization and greening (DGS) by enhancing the diversification of supply chains. Diversification offers broader market opportunities and mitigates risks, facilitating the sharing of information and resources while lowering external transaction costs [97]. This strategic arrangement enhances firms' ability to be resilient and flexible in the face of risks, thus stabilizing supply chain relationships. As a result, it leads to sustainable cash flow and supports the efforts of firms in digitalization and green initiatives.

Therefore, the SCIN policy drives the modernization of industrial chains, creating more opportunities for collaborative development of digitalization and greening. The policy uses big data to establish intelligent supply chain systems, enhance information sharing, and enable collaborative operations across all industry segments. This, in turn, decreases labor, logistics, and information exchange costs, thereby propelling the industry toward becoming more intelligent. Such a transformation not only improves the efficiency of resource utilization but also diminishes energy consumption and waste emissions [98]. Consequently, it supports industrial transformation and upgrading, enabling enterprises to more effectively respond to market demands and secure competitive advantages.

Supply chain efficiency accelerates the integration of digital technologies into greening efforts by improving total factor productivity and dynamic resource allocation capabilities. The SCIN policy promotes supply chain digitalization, and smart supply chains rely on real-time decision-making hubs built with big data and artificial intelligence to dynamically optimize carbon paths in procurement, warehousing, and transportation, embedding environmental governance logic into operational processes [99]. Resilient inventory management driven by intelligent algorithms reduces the risk of operational disruption while optimizing resource turnover efficiency, achieving a dynamic balance between operational optimization and carbon footprint reduction [100]. In addition, a highly resilient supply chain enhances the adaptability and redundancy of ecological niches, enabling companies to improve their environmental governance performance in parallel with technological iterations. Entrepreneurship bridges the synergy gap between digitalization and green transformation through strategic foresight and resource integration capabilities.

The core findings of this study systematically engage with the existing literature. First, the main effect of SCIN policies in significantly promoting the synergy between digitalization and greening confirms that supply chain innovation can enhance corporate innovation efficiency. In contrast, while some studies have warned of potential inherent conflicts between digitalization and greening, our results indicate that the two can coexist through appropriate policy design, likely because SCIN policies provide a threefold support system encompassing resources, structure, and ecosystem. Second, at the mechanism level, the mediating role of financing constraints supports the core logic of the resource-based view, aligning with the argument that transformation requires substantial long-term investment, while providing new evidence that improved financing simultaneously benefits greening efforts. The mediating role of supply chain diversification validates the applicability of transaction cost theory and resource dependence theory in a dual-transition context. The mediating role of industrial chain modernization extends innovation ecosystem theory, revealing “externalities” as a micro-level transmission mechanism. Third, regarding moderating effects, the positive moderating roles of supply chain efficiency and resilience confirm the efficiency amplification effect and highlight the new role of resilience as a buffer for transformation; the significant moderating effect of entrepreneurship resonates with innovation-driven research findings and extends this logic to the dual-transition context.

In summary, supply chain innovation (SCIN) policies promote the collaborative development of digitalization and greening (DGS) within enterprises through multidimensional mechanisms. These include establishment of smart supply chains, enhancement of supply chain diversification, and modernization of industrial chains. In addition, supply chain efficiency, supply chain resilience, and entrepreneurship play a positive moderating role in the process by which SCIN policies promote the dual synergy development of firms. Such initiatives contribute to cost reductions, improved financial capabilities, and the fostering of foster innovation alongside sustainable development. Moving forward, the continuous evolution and application of these policies are expected to create even greater opportunities for the synergistic advancement of enterprise digitalization and greening.

7. Conclusions

This research examines A-share listed companies in the Yangtze River Basin of China, covering the period from 2010 to 2022. Drawing on a robust theoretical framework, it treats enterprise digitalization and greening as distinct yet interconnected subsystems. A composite system synergy algorithm is employed to quantitatively evaluate the degree of synergistic development between these two domains. Furthermore, the study investigates

the influence of supply chain innovation policies on this synergistic relationship through a difference-in-differences approach.

Findings suggest that supply chain innovation policies serve as an important tool for promoting the collaborative development of digitalization and greening within enterprises since results persist steadily through different kinds of analytical tests. The effect of these policies on the enterprises examined also varies across firms, but they tend to improve digitalization–greening synergy while alleviating financing constraints, fostering supply chain diversity, and modernizing industrial structure. It is worth mentioning that the policy comprehensively addresses issues related to company size, operational capacity, and information asymmetry. This reconciles usually conflicting short-term and long-term objectives of enterprises. This strategic alignment allows for the smooth integration of digital initiatives with greening efforts, which will eventually lead to a robust foundation for sustainable and high-quality development within these organizations.

Based on the above research findings, the following policy recommendations are proposed:

Therefore, the priority should be to strengthen targeted support through intermediary mechanisms. Research has confirmed that SCIN policy promotes the coordinated digital and green development of enterprises by alleviating financing constraints, enhancing supply chain diversification, and driving the modernization of industrial chains. Local governments should focus on these three core pathways to refine supporting policies: To address the effect of easing financing constraints, establish interest-subsidized loans and special subsidies for digital and green transformation for enterprises in pilot cities—particularly small and medium-sized enterprises—to reduce the financing costs of transformation. To address the effect of enhancing supply chain diversification, local governments should build cross-regional supply–demand matching platforms, guide enterprises to expand diverse cooperation networks, and provide supply chain stabilization support to enterprises that reduce the concentration of supply and demand. To promote industrial chain modernization, establish industrial chain collaborative innovation funds to support upstream and downstream enterprises in jointly tackling digital and low-carbon technology challenges, drive the intelligent and green upgrading of traditional industries, and develop replicable and scalable models. Additionally, the government should remove barriers to transformation by streamlining approval processes and cutting taxes and fees, thereby guiding enterprises to achieve synergistic improvements in supply chain and digital–green development through policy incentives.

Second, a differentiated policy should be implemented to account for enterprise-level heterogeneity. Empirical evidence shows that policy effects vary significantly depending on enterprise size, market competitiveness, and the degree of information asymmetry. The government should avoid a “one-size-fits-all” approach and instead implement a tiered supply chain innovation strategy: for small, less competitive enterprises with high information asymmetry, the government should increase investment in new infrastructure, establish dedicated data service platforms for small and medium-sized enterprises (SMEs), provide free access to basic digital tools, address shortcomings in digital transformation, and narrow the information gap; for large, highly competitive leading enterprises with low information asymmetry, streamline the approval process for innovation projects and provide targeted fiscal incentives to encourage them to play the role of “chain leaders.” They should spearhead the development of collaborative innovation ecosystems, driving upstream and downstream enterprises to advance the integration of digital and green technologies, thereby fostering a development model where all levels of the supply chain progress together.

Finally, measures to enhance the effectiveness of supporting regulatory factors should be improved. Research has shown that supply chain efficiency, supply chain resilience, and entrepreneurship strengthen the synergistic effects of digital and green transformation policy. The government should incorporate these moderating factors into its policy framework. Specifically, it should: optimize regional logistics networks, establish early-warning mechanisms for supply chain risks, and enhance supply chain efficiency and resilience to provide a stable operating environment for enterprises undergoing digital and green transformation; conduct training to build entrepreneurs' capabilities for digital and green transformation, and establish innovation incentive funds to stimulate entrepreneurs' innovative spirit and willingness to take risks, thereby realizing their positive moderating effects and further amplifying the impact of supply chain innovation policy on enterprises' high-quality development.

Research limitations: First, due to the lack of granular firm-level data during the sample period, the output indicators for the digitalization subsystem are relatively broad and primarily reflect overall operational performance, which may introduce measurement noise and fail to capture the pure level of digital transformation. Second, the conventional mediation testing approach applied within the DID framework may raise concerns of "bad control/bad mediation," whereas formal causal mediation analysis—requiring stronger assumptions and greater implementation complexity—could not be adopted given the current sample constraints.

Future research directions: This study also provides several directions for future research. First, future studies could expand the sample scope to firms in other regions, industries, and international contexts, which would help to obtain generalizable insights into how supply chain innovation policies drive the synergistic development of digitalization and greening. Second, longitudinal research is needed to evaluate the long-term impacts of these policies on corporate innovation performance, carbon reduction effects, and sustainable growth. Third, future research could further explore potential mechanisms that shape the effectiveness of policy interventions, such as organizational culture, inter-firm network collaboration, and technological maturity. Fourth, cross-country or cross-regional comparative studies could reveal how institutional and regulatory environments shape corporate digital and green transformation. Finally, developing more refined micro-level indicators (e.g., environmental performance metrics or carbon intensity measures) would contribute to a more precise understanding of corporate digital and green development. These directions provide a roadmap for deepening theoretical and practical understanding of policy-driven digital–green transformation in firms.

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