RESEARCH ON THE CONFIGURATIONAL PATHWAYS OF SUPPLY CHAIN DIGITALIZATION DRIVING CORPORATE CARBON EMISSION REDUCTION FROM THE TOE PERSPECTIVE—BASED ON CHINESE ENTERPRISES

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Abstract. With the support of state initiatives such as supply chain digitalization pilots and the "dual-carbon" regulatory framework, Chinese businesses are currently undergoing an integrated transformation towards digitalization and green development. For businesses engaged in supply chain digitalization projects, understanding the logic of their carbon-emission reduction efforts is crucial. This paper explores the theoretical mechanism by which supply chain digitalization impacts carbon-emission reduction in pilot enterprises. Using the TOE framework, it systematically identifies the drivers of corporate carbon emission reduction and analyzes the configurational effects of various factors through NCA and fs-QCA methods. The three main pathways to significant carbon emission reduction all involve a high level of digital technology application and differ in the following characteristics: high level of supply chain dominance; high level of green management innovation; high level of foundational digital technology and local data factionalization. Additionally, in some pilot enterprises, low level of digital technology application is a key barrier to carbon emission reduction. This study provides a new analytical framework for understanding the impact of supply chain digitalization on corporate carbon emission reduction and offers insights for enterprises aiming to align digitalization with green development.
Keywords: *supply chain digital transformation, enterprise carbon emission, NCA, fs-QCA, configurational effects*

Introduction

Since 2018, the Chinese government has been advancing supply chain digitalization. According to the "General Office of the State Council's Guidelines on Actively Promoting Supply Chain Innovation and Application", released by eight departments including the Ministry of Commerce, pilot enterprises are selected in batches to cultivate supply chain-leading enterprises with strong industry-driving ability and to build a digital supply chain ecosystem. In 2020, China further proposed the "dual-carbon" goals, aiming to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. Thus, for supply chain digitalization, collaborative promotion of digitalization and carbon emission reduction is now the most urgent task for pilot enterprises in China.

For supply chain digitalization pilot enterprises, when implementing carbon reduction goals, they are influenced by cross-level factors like internal technical and managerial capabilities and external environmental pressures. The effect paths of these factors on carbon reduction vary greatly among enterprises. How do internal and external factors

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jointly impact the carbon reduction of pilot enterprises? Are there commonalities in the influence paths of different pilot enterprises? Answering these questions is crucial for summarizing advanced pilot enterprise experiences and better leveraging supply chain digital transformation for corporate carbon reduction. However, extant research has yet to provide answers to these questions.

Prior studies have merely examined the average effect of pilot policies on corporate carbon reduction, leaving the black-box mechanisms and causal pathways largely unexplored. To bridge this gap, this paper integrates the TOE framework for the first time and single out the technical, organizational and environmental drivers of carbon abatement among China's pilot enterprises. Combining NCA with fs-QCA, this paper uncovers the configurational paths through which these drivers jointly trigger emission reductions. Consequently, this paper aims to reveal, at a structural level, how pilot firms can translate supply-chain digitalization into tangible carbon savings, thereby offering actionable insights for China and other countries pursuing digital supply-chain transitions to enhance corporate climate performance.

Literature review

Studies on factors affecting corporate carbon emission reduction

Existing literature mainly analyzes the factors affecting corporate carbon emission reduction from two aspects: internal management and external environment.

Internal management of enterprises

Internal management focuses on two key dimensions: technological innovation and green governance. In terms of technological innovation, green innovation has proven to be an effective way to balance economic growth and environmental protection (Chen et al., 2012; Xu et al., 2021). In practice, it has a positive effect on cutting carbon emissions and boosting firms' environmental performance (Huang et al., 2021; Liang et al., 2022). Amid the accelerating trend of corporate digital transformation, many studies have analyzed how digital technology R&D and application impact corporate carbon reduction. It is believed that by developing or using digital technologies and creating new digital business models, firms can gain a competitive edge and generate more value (Kohtamäki et al., 2019; Annarelli et al., 2020). On one hand, digital technologies speed up knowledge sharing, leverage spillover effects, and cut pollution (Ma and Li, 2022). Boosting investment in digital technologies can optimize firms' factor structures, increase the proportion of knowledge and technology in resource allocation, promote the shift to low-pollution, knowledge- and technology-intensive models, and reduce production-related carbon emissions (Ghasemaghaei and Calic, 2019; Bai et al., 2023). On the other hand, digital technologies upgrade production models and enhance environmental supervision and governance, thus driving carbon reduction (Hao et al., 2023). By changing production models and enabling scaled-up production, digital technologies can lower firms' costs and energy use, and in turn reduce carbon emissions overall (Lee, 2023; Pratama et al., 2025).

Regarding corporate green governance, in the face of environmental challenges, knowledge-centered firms focus on maximizing resource use and minimizing environmental impact (Hart, 1995; Muñoz-Pascual et al., 2021). As a result, green knowledge management (GKM) has become a vital strategic resource for many companies (Yu et al., 2022). Green innovation, enabled by knowledge management, can help firms adopt new management

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models or strategies to improve production processes (Chaithanapat et al., 2022). Through green management innovation, firms can gain financial returns while minimizing environmental impact (Naqshbandi and Jasimuddin, 2022). For firms that take the lead in introducing green technological and management innovations, customer trust, loyalty, and profitability are likely to increase (Rehman et al., 2021).

External environment of enterprises

Existing research has pinpointed three key dimensions that shape the external environment affecting firms' Carbon Emission Cuts: market competition, government regulation, and social pressure.

Firstly, in terms of market competition, the degree to which firms achieve carbon emission reduction is influenced by ESG competition and imitation among peer companies within the same industry. This enables the "invisible hand" of the market to function more effectively, offering an external governance mechanism that combines incentives and punishments for corporate low-carbon participation. On the one hand, based on reputation theory, companies strive for a good reputation amid low-carbon transitions. They signal responsibility through strong ESG performance, reduce information asymmetry with stakeholders, and attract investments for green technology upgrades (Kim and Li, 2021; He et al., 2022). On the other hand, according to dynamic competition theory, there's intense competition among peer firms. Managers constantly adjust to competitors' actions, making ESG performance more influential for triggering competition and imitation, while also increasing internal peer pressure (Kaustia and Rantala, 2015). Therefore, the ESG performance of peer companies makes the competitive and imitative behaviors of other firms more widespread (Feng et al., 2025), and the internal peer pressure within firms is also growing (Zhang and Liu, 2023).

Secondly, in terms of government regulation, studies grounded in neoclassical economics posit that environmental regulations can lead to higher costs, such as pollution charges, and divert funds from promising innovation projects to those solely focused on emission reduction (Xie et al., 2017; Wei et al., 2022). However, the "compensation effect" perspective indicates that in an effective environmental regulatory system, the benefits from enhanced environmental efficiency of resource utilization can offset the costs resulting from the internalization of environmental expenses (Porter and van der Linde, 1995; Luo et al., 2021).

Finally, besides the government, the media and the public also play a role in overseeing firms' environmental performance (Yang et al., 2022). Under social pressure, companies must implement carbon reduction measures to maintain their reputation and credibility (Xu et al., 2024). Research has found that, on the one hand, the role of the Chinese public in successfully promoting corporate green innovation is mainly reflected in the restrictions imposed by news media and community residents (Cheng and Liu, 2018; Zhao et al., 2022). On the other hand, in their dual roles as consumers and investors, public environmental awareness drives eco-friendly behavior in heavily polluting enterprises (Bénabou and Tirole, 2010; Zhou and Ding, 2023).

Studies on the impact of supply chain digitalization on corporate carbon emission reduction

The true transformation of the supply chain began with the rise of digitalization, which involves not only converting analog information into digital form but also using digital

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technologies to fundamentally change the conception and execution of supply chain processes (Hunjra et al., 2024). Supply chain digitalization can integrate digital technologies into the supply chain ecosystem to enhance the connectivity, visibility, responsiveness, and efficiency of the entire supply chain network (Jiang et al., 2024). Existing literature provides substantial evidence supporting the relationship between supply chain digitalization and decarbonization. Digital technologies such as the Internet of Things, artificial intelligence, and blockchain can better track and manage emissions across the entire supply chain (Fang et al., 2024). Theoretically, the digital transformation of the supply chain can strengthen information sharing and resource allocation between upstream and downstream partners, thereby reducing CCE (carbon emission concentration equivalents) through lowering transaction costs, promoting green innovation, and increasing external attention.

Transaction cost mechanism

In fact, digitalization alone will not automatically lead to decarbonization. Transaction cost economics theory holds that in complex supply chains, transaction costs can become very high, especially when dealing with multiple suppliers in different regions. Therefore, digitalization enhances supply chain mapping by providing visibility into the various participants, activities, and processes involved in the supply chain, thereby reducing information asymmetry and transaction costs (Steiner et al., 2023). That is to say, the intermediate step of supply chain mapping plays a crucial role in facilitating the transition to a low-carbon supply chain (Zhao et al., 2023). By acting as a key intermediary, supply chain mapping transforms digital capabilities into actionable insights and strategies to reduce carbon emissions across the entire supply chain (Khan et al., 2022). With the help of digital technologies, supply chain mapping can go beyond a simple supplier relationship diagram to include data layers on carbon emissions, energy use, and other environmental impacts at each stage of the supply chain (Schoenherr et al., 2023). This transition effectively raises the level of information sharing among companies (Dolgui and Ivanov, 2021; Ivanov et al., 2022).

Green innovation mechanism

The digital transformation of the supply chain involves the allocation and integration of resources, which has a significant impact on technological progress (Schniederjans et al., 2020; Ling et al., 2023). Specifically, in terms of green innovation, the digitalization of the supply chain encourages firms to align with the carbon emission standards of green and low-carbon enterprises in the supply chain, thereby achieving carbon emission reduction (Doda et al., 2016). At the same time, the digitalization of the supply chain enhances the openness and sharing of resources, promotes the dissemination of data and technological knowledge, and plays a role in technological spillover and knowledge spillover effects. This provides learning resources for corporate green transformation, improves the integration and joint innovation capabilities of green innovation resources, and reduces pollution emissions (Ma and Li, 2022). In addition, the digitalization of the supply chain increases the efficiency of innovation-related factors flowing between upstream and downstream supply chains and breaks down barriers to closed-innovation (Huang et al., 2023).

External pressure mechanism

The digital transformation of the supply chain can enhance the motivation to reduce CCE (carbon emission concentration equivalents) by increasing external attention and

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pressure, as well as by the incentives driven by sustainable development goals under the dual-carbon targets. It improves the overall operational efficiency of supply chain firms (Bigliardi et al., 2022), and promotes their fulfillment of more environmental, social, and governance responsibilities (He et al., 2023; Zhao et al., 2023). It also enables timely access to market competition information and the direction of technological changes, increases the R&D and innovation efforts in green and clean products, and reduces pollution emissions (Zhang et al., 2024).

The digital transformation of the supply chain strengthens firms' willingness and motivation to reduce carbon emissions. In addition, SCD (Supply Chain Digitalization) is in line with the current trend of digital economic development and national policy directives, indicating an optimistic future prospect for companies in the external environment (Shen et al., 2025).

Analytical framework

Theoretical foundation

By reviewing the existing literature, it can be found that, on the one hand, supply chain digitalization affects corporate carbon emission reduction through three major mechanisms: green innovation, transaction costs, and external pressure. On the other hand, factors influencing corporate emission reduction include internal management (technological innovation, green governance) and external environment (market competition, government regulation, and public opinion pressure). In fact, during the process of supply chain digitalization driving corporate carbon emission reduction, these mechanisms and factors often work simultaneously. However, the existing literature lacks research on this synergistic effect from a systematic perspective. Therefore, this paper will use the TOE (Technology-Organization-Environment) theory to integrate the above-mentioned theoretical mechanisms and influencing factors, and discuss the configurational effect of supply chain digitalization on carbon emission reduction of pilot enterprises.

The TOE (Technology-Organization-Environment) framework, as a comprehensive analytical tool focusing on the application scenarios of technology, was initially used to analyze the factors influencing corporate adoption of innovative technologies (Depietro et al., 1990). With the development and evolution of the TOE framework, scholars have made appropriate adjustments to the framework in practical applications according to different research questions and contexts, and used it as a "universal" framework (Oliveira and Martins, 2011). It emphasizes the interplay and interdependence of the three dimensions of technology, organization and environment, and can systematically analyze the multidimensional factors and their dynamic relationships in complex situations (Awa and Ojiabo, 2016).

Theoretical identification of technical dimension factors

Digital technology application

Emerging digital technologies have been deeply integrated into all production links of enterprises, and have had a disruptive impact on the improvement of their technological application levels. On the one hand, the application of digital technologies can promote the development of environmentally friendly products by enterprises, optimize product development processes, and shorten R&D cycles, thereby reducing resource consumption

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in the product life cycle and promoting the production and development of green products. On the other hand, digital technologies can help enterprises and stakeholders share information on energy conservation and emission reduction, and establish a credible data access channel between enterprises and environmental protection departments, thus promoting efficient waste treatment and resource recycling.

Foundational digital technology

When enterprises engage in the R&D of digital technologies, it enhances their level of green technological innovation, making the production and manufacturing processes more modern and environmentally friendly, and expanding the technological development boundaries for enterprises in the prevention and control of environmental pollution.

In terms of predicting carbon emissions, foundational digital technologies can forecast future carbon emissions based on the current tasks and needs of carbon emission reduction, providing guidance for enterprises to reduce carbon emissions. In terms of monitoring carbon emissions, foundational digital technologies can track carbon footprints in real-time, collect data from the entire industrial chain process, and improve the accuracy of monitoring. In terms of reducing carbon emissions, after enterprises collect data from various links and determine the carbon footprint through foundational digital technologies, they can optimize and adjust the workflow of each link in real-time from a holistic perspective, reducing energy consumption and improving energy efficiency.

Theoretical identification of organizational dimension factors

Green management innovation

Green management innovation is a comprehensive concept that involves integrating environmental protection, resource conservation, and social responsibility into a company's management practices, ultimately forming a corporate culture centered on green development. On the one hand, green management innovation can enhance a firm's green learning capabilities during the digital transformation process. The development and application of digital technologies help managers weigh the consequences of polluting the environment, prompting firms to adopt environmental strategies consistent with external government and societal demands, thereby promoting their own carbon emission reduction. On the other hand, green management innovation enables firms to establish good stakeholder relationship networks. To meet stakeholders' green market demands, firms need to send an important signal to the outside world that "the firm can actively take social responsibility," generating a positive reputation effect.

Supply chain dominance

In the process of digital transformation, leading firms in a supply chain can, on the one hand, leverage their influence and resources to enhance the collection and application of green innovation knowledge among upstream and downstream enterprises in the supply chain. This provides a solid knowledge base and technological guarantee for the development of low-carbon technologies across the entire supply chain. On the other hand, leading firms can communicate their carbon-emission reduction targets and requirements to their partners, guiding and incentivizing them to take corresponding reduction measures.

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Specifically, first, suppliers and customers upstream and downstream of the leading firm are motivated to align with the digital transformation of the focal firm to maintain strategic consistency and cooperation stability. Under the digital leadership of the focal firm, these enterprises optimize their production and sales structures by developing digital business segments, thereby reducing their direct carbon emissions.

Second, as products flow downstream in the supply chain, the technological and green attributes imparted to the products during the production process have a cumulative effect. Influenced by the digital transformation of the focal firm, other enterprises can benefit from the digital empowerment of products provided by the leading firm, thus promoting collaborative emission reduction across the supply chain.

At the same time, under the dual pressures of environmental regulation and social responsibility, leading firms, in order to maintain the security and stability of the supply chain, are committed to reducing the green risks in the production processes of suppliers and the sales processes of customers. This strengthens their environmental supervision over upstream and downstream enterprises, reducing the total carbon emissions and intensity of the supply chain.

Theoretical identification of environmental dimension factors

Peer companies' ESG pressure

The degree of corporate carbon emission reduction is also affected by ESG competition and imitation behaviors among peer firms within the same industry. This enables the "invisible hand" of the market to function more effectively and provides an external governance mechanism that combines incentives and punishments for companies to participate in low-carbon emission reduction. First, based on the reputation theory, companies seek to gain a good reputation in the context of the low-carbon transition. They signal their responsibility through strong ESG performance, reducing information asymmetry between the firm and its stakeholders. This, in turn, attracts external investment for green technology iteration and upgrading. Second, based on the dynamic competition theory, there is intense competition and interaction among peer firms. Corporate management constantly adjusts and responds to the actions of competitors. Therefore, the ESG performance of peer firms makes competition and imitation behaviors more common among other companies, and the internal peer pressure within firms also increases.

Local environmental regulation

After years of significant economic growth and persistent environmental degradation, China is determined to address the negative externalities caused by environmental pollution through strict environmental regulation. A large number of studies have analyzed the impact of government environmental regulation on corporate emission reduction. The results mostly suggest that environmental regulations can effectively reduce carbon emissions due to the existence of "forced emission reduction". In terms of the mechanism of action, environmental regulation can effectively reduce corporate carbon dioxide emissions through channels such as reducing industrial pollution, improving energy efficiency, and promoting green innovation.

Local public environmental concern

The public environmental concern and resulting public opinion in the location of a company's headquarters can attract external attention to the company, amplifying

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negative externalities such as carbon emission reduction. This, in turn, increases the internal and external pressures faced by the company. Under such strict external scrutiny, in order to protect its reputation, the company tends to avoid negative performance in the environmental, social, and governance dimensions, which is conducive to increasing the intensity of carbon emission reduction.

Local data factionalization

On the one hand, the data factionalization in a firm's region can reduce its carbon emissions through several main channels, such as improving corporate governance to stimulate green technological innovation, strengthening external supervision and internal management optimization, alleviating corporate financing constraints, saving energy consumption, and reducing energy intensity.

On the other hand, the improvement of data factionalization levels can break the spatial and temporal barriers to knowledge flow, providing channels for accelerating the dissemination of green technologies. Meanwhile, it effectively reduces communication costs and information search costs between firms, alleviating information asymmetry, and thus facilitating green transformation cooperation among firms.

Based on the identification of antecedent factors from the TOE perspective mentioned above, this paper constructs the analytical framework shown in *Figure 1*.

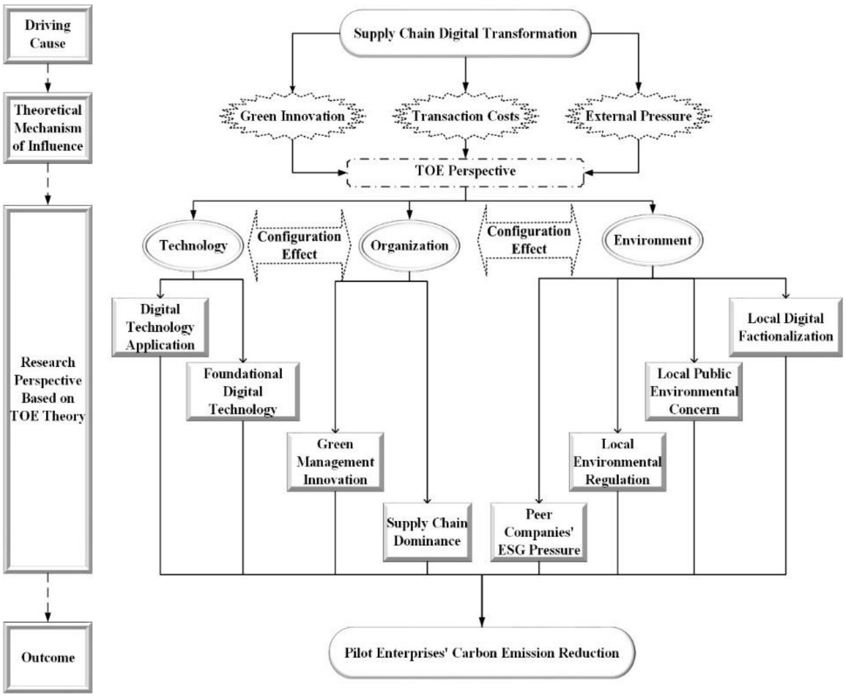

Figure 1. *Analytical framework based on TOE theory*

Materials and methods

Variable description

Pilot enterprises' carbon emission reduction

This paper collects carbon emission data from the annual social responsibility, sustainability, and environmental reports of pilot firms in the supply chain innovation and

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application program. Then, it calculates carbon emissions per the standards of the "Greenhouse Gas Protocol".

Under this protocol, firms must disclose Scope 1 and 2 emissions. Scope 1 refers to direct emissions from sources owned or controlled by the firm, such as combustion emissions from boilers, furnaces, or vehicles, or emissions from chemical production using owned or controlled process equipment. Scope 2 involves indirect emissions from purchased electricity and heat. The sum of these two scopes is the total carbon-emission figure typically disclosed by firms and is the focus of this paper.

To measure a firm's carbon-emission reduction intensity, the paper calculates the year-on-year change in emissions as a percentage of the previous year's emissions and normalizes this figure.

Digital technology application

To create an index of corporate digital transformation, this paper first uses Python to collect and organize the annual reports of pilot listed firms and leverages the Java PDFbox library to extract all textual content, forming a data pool for subsequent feature word screening.

Drawing on China's recent key policy documents and research reports on digital transformation, we compile a set of specific keywords related to it, forming a feature-word database. As per the earlier analysis, these words are structurally categorized into "Digital Technology Application" and "Foundational digital technology", creating a feature word database (*Fig. 2*).

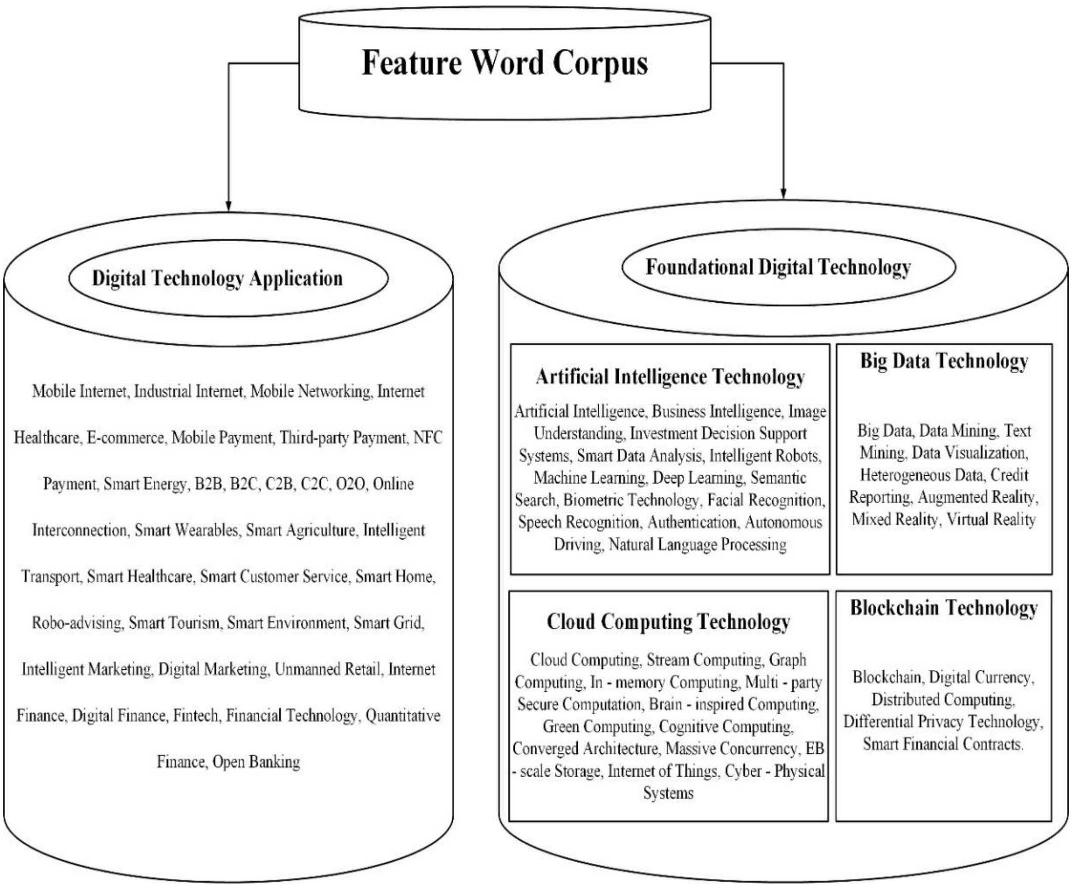

***Figure 2.** Feature word database*

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Next, using Python, we search for and match the feature words from *Figure 2* within the data pool of the listed firms' annual reports. After counting the frequency of these words, we aggregate the key technology related word frequencies. This aggregated count serves as the foundation for building an indicator system of corporate digital transformation. Given the typical right-skewness of this data, we apply logarithmic transformation to obtain an overall indicator of corporate digital transformation.

In this paper, based on the feature word database under the "Digital Technology Application" category in *Figure 2*, we calculate the corresponding word frequency for each enterprise to measure the digital technology application (DTA) level of the pilot enterprises.

Foundational digital technology

In this paper, based on the feature word database under the category of "Foundational Digital Technology" in *Figure 2*, the corresponding word frequency is calculated for each enterprise to measure the FDT level of each pilot enterprise.

Green management innovation

Following the study of Zhao et al. (2015), five indicators are used to measure green management innovation. Considering data availability, the presence of ISO 14001 certification and ISO 9001 certification as disclosed in the "Environmental Regulation and Certification Disclosure Table" of the CSMAR environmental database, and the environmental management system, environmental education and training, and environmental special actions as disclosed in the "Management Disclosure Table" of listed companies, are all summed up to obtain a composite score. This composite score is used as a proxy indicator for corporate green management innovation.

Supply chain dominance

This paper uses supply chain concentration to measure the discourse power of enterprises in the supply chain, and divides it into two parts: supplier discourse power and customer discourse power. Specifically, it is represented by the average of the sum of the purchase and sales proportions of the top five suppliers and the top five customers of the pilot listed companies. In *Equation 1*, the suppliers of pilot firm i in year t are denoted by j, and the customers by k. It is assumed that the enterprise has a total of n suppliers and m customers, with the purchase quantity of suppliers being S and the sales quantity of customers being C.

$$SCD_{i,t} = \frac{1}{2} \times \left(\frac{\sum_{j \in top5} S_{i,j}}{\sum_{j=1}^{n} S_{i,j}} + \frac{\sum_{k \in top5} C_{i,k}}{\sum_{k=1}^{m} S_{i,k}} \right) \quad \text{(Eq.1)}$$

Peer companies' ESG pressure

Referring to the calculation method of Manski (1993), this paper constructs *Equation 2* to measure this variable. Here, i, j, and t represent the enterprise, industry, and year, respectively. N denotes the number of firms in the industry to which enterprise i belongs, and ESG represents the firm's Bloomberg ESG score. Specifically, it indicates the average level of ESG information disclosure by enterprise i's peer firms (excluding enterprise i) in industry j in year t. The formula is as follows.

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$$PCESGP_{i,j,t} = \frac{1}{N-1}\left(\sum_{i=1}^{N} ESG_{i,j,t} - ESG_{i,j,t}\right) \quad \text{(Eq.2)}$$

Local environmental regulation

The measure is the ratio of region c's annual investment in waste gas and wastewater pollution control (E) to the industrial output value (I) for firm i in year t, as shown in *Equation3*.

$$LER_{c,t} = \frac{E_c}{I_c} \quad \text{(Eq.3)}$$

Local public environmental concern

Baidu holds over 70% of China's search engine market. Share Baidu's Search Index analyzes the weighted sum of keyword search frequencies based on search volumes from Baidu. The paper uses "pollution" as a Baidu search keyword to gauge public environmental concern in the locations of pilot firms.

Local digital factionalization

Data elements, made up of databases, etc., are categorized into self-use, marketable, and public-welfare assets. Marketable assets are further divided into licensed services (valued by cost-profit-tax rate) and outright sales (measured by market price). Based on this, the paper uses software business revenue as a proxy variable for data factionalization to measure the level of data factionalization in the regions where firms are located.

The categories, TOE dimensions, definitions, and data sources of the above variables are shown in *Table 1*.

Table 1. *Variable definitions and data sources selected along the TOE dimensions*

Type	Dimension	Name	Definition	Data source
Outcome variable	--	PECER	Pilot enterprises' carbon emission reduction	Social responsibility, sustainability, and environmental reports annually disclosed by pilot enterprises
Condition variable	Technology	DTA	Digital technology application	The annual reports of listed enterprises
		FDT	Foundational digital technology	The annual reports of listed enterprises
	Organization	GMI	Green management innovation	CSMAR Database
		SCD	Supply chain dominance	CSMAR Database
	Environment	PCESGP	Peer companies' ESG pressure	Bloomberg ESG Index
		LER	Local environmental regulation	China Urban Statistical Yearbook
		LPEC	Local public environmental concern	Baidu Search Index
		LDF	Local digital factionalization	Local statistical yearbooks

This paper selects the above data of each pilot firm from 2018 to 2022, constructs cases in the "firm-year" format, and gets 129 valid cases based on data availability.

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Methods

NCA

Necessary Condition Analysis (NCA) is primarily used to examine the necessary conditions for a specific outcome. NCA can not only identify necessary conditions but also measure the effect size of these conditions, also known as the bottleneck level. This represents the minimum value required for a necessary condition to achieve a certain outcome level.

In this paper, a strict NCA method for screening necessary conditions is adopted, which requires satisfying three criteria: (1) The effect size (d) is no less than 0.1; (2) The precision is no less than 95% (Dul, 2016); (3) The Monte Carlo simulation permutation test indicates that the effect size is highly significant ($P \leq 0.01$) (Dul et al., 2020). Depending on the nature of the antecedent and outcome conditions, NCA can use either ceiling regression (CR) or ceiling envelopment (CE) to generate the corresponding functions and analyze the effect sizes.

fs-QCA

Fuzzy-set qualitative comparative analysis (fs-QCA) is a qualitative comparative analysis method based on fuzzy-set theory. This method posits that the characteristics and attributes of things are fuzzy and uncertain, and thus should be described using fuzzy sets. The basic assumption of fs-QCA is that the complexity of social phenomena can be described through the combinations and relationships among multiple factors.

Therefore, based on the necessity analysis using NCA, this paper employs fs-QCA to conduct a configurational analysis of multiple factors. The aim is to reveal the sufficiency effects of the combinations of factors under the TOE framework on the carbon emission reduction intensity of enterprises. In this paper, the consistency threshold is set at 0.8, the PRI consistency at 0.6, and the frequency threshold at 2.

Results

Results of the NCA

Findings of necessity analysis

The paper uses two methods, Consistency and Coverage (CE and CR), for necessity analysis of variables, and the results are in *Table 2*. As shown in *Table 2*, among the conditional variables, except for LDF, the p-values are all above 0.01, so they are not necessary conditions. For LDF, even though its CR p-value and effect size are over 0.01 and 0.1 respectively, its precision is below 95%. Following criteria proposed by Dul (2016), it is also not a necessary condition.

Findings of bottleneck level analysis

To explore the minimum levels of antecedent conditions required for pilot firms to achieve specific carbon-emission reduction targets, the paper conducts bottleneck-level analysis, with results in *Table 3*. As can be seen from *Table 3*, to achieve a 100% PECER level, at least 14% DTA, 39.6% SCD, 29.6% PCESGP, 7.7% LER, 19.4% LPEC, and 50.3% LDF are required. NCA analysis focuses on individual-condition necessity and cannot effectively analyze complex condition combinations. To explore the interactive

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and combinational effects of antecedent variables on pilot firms' carbon-reduction efforts, this paper uses fs-QCA to identify sufficient-condition combinations.

Table 2. *Results of the necessity analysis for each variable*

Condition variables	Method	C-accuracy	Ceiling zone	Effect size	p-value
DTA	CR	100%	0.001	0.001	0.322
	CE	100%	0.003	0.003	0.322
FDT	CR	100%	0.000	0.000	1.000
	CE	100%	0.000	0.000	1.000
GMI	CR	100%	0.000	0.000	1.000
	CE	100%	0.000	0.000	1.000
SCD	CR	90.7%	0.087	0.090	0.013
	CE	100%	0.046	0.048	0.051
PCESGP	CR	98.4%	0.005	0.006	0.618
	CE	100%	0.004	0.004	0.747
LER	CR	98.4%	0.012	0.013	0.189
	CE	100%	0.016	0.017	0.113
LPEC	CR	97.7%	0.017	0.017	0.423
	CE	100%	0.019	0.020	0.393
LDF	CR	84.5%	0.101	0.104	0.005
	CE	100%	0.031	0.032	0.030

Table 3. *Results of the bottleneck level (%) analysis for each variable*

PECER	DTA	FDT	GMI	SCD	PCESGP	LER	LPEC	LDF
0	NN	NN	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN	NN	NN	NN
60	NN	NN	NN	4.8	NN	NN	NN	1.5
70	NN	NN	NN	13.5	NN	0.7	NN	13.7
80	NN	NN	NN	22.2	NN	3	NN	25.9
90	NN	NN	NN	30.9	NN	5.3	8.4	38.1
100	14	NN	NN	39.6	29.6	7.7	19.4	50.3

NN stands for not necessary

Results of the fs-QCA

As research on carbon reduction pathways for supply chain digitalization pilot enterprises remains exploratory with multi-perspective interpretations across dimensions, this study configures all antecedent variables as "Present or Absent" to construct the truth table. Following the principle of prioritizing intermediate solutions while supplementing with parsimonious solutions, we performed contrastive nesting to derive conditional configurations. The results, presented in *Table 4*, yielded several distinct configurations.

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Findings of configuration analysis

As shown in *Table 4*, regarding the high PECER, six configurations can provide an explanation. Based on three prime implicants and with a consistency of over 0.8, they are sufficient conditions for the outcome variable.

For the result variable of low PECER, four configurations have a consistency of over 0.8, making them sufficient conditions for the outcome variable.

Table 4. *Results of conditional variable configuration analysis*

Condition variables	**High PECER**						**Low PECER**			
	H1		**H2**		**H3**		**L1**	**L2**	**L3**	**L4**
	H1a	**H1b**	**H2a**	**H2b**	**H3a**	**H3b**				
DTA	●	●	●	●	●	●	⊗	⊗	⊗	⊗
FDT	⊗	•	•	•	●	●	●	⊗	●	⊗
GMI	●	●	⊗	⊗	⊗		•	⊗	⊗	•
SCD	⊗	⊗	●	●		•	•	⊗	•	•
PCESGP	•	⊗	•	⊗	⊗	⊗	⊗	•	•	⊗
LER	⊗	•	•	⊗	⊗	⊗	•	•	•	⊗
LPEC	⊗	⊗	•	⊗	•	•	⊗	⊗	⊗	⊗
LDF	⊗	⊗	⊗	⊗	●	●		⊗	•	●
Raw coverage	0.193	0.191	0.167	0.169	0.227	0.231	0.178	0.215	0.171	0.171
Unique coverage	0.051	0.020	0.018	0.012	0.019	0.024	0.021	0.082	0.033	0.028
Consistency	0.915	0.929	0.929	0.939	0.846	0.871	0.922	0.867	0.941	0.926
Solution coverage	0.410						0.346			
Solution consistency	0.831						0.870			

Following the approach of Fiss (2011), ● indicates a high level of antecedent conditions, ⊗ indicates a non-high level of antecedent conditions, where the larger circle represents core conditions, the smaller circle represents peripheral conditions, and a blank space indicates that the condition variable can either exist or not exist, being an irrelevant condition

Robustness test

Additionally, this paper has conducted a robustness test on the results in *Table 4*. The robustness test for fs-QCA typically involves adjusting the consistency threshold for cases. Hence, this paper increased the consistency threshold from 0.8 to 0.85. The resulting configurations aligned with those in *Table 4*, confirming the reliability of the *Table 4* results. For conciseness, the results will not be repeated.

Discussion

Based on the results of the aforementioned NCA and fs-QCA, this paper will discuss both high and low carbon reduction efforts, examining case enterprises corresponding to different configuration pathways (represented by stock codes). The information on the pilot enterprises involved in this section is presented in *Table 5*.

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Table 5. *Sample pilot enterprises' listing codes, company names and locations*

Stock code	Company name	Location
SZ000338	Weichai Power Co., Ltd.	Shandong Province
SH600660	Fuyao Glass Industry Group Co., Ltd.	Fujian Province
SH600006	Dongfeng Automobile Co., Ltd.	Hubei Province
SH600808	Maanshan Iron & Steel Co., Ltd.	Anhui Province
SH601058	Sailun Group Co., Ltd.	Shandong Province
SH600811	Oriental Group Co., Ltd.	Heilongjiang Province
SH600839	Sichuan Changhong Electric Co., Ltd.	Sichuan Province
SZ000016	Konka Group Co., Ltd.	Guangdong Province
SH603288	Foshan Haitian Flavouring & Food Co., Ltd.	Guangdong Province
SH600166	Beiqi Foton Motor Co., Ltd.	Beijing City
SH600597	Bright Dairy & Food Co., Ltd.	Shanghai City
SH600079	Huaren Pharmaceutical Co., Ltd.	Shandong Province
SZ002582	Better Life Commercial Chain Share Co., Ltd.	Hunan Province
SH601869	Yangtze Optical Fibre and Cable Joint Stock Limited Co., Ltd.	Hubei Province
SZ002156	Nantong Fujitsu Microelectronics Co., Ltd.	Jiangsu Province
SZ002202	Xinjiang Goldwind Science & Technology Co., Ltd.	Xinjiang Province
SH601100	Jiangsu Hengli Hydraulic Co., Ltd.	Jiangsu Province
SH600309	Wanhua Chemical Group Co., Ltd.	Shandong Province
SZ000401	Tangshan Jidong Cement Co., Ltd.	Hebei Province
SH603188	Jilin Jien Nickel Industry Co., Ltd.	Jilin Province
SZ000825	Taiyuan Iron & Steel Co., Ltd.	Shanxi Province

Configuration paths corresponding to the high level of PECER

Driven by high level of DTA and GMI

The pilot case enterprises corresponding to this configuration path are "SZ000338", "SH600660", "SH600006" and "SH600808". Despite low level of LPEC and LDF, these firms achieve significant carbon emission reduction due to their high level of DTA and GMI.

Take the firm with stock code "SZ000338" as an example. Firstly, its high level of DTA is key for carbon emission reduction. In recent years, the firm has integrated the 5A architecture system into its business processes and developed a unified AI large model R&D and operation platform. This has shifted decision-making from experience-based to data-driven, achieving full-chain digital and intelligent coverage in R&D, production, sales, supply and services. As a result, the efficiency of component product design and testing has improved, and park energy consumption has decreased.

Secondly, its high level of GMI also strongly promotes carbon emission reduction. On the one hand, the firm's three-layer mechanism of "strategic decoding-architecture design-project implementation" has enabled systematic digitalization and greening of the entire value chain. On the other hand, the digitalization and intelligentization promotion committee established as a "top-priority project" has formed a vertical and horizontal governance structure. It uses technology salon matrices to break through key technologies and create a fast track for green technology transformation.

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Driven by high level of DTA and SCD

The pilot case enterprises corresponding to this pathway include: “SH601058”, “SH600811”, and “SH600839”. It can be observed that although these case enterprises operate in regions with relatively low levels of LDF at the environment dimension, they have nonetheless achieved carbon reduction benefits. This is attributable to their high level of DTA and SCD at the technology dimension and the organization dimension.

Taking the enterprise corresponding to stock code “SH601058” as an example. The company has implemented visual energy management through an industrial internet platform, enabling real-time integration of energy consumption data per unit product into its systems, which has significantly reduced electricity consumption. In recent years, it has applied 5G technology to intelligent demonstration production lines, achieving “digital twin” manufacturing. By collecting data from each production line and optimizing processes through AI algorithms, the company has reduced energy consumption. This integrated model of “intelligent manufacturing + green manufacturing” earned it designation as a “Green Factory” demonstration enterprise by China’s Ministry of Industry and Information Technology (MIIT), showcasing how its advanced DTA drives carbon reduction.

Concurrently, the enterprise has focused on optimizing its supplier management system. It has established behavioral standards through agreements with hundreds of suppliers while conducting quality and ESG procurement training, thereby strictly controlling raw material quality. Collaborating with partners to build a green supply chain, it promotes shared responsibility across the industrial chain through “sustainable procurement.” This demonstrates how the company leverages its strong SCD to enhance upstream-downstream collaboration, ultimately advancing its carbon reduction goals.

Jointly driven by high level of DTA, FDT and LDF

The pilot case enterprises corresponding to this pathway include: “SZ000016”, “SH603288”, “SH600166”, “SH600597”, “SH600079”, “SZ002582”, and “SH601869”.

It can be observed that although these case enterprises face relatively low level of PCESGP and relatively weak LER, they have achieved significant carbon reduction efforts. This is primarily due to their high level of DTA and FDT, combined with the high level of LDE. The synergy of these three factors has enabled substantial carbon reductions.

Taking the enterprise corresponding to stock code “SZ000016” as an example, in recent years, it has leveraged its advanced DTA to achieve carbon reduction, primarily manifested in three key areas. First, the enterprise has minimized waste generation through initiatives such as establishing “Green Factories,” enhancing intelligent manufacturing capabilities, and optimizing production processes. Second, it utilizes big data technology to conduct real-time monitoring and data analysis of critical indicators like energy consumption and environmental impact during production. This enables optimization of disassembly-friendly structural designs and low-carbon processes, while increasing the application of eco-friendly materials like biodegradable packaging. Finally, it employs photovoltaic power generation and IoT technology to reduce energy consumption and emissions, achieving efficient resource utilization.

Concurrently, in recent years, the company has established a dual-core technology system of “Chip + Mass Transfer.” Within its semiconductor industry layout, it has formed a comprehensive industrial chain encompassing “design + packaging/testing + distribution” for memory chips. Building on its technological and industrial advantages,

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the company first successfully entered the environmental protection sector and subsequently made large-scale investments in the new energy industry. Today, new energy has become one of its three main industrial pillars. Propelled by its R&D capabilities in FDT, the enterprise has achieved significant carbon reduction.

Furthermore, the company's headquarters is located in Shenzhen, one of China's most developed regions. The high level of LDF has also facilitated the company in achieving substantial carbon reduction through the digital transformation of its supply chain.

Configuration paths corresponding to the low level of PECER

Meanwhile, based on fsQCA, this paper has found four paths that hinder carbon emission reduction in digitalization pilot enterprises.

Path L1 corresponds to the case enterprises of "SZ002156", "SZ002202" and "SH601100". In this path, even though the sample enterprises have a high ability in FDT, their low level of DTA prevents effective carbon emission reduction.

Path L2 corresponds to the case enterprises of "SH600309" and "SZ000401". In this path, the sample enterprises have shortcomings in technology, management and the environment. The joint effect of these three factors restricts the PECER.

Path L3 corresponds to the case enterprises of "SZ002202" and "SH601100". In this path, despite having a high level of FDT, the sample enterprises are subject to low DTA, poor GMI and little LPEC, leading to weak PECER.

Path L4 corresponds to the case enterprises of "SH603188" and "SZ000825". In this path, even if the places where the enterprises are located have high LDF, the enterprises' low DTA hinders PECER. Also, as there is low PCESGP in the industry, the enterprises are less motivated to reduce carbon emissions.

Conclusions and implications

Conclusions

In the context of China's supply chain digitalization pilot policy, to examine how supply chain digitalization affects pilot enterprises' carbon emission reduction, this paper, based on TOE theory, identifies driving factors from three dimensions: technology, organization, and environment. It considers the joint effects of these factors on pilot enterprises' carbon emission reduction and analyzes the configuration effects of enterprise carbon emission reduction paths. Based on the analysis, the paper draws the following main conclusions.

Firstly, NCA shows that no single factor from the three dimensions can independently meet the necessary conditions for corporate carbon emission reduction. Thus, carbon emission reduction in pilot enterprises is the result of the joint action of multiple prior conditions in technology, organization, and the environment.

Secondly, fs-QCA reveals three main pathways for listed Chinese enterprises conducting supply chain digitalization pilots to achieve significant carbon emission reduction. These are: high level of digital technology application and green management innovation; high level of digital technology application and supply chain dominance; and the combination of high level of digital technology application, strong capacity of foundational digital technology, and high level of local data factionalization.

Thirdly, based on the fs-QCA results, this paper finds that low level of digital technology application is a key factor restricting carbon emission reduction in some pilot enterprises.

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Implications

Based on the above research conclusions, this paper derives the following research insights.

Firstly, from the technical perspective, the case of supply chain digitalization pilot enterprises shows that the application ability of digital technology is crucial for promoting corporate carbon emission reduction. Therefore, both pilot and non-pilot enterprises should focus more on and invest more in digital technology application to enhance carbon emission reduction in the future.

Secondly, from the organizational perspective, to reduce emissions via supply chain digital transformation, enterprises need to improve not only their digital technology capabilities but also their green management innovation ability and supply chain influence. On the one hand, green management innovation can boost the overall green learning ability and help establish a green development culture during digital transformation. On the other hand, enhancing the enterprise's position in the supply chain can drive coordinated emission reduction among upstream and downstream enterprises, ensuring sustainable emission reduction.

Lastly, from the environmental perspective, local governments should speed up data factionalization to support enterprises' digital transformation, helping them cut costs and improve efficiency, which in turn promotes carbon emission reduction. The public should also closely monitor enterprises' carbon emission reduction performance. In particular, they should pay attention to enterprises with weak digital technology application and green management innovation. Additionally, enterprises with poor digital technology application and low ESG peer pressure should be closely watched.

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