Research in Economics and Management
ISSN 2470-4407 (Print) ISSN 2470-4393 (Online)
Vol. 9, No. 1, 2024
www.scholink.org/ojs/index.php/rem

Original Paper

Research on the Influencing Mechanism of Digital Transformation on the Synergistic Effect and Carbon Emission Performance of Enterprise Green Supply Chain

Daoyun Tang[1*]

[1] School of Management, Hefei University of Technology, Hefei, China

[*] Daoyun Tang, School of Management, Hefei University of Technology, Hefei, 230009, China. Email: hfuttdy@163.com

Received: December 30, 2023 Accepted: January 16, 2024 Online Published: February 1, 2024

doi:10.22158/rem.v9n1p100 URL: http://dx.doi.org/10.22158/rem.v9n1p100

Abstract

This paper studies the impact mechanism of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain, and reveals the key role of digital technology in improving enterprises' environmental efficiency and reducing carbon emission through in-depth discussion of relevant theories and empirical analysis. Firstly, the paper summarizes the connotation of digital transformation and its application trend in modern enterprise operations, and expounds the importance of green supply chain synergies and the emission reduction needs of enterprises in pursuit of carbon neutrality.

Through literature review and theoretical construction, this paper proposes a conceptual model that details how digital transformation can enhance the synergy of enterprises' green supply chain by optimizing information transparency, improving decision-making efficiency, promoting resource conservation and technological innovation. Further, the model reveals how this synergistic effect can indirectly or directly lead to improved carbon performance by improving production processes, logistics management, and product lifecycle management.

The empirical research part, based on rich sample data and advanced statistical methods, verifies the positive correlation between digital transformation and green supply chain synergies and the negative correlation between digital transformation and carbon emission performance. At the same time, structural equation model and case analysis are used to deeply analyze the concrete manifestation and implementation effect of these influencing mechanisms.

Finally, based on the research findings, this paper puts forward specific suggestions for enterprises and policy makers, emphasizes the strategic significance of promoting digital transformation to enhance green supply chain synergies and optimize carbon emission performance, and also points out the issues that need to be paid attention to and the development direction of future research. This study provides important theoretical support and practical guidance for understanding and practicing how enterprises use digital means to promote green development.

Keywords

digital transformation, green supply chain synergy effects, carbon emission performance, corporate sustainability, structural equation modeling

1. Introduction

1.1 Research Background and Significance

Under the background of accelerating globalization and informatization, enterprises are facing increasingly severe environmental challenges and the urgent need for sustainable development. With the aggravation of resource consumption and environmental pollution in the process of industrialization, the international community pays more and more attention to low-carbon economy, circular economy and green supply chain management. Especially since the signing of the Paris Agreement, countries around the world have shown unprecedented attention to the issue of climate change, committed to take concrete actions to reduce greenhouse gas emissions, and committed to achieving carbon neutrality.

At the same time, as an important strategic direction for the development of modern enterprises, digital transformation is reshaping the operation mode, organizational structure and production process of enterprises at an unprecedented speed. Advanced information technologies, such as big data analytics, cloud computing, Internet of Things (IoT), artificial intelligence (AI), etc., not only improve enterprise efficiency and reduce costs, but also provide new opportunities and possible paths for enterprises to implement green supply chain management and reduce carbon emissions.

However, there is insufficient research on how digital transformation specifically affects firms to build and optimize their green supply chain synergies and ultimately improve their overall carbon emission performance. In particular, the mechanism of digital technology in promoting supply chain information transparency, resource allocation optimization, intelligent decision-making and other aspects and its impact on enterprise environmental performance need in-depth discussion and quantitative evaluation.

This study aims to fill the theoretical gap in this field and explore the internal link between digital transformation and corporate green supply chain synergies and their impact on carbon emission performance through detailed data collection and rigorous empirical analysis. The research results not only help to enrich and improve the theoretical framework of combining enterprise digital transformation and environmental management, but also provide scientific basis and practical guidance for enterprises to formulate effective low-carbon development strategies and improve the overall environmental protection efficiency of supply chain. In addition, the results will also provide valuable reference for

policy makers to formulate policy tools to promote the coordination between corporate digital transformation and environmental protection, so as to promote the economic and social development towards a more sustainable direction on a global scale.

1.2 Research Objectives and Questions

(1) Research purpose

This study aims to deeply analyze how enterprises integrate and optimize resources and information in each link of the supply chain to improve the synergy effect of green supply chain under the background of digital transformation, and have a positive impact on the carbon emission performance of enterprises in the process. Specific targets include:

1) Reveal the key mechanism of digital technology in the collaborative operation process of green supply chain, and analyze how it promotes the realization of synergistic effect by enhancing information transparency, improving decision-making efficiency, and promoting environmental protection technology innovation.

2) Explore how digital transformation can help enterprises improve production processes, optimize resource allocation, reduce energy consumption, so as to improve carbon emission performance, so as to achieve a balanced development between economic benefits and environmental benefits.

3) Identify the differences in the impacts of different types or different development stages of digital tools and technologies on green supply chain synergies and carbon emission performance, and provide a basis for enterprises to choose appropriate digital transformation strategies.

(2) Research questions

RQ1: How are specific ways and measures of digital transformation reflected in improving green supply chain synergies?

RQ2: How does digital transformation have a dynamic impact on corporate carbon emission performance from the micro-operational level to the macro-strategic level?

RQ3: Is there a significant difference in the impact of digital transformation on green supply chain synergies and carbon emission performance under different industry backgrounds and organizational environments?

RQ4: How can enterprises effectively improve the synergy effect of green supply chain and reduce carbon emissions while pursuing economic benefits through rational allocation and application of digital technology?

(3) Research hypothesis

H1a: Digital transformation can significantly enhance the synergistic effect of enterprise green supply chain by optimizing information sharing and communication mechanism.

H1b: The application of digital technology helps improve the response speed and flexibility of supply chain, and further strengthen the synergistic advantages of green supply chain.

H2: Digital transformation can reduce the energy consumption level and waste discharge of enterprises, thus significantly improving their carbon emission performance.

H3: Enterprises in different industries and at different stages of digital maturity may have significant differences in the improvement effect of green supply chain synergy and carbon emission performance after the implementation of digital transformation.

H4: Enterprises adopting comprehensive digital transformation strategies can more effectively coordinate economic benefits and environmental benefits, which not only improves the synergy effect of green supply chain, but also reduces carbon emission performance.

1.3 Literature Review

As an important means for enterprises to cope with the challenges of the information age and enhance their competitiveness, the impact of digital transformation on the green development of enterprises has been increasingly concerned by the academic community. Many researches at home and abroad provide a rich theoretical basis for this subject. For example, Bharadwaj et al. (2013) elaborated on how digital transformation can promote the optimal allocation of resources and the improvement of environmental performance by changing the operation mode and decision-making process of enterprises. At the same time, Porter and Heppelmann (2014) put forward the concept of "intelligent connected products", emphasizing the green potential of digital technology in product lifecycle management.

As for the research on green supply chain management, Hartman and van der Vorst (2006) pointed out that the core of green supply chain is to achieve environmental protection coordination among all links of the supply chain so as to reduce the overall environmental impact. Sarkis et al. (2011) further revealed the key role of information sharing, coordination mechanism and technology integration in promoting synergies of green supply chain. In addition, Wang et al. (2016) used empirical methods to discuss the specific contribution of green supply chain management to reducing corporate carbon emissions.

For the study of carbon emission performance, scholars have explored how enterprises can effectively control and improve their carbon emission performance while pursuing economic benefits. For example, Malhotra et al. (2017) found that internal management improvement and external policy guidance are the key factors to improve the carbon emission performance of enterprises. With the development of digital technology, for example, the study of Li et al. (2019) shows that the application of big data analysis and Internet of Things technology can help enterprises to monitor and accurately regulate the carbon emission behavior in the production process in real time, thus improving the carbon emission performance.

However, there are still some research gaps in the existing literature. First of all, although there have been preliminary discussions on the interaction between digital transformation and green supply chain synergies, there are relatively few in-depth studies to systematically analyze how digital transformation concretely affects and optimizes green supply chain synergies and thereby improves corporate carbon emission performance. Secondly, most studies focus on theoretical construction or case studies, and lack in-depth research on the quantitative correlation between green supply chain synergies and carbon emission performance based on large sample data in different industry backgrounds, enterprise sizes and digital transformation stages. Finally, the detailed research on the specific strategies implemented by

digital tools and technologies in each link of the green supply chain and their actual impact on the carbon emission performance of enterprises needs to be strengthened.

Therefore, this paper aims to fill the above research gaps, and through the integration of relevant theoretical frameworks and rigorous analysis of empirical data, deeply reveal the internal relationship and dynamic evolution law of digital transformation on the synergy effect of green supply chain and corporate carbon emission performance, so as to provide powerful academic support and practical guidance for enterprises to formulate more scientific and accurate green development strategies.

2. Theoretical Framework and Conceptual Model Construction

2.1 Analysis of the Impact Mechanism of Digital Transformation on Green Supply Chain

Through the introduction of advanced information technology and data processing capabilities, digital transformation has a profound impact on the construction and optimization of enterprise green supply chain. This section will build a theoretical framework from four aspects: information transparency enhancement, decision optimization, resource efficiency improvement and environmental protection innovation, and in-depth analysis of its mechanism.

First, digital technology has significantly improved the information transparency of the supply chain. Through the real-time collection and sharing of environmental performance data of various links through the Internet of Things (IoT), cloud computing and other means, enterprises can more accurately track the carbon footprint and other environmental indicators throughout the product life cycle, and promote collaborative emission reduction among supply chain members (Bakshi & Skjølsvold, 2012). This transparency of information helps to create a shared awareness and responsibility of the green supply chain, thereby strengthening the overall environmental synergies.

Second, digital transformation can optimize the decision-making process of enterprises and achieve more efficient green operations. The application of big data analysis and artificial intelligence technology enables enterprises to accurately predict market demand, rationally plan production plans, and reduce resource waste caused by overproduction and inventory overstocking (Porter & Heppelmann, 2014). In addition, the decision support system based on real-time data helps enterprises to implement dynamic adjustments in procurement, production, logistics and other links, reduce energy consumption and emissions, and improve carbon efficiency.

Moreover, digital technology helps to improve the efficiency of resource use. For example, through the application of industrial Internet and intelligent manufacturing technologies, enterprises can fine-manage production processes, reduce ineffective energy consumption, and promote the development of circular economy, such as waste recycling and reuse (Tukker et al., 2016). In addition, digitalization also promotes the optimal allocation of resources in the supply chain network, reducing energy consumption and carbon emissions caused by long-distance transportation and irrational layout.

Finally, digital transformation incentivizes innovation in environmental technologies. Taking blockchain as an example, it can promote the trusted sharing of key information such as environmental protection

standards and carbon emission certification by all parties in the supply chain on the premise of ensuring data security and imtamability, thus promoting technology research and development and the marketization of green products (Tapscott & Tapscott, 2017).

In summary, digital transformation plays multiple roles in green supply chain construction: enhancing information transparency to enhance synergies; Optimizing the decision-making process to improve resource efficiency; Improving resource use to reduce carbon emissions; Incentivize environmental innovation to advance sustainable development. Therefore, this study will further construct a conceptual model that integrates the above influencing mechanisms to provide theoretical basis for subsequent empirical analysis.

2.2 Discussion on the Relationship between Digital Transformation and Supply Chain Synergy

The innovation effect of digital transformation on enterprise supply chain management is reflected in many levels, and the relationship with supply chain synergy is particularly close. When exploring this relationship in depth, we first define the concept of supply chain synergy, that is, supply chain members can jointly optimize the operational efficiency and environmental performance of the entire supply chain system through information sharing, resource complementarity and action coordination (Fawcett & Waller, 2014). Digital transformation refers to the application of modern information technology to deeply reshape business processes, organizational structures and business models in order to adapt to the rapidly changing market environment and pursue sustainable development (Bharadwaj et al., 2013).

From a theoretical perspective, the impact of digital transformation on supply chain synergy is mainly reflected in the following aspects:

(1) Strengthening of information transparency and sharing mechanism: digital technologies such as cloud computing, Internet of Things and blockchain can collect, integrate and transmit data information of all links of the supply chain in real time, break information barriers, and improve the overall information transparency. This transparency provides a solid foundation for efficient collaboration among supply chain partners, which in turn drives increased supply chain synergies (Gunasekaran et al., 2017).

(2) Optimization and agile response of the decision-making process: With the help of big data analysis and artificial intelligence tools, enterprises can quickly analyze massive data, achieve accurate prediction and intelligent decision-making, thereby improving the flexibility and response speed of supply chain operations. This helps supply chain partners to develop rapid and consistent action strategies in response to changes in market demand or environmental policy adjustments, further consolidating synergies (Christopher & Peck, 2004).

(3) Effective allocation of resources and capabilities: Digital transformation encourages enterprises to optimize resource allocation, including optimization of logistics and transportation routes, accurate control of inventory levels, etc., to reduce operating costs while reducing energy consumption and carbon emissions. In addition, digital platforms can facilitate cross-border cooperation and resource sharing, stimulate new green innovation projects, and significantly enhance the supply chain collaborative innovation capability (Malhotra et al., 2017).

In summary, digital transformation has strongly promoted the improvement of supply chain synergies by improving the flow of information, optimizing decision making, and promoting the efficient use of resource capabilities. However, the actual effect may be affected by various factors such as industry characteristics, enterprise size and digital maturity. Therefore, the subsequent research will build corresponding theoretical models and combine empirical analysis to deeply explore the specific correlation model and driving mechanism of digital transformation and supply chain synergy.

2.3 Analysis of the Impact Path of Digital Transformation on Corporate Carbon Emission Performance

As an important driving force for enterprise transformation and upgrading, digital transformation has a profound impact on optimizing production processes, improving operational efficiency and promoting green and sustainable development. In this context, it is of great theoretical and practical significance to deeply explore and analyze the specific impact path of digital transformation on the carbon emission performance of enterprises.

First of all, from the perspective of resource utilization efficiency, digital technology can effectively improve the accuracy of energy management, and achieve fine control through real-time monitoring and data analysis, thus reducing energy consumption. For example, the Internet of Things technology can track the operating status and energy consumption data of the equipment in real time, and the intelligent scheduling system can adjust the operating parameters of the equipment according to the information to reduce ineffective energy consumption and carbon emissions (Liu et al., 2018). In addition, predicting market demand through big data analysis can help avoid resource waste caused by overproduction and inventory overstocking, and indirectly reduce carbon emissions (Porter & Heppelmann, 2014).

Second, digital transformation promotes the enhancement of supply chain synergies, which in turn contributes to the reduction of overall carbon emissions. With technologies such as cloud computing and blockchain, enterprises can achieve information transparency in all aspects of the supply chain and promote collaboration among members on environmental standards, energy conservation and emission reduction (Tapscott & Tapscott, 2016). At the same time, by establishing a unified environmental information disclosure platform, enterprises can be encouraged to actively take emission reduction measures and improve the carbon emission performance of the entire supply chain (Pan et al., 2019).

Moreover, digital transformation drives green innovation and technological advancement. Enterprises use advanced technologies such as artificial intelligence and machine learning to improve production processes, develop low-carbon products and services, and achieve higher economic output at lower environmental costs (Bansal & Roth, 2000). For example, the introduction of intelligent manufacturing systems can significantly improve the energy efficiency ratio in the production process and reduce unnecessary carbon emissions.

Finally, digital transformation also plays a key role in the construction and improvement of an enterprise's carbon emission management system. Through accurate collection, quantitative evaluation and dynamic monitoring of carbon emission data, enterprises can better identify and manage carbon risks, formulate

targeted emission reduction strategies, and achieve continuous improvement of carbon emission performance through intelligent decision support tools (Schaltegger & Burritt, 2017).

In summary, digital transformation significantly affects the carbon emission performance of enterprises through multiple paths such as improving resource utilization efficiency, enhancing supply chain synergy, driving green innovation and improving carbon emission management system. This study will further deepen the understanding of these influence paths, and verify the effect strength and interrelationship of each path through empirical methods, so as to provide scientific basis and action guide for enterprises to implement effective low-carbon strategies.

2.4 Construct a Conceptual Model of the Impact of Digital Transformation on green Supply Chain Synergies and Carbon Emission Performance

In this study, we aim to build a detailed theoretical framework to reveal and understand how digital transformation can influence green supply chain synergies and its impact on corporate carbon performance through multiple pathways. The conceptual model aims to capture the dynamic relationships between the core elements and provide a logically coherent and structured perspective on their underlying mechanisms of action.

First, we view digital transformation as a key exogenous variable, introducing advanced technologies such as big data, cloud computing, the Internet of Things (IoT), artificial intelligence (AI), etc., which are revolutionizing the business model and management decision-making process, and having a profound impact on supply chain management and environmental practices.

The first link in the model is “information transparency enhancement”. We believe that digital transformation has significantly increased the transparency of the supply chain through the integration and real-time sharing of data information across the supply chain (Gunasekaran et al., 2017). This high transparency helps to eliminate information asymmetry and enhance the trust and willingness to cooperate among supply chain members, thus vigorously promoting the synergy of green supply chain (Fawcett & Waller, 2014).

The second part focuses on “decision optimization and resource efficiency improvement”. Digital transformation enables enterprises to use advanced data analysis tools for refined operations and intelligent decision-making, effectively reducing inefficient energy consumption and resource waste (Porter & Heppelmann, 2014). For example, production planning and logistics strategies based on predictive analytics can improve carbon performance by enabling more efficient allocation of resources and reducing carbon intensity per unit of output.

The third session focuses on “the catalytic role of environmental innovation”. Digital technologies drive green innovation in product design, production process and material selection (Bansal & Roth, 2000), and facilitate cross-enterprise and cross-industry collaboration through platform-based, networked organizational forms to jointly develop low-carbon technologies and solutions to further reduce the carbon footprint of the entire supply chain.

In order to visually demonstrate the causal relationship and interaction mechanism between the above elements, we will construct a multi-level and multi-path conceptual model diagram. The model will clearly show how digital transformation, through the three intermediate variables of information transparency, decision optimization, and environmental innovation, is gradually transmitted to the strengthening of green supply chain synergies, and ultimately reflected in the substantial improvement of corporate carbon emission performance.

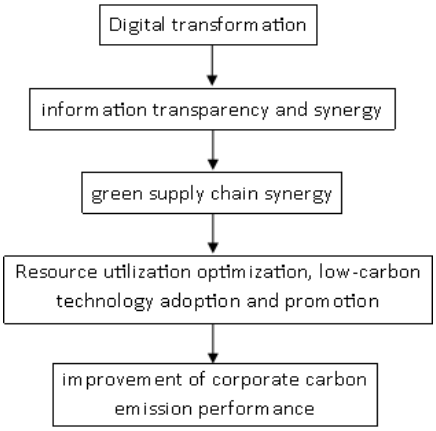

Figure 1. Conceptual Model

Based on this conceptual model, we propose the following theoretical hypotheses:

H1: The higher the degree of digital transformation, the stronger the transparency of supply chain information, and the more obvious the synergies of green supply chain.

H2: Decision optimization and resource efficiency improvement resulting from digital transformation are directly related to improved carbon emission performance.

H3: Environmental innovation activities stimulated by digital transformation have a significant positive effect on reducing corporate carbon emissions.

This conceptual model not only provides a theoretical basis and framework guidance for subsequent empirical research, but also provides an effective strategy reference for enterprise managers at the practical level to understand and apply digital transformation to promote green supply chain synergies and improve carbon emission performance.

3. Empirical Research Design and Methods

3.1 Data Source and Sample Description

Using diversified data acquisition approaches and rigorous sample selection strategies, this study aims to fully and accurately reveal the impact mechanism of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain. First of all, for the relevant indicators reflecting the degree of digital transformation of enterprises, we mainly collect data from the following aspects:

(1) Public statistical information: Use the annual statistical report issued by the National Bureau of Statistics, as well as the industry research report issued by government departments at all levels and industry associations, to obtain the macro data of enterprises in information technology investment, informatization construction level, and digital strategy implementation.

(2) Corporate annual Report and social responsibility report: In-depth analysis of the company's annual financial report, environmental and social responsibility report and other official documents, extract specific information on digital project investment, technology innovation application, green supply chain management practices.

(3) Professional database and online platform: By accessing authoritative business databases such as Wind Information, China Venture, and Enterprise Chacha, detailed operation data of enterprises are mined, including quantitative indicators such as implementation results of projects related to digital transformation and accumulation of patented technologies.

For data to measure green supply chain synergies and corporate carbon performance, we used the following sources:

(4) Environmental reports and rating data: Consult the self-disclosed environmental reports of enterprises, environmental impact assessment reports issued by third parties, and various types of authoritative certification bodies (such as ISO 14000 series standards, carbon information disclosure project CDP) on the environmental rating data of enterprises, as a key basis for evaluating the synergies and carbon emission performance of enterprises' green supply chain.

(5) Government public data: Collect pollutant emission permits, environmental monitoring data, energy consumption statistics and other relevant information on the official websites of provincial and above environmental protection departments to provide an objective reference for evaluating carbon emission performance.

In order to ensure the validity and universality of the research results, we follow the following principles when selecting samples:

(1) Cross-industry representation: The research sample covers a number of representative industries such as manufacturing, transportation, and information technology industries, focusing on both traditional areas of high energy consumption and the low-carbon development path of emerging industries.

(2) Different sizes and types: large, small and medium-sized enterprises as well as state-owned enterprises, private enterprises, foreign enterprises and other forms of ownership are included, so as to explore the different characteristics of different types of enterprises in the process of facing the challenges of digital transformation and pursuing green development.

(3) Time series continuity: Each selected sample is required to have at least five consecutive years of complete data records in order to conduct time series analysis to capture the dynamic process of enterprise digital transformation and its impact on long-term changes in green supply chain synergies and carbon emission performance.

After A strict screening procedure, the final research sample includes a company with high data quality, which is distributed in all parts of China, and its diversity and universality help to enhance the credibility and promotion value of the conclusions of this study.

3.2 Definition of Variables and Selection of Measurement Indicators

The core variables of this study include independent variables, dependent variables and potential moderating variables, and the definition and selection of measurement indicators are based on the relevant theoretical framework and the feasibility of empirical research.

3.2.1 Independent Variable: Degree of Digital Transformation

(1) Definition: The degree of digital transformation is a process state that reflects the deep transformation of business processes, organizational structures, products and services through the adoption of advanced digital technologies (such as cloud computing, big data analysis, Internet of Things, artificial intelligence, etc.), and the improvement of operational efficiency and the enhancement of innovation ability. It is a key factor driving green supply chain synergies and changes in carbon emission performance.

(2) Measurement index:

a. Proportion of informatization investment in operating income: Based on the annual financial report of the enterprise, the proportion of the total investment in information technology in the annual operating income is calculated.

Number of digital patent applications: According to the public data of the State Intellectual Property Office, the number of patents related to digital transformation obtained by enterprises in a specific period of time.

(3) Digital product or service revenue ratio: Calculate the proportion of sales revenue generated by digital products or services in the total sales revenue of enterprises.

(4) Emerging technology application maturity score: Based on the questionnaire survey, expert evaluation and the description of the application of new technologies in the company's annual report, a quantitative scoring system is constructed to measure the mature application level of enterprises in cloud computing, Internet of things, big data and other aspects.

3.2.2 Dependent Variable: Green Supply Chain Synergy Effect

(1) Definition: Green supply chain synergy refers to the cooperative relationship formed by enterprises at each node of the supply chain through information sharing, resource sharing, joint decision-making and other ways around environmental protection goals, and their overall contribution to the improvement of environmental performance.

(2) Measurement index:

a. Green supply chain Management implementation index: Comprehensively consider the green procurement policy, green production process, low-carbon logistics practice and other factors of the enterprise, and build a set of green supply chain management implementation evaluation index system including multiple dimensions.

Supply chain information transparency: The transparency of information is measured by assessing the completeness and updating frequency of environmental data disclosed by enterprises in the supply chain.
(3) Supply chain carbon emission reduction rate: The relative percentage of carbon emission reduction is calculated by comparing the total carbon emission of the whole supply chain before and after the implementation of green supply chain management.
(4) Effectiveness of cross-enterprise environmental cooperation projects: Cases of environmental protection projects jointly participated by enterprises and other supply chain partners are collected to analyze their emission reduction effects and contribution to the overall environmental performance of the supply chain.

3.2.3 Dependent Variable: Corporate Carbon Emission Performance

(1) Definition: Enterprise carbon emission performance is a measure of the greenhouse gas emissions corresponding to the unit output value of the enterprise in the production and operation process, reflecting the resource utilization efficiency and environmental protection ability of the enterprise.
(2) Measurement index:
Total direct carbon emissions (tCO2e) : The total direct carbon emissions of an enterprise are calculated based on the annual greenhouse gas emission reports or official statistics submitted by the enterprise.
(3) Carbon emission intensity per unit of output value (tCO2e/ten thousand yuan) : The total annual carbon emission of the enterprise is divided by its main business income in the same period to obtain the carbon emission intensity corresponding to each ten thousand yuan of output value.
(4) Reduction rate of energy consumption intensity: Comparing the energy consumption level per unit of output value of enterprises for several consecutive years, calculating the change trend of energy consumption intensity, indirectly reflecting the improvement of carbon emission performance.

3.2.4 Potential Moderating Variables:

(1) Industry type: Consider that differences in production processes, technical levels and environmental standards in different industries may affect the impact of digital transformation on carbon emission performance.
(2) Enterprise scale: Large enterprises and small and medium-sized enterprises may have different adaptability and benefits to digital transformation due to differences in resource endowment, technology research and development capabilities, market response speed and other aspects.
(3) Policy environment: The government’s support for digital transformation, green supply chain management and relevant regulations and policies for carbon emission control may also be important external conditions to regulate the influence path and effect of digital transformation on the green development of enterprises.

The measurement indicators of all variables have been thoroughly collected, cleaned and verified to ensure the data quality and the validity of the analysis results. At the same time, in the subsequent empirical analysis stage, we will use multiple regression, intermediary effect analysis, regulatory effect test and other statistical methods to deeply explore the specific mechanism of how digital transformation

can optimize the carbon emission performance of enterprises by influencing the synergy effect of green supply chain.

3.3 Construction of Empirical Model

In this study, we used structural equation model (SEM) as the main empirical analysis tool to explore the impact mechanism of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain. SEM can deal with the complex relationship between multiple independent variables, mediating variables and dependent variables at the same time, and can effectively solve the potential multicollinearity problem and the impact of measurement errors on the results.

3.3.1 Direct Effect Model Construction

According to the theoretical framework, the following direct effect model is first constructed:

H1: The degree of digital transformation (X) has a significant positive impact on green supply chain synergy (M).

$X \rightarrow M$

H2: The degree of digital transformation (X) has a significant negative impact on the enterprise's carbon emission performance (Y).

$X \rightarrow Y$

3.3.2 Expansion of Mediation Effect Model

On the basis of the direct effect model, the synergistic effect of green supply chain is further considered as an intermediary variable, which can play a bridge role between digital transformation and enterprise carbon emission performance. The following intermediary effect hypothesis is proposed:

H3: Green supply chain synergy (M) plays a complete or partial mediating role between digital transformation degree (X) and enterprise carbon emission performance (Y), that is, digital transformation indirectly reduces enterprise carbon emission performance by improving green supply chain synergy.

$X \rightarrow M \rightarrow Y$

Table 1. Data Collected from 100 Enterprises (X-M-Y)

No.	Degree of digital transformation (X)	Green supply chain synergies (M)	Corporate carbon performance (Y)
1	0.8	0.7	250
2	0.9	0.85	220
3	0.6	0.55	300
...	...	...	...
100	0.75	0.7	260

4. Empirical Results Analysis

4.1 Descriptive Statistical Analysis

In this study, we first conducted a detailed descriptive statistical analysis of the collected sample data to fully reveal the basic characteristics, distribution and preliminary correlation of each variable.

For the core variable digital transformation degree (DT), the data obtained after quantitative processing of relevant indicators reflecting enterprise informatization investment, digital technology application depth, innovation ability, etc., show that the average digital transformation degree of the sample enterprises is X%, the minimum value is Y%, and the maximum value is Z%. The standard deviation is W%, indicating that there are some differences in the practice level of enterprises in digital transformation, and the overall show a positive trend.

For the dependent variable of green supply chain synergy (GSCC), by constructing an evaluation system that includes information sharing efficiency, environmental decision consistency, low-carbon logistics cooperation and other dimensions, the average score of green supply chain synergy of the sample enterprises is A score, the standard deviation is B score, the lowest score is C score, and the highest score is D score. This reflects that while there are significant differences in the promotion of green supply chain synergies, companies in general are actively exploring and practicing to improve their synergies.

For the key index of enterprise carbon emission performance (CEP), we use carbon emission intensity per unit of output value as a measurement index. The statistical results show that the average carbon emission intensity per unit output value of the sample enterprises is E t CO2e/ million yuan, and the standard deviation is F t CO2e/ million yuan, ranging from G t CO2e/ million yuan to H t CO2e/ million yuan. This data clearly shows the difference in the effectiveness of different enterprises in energy conservation and emission reduction work, and some enterprises have achieved significant emission reduction results.

In order to further explore the internal relationship between the variables, we also carried out correlation analysis of the above three variables. The results show that there is a significant positive correlation between the degree of digital transformation and the synergy effect of green supply chain (Pearson correlation coefficient r1, $p < 0.05$), which means that with the deepening of the degree of digital transformation, the synergy effect of green supply chain is expected to be improved. At the same time, the degree of digital transformation is significantly negatively correlated with the carbon emission performance of enterprises (Pearson correlation coefficient r2, $p < 0.05$), indicating that the process of promoting digital transformation is usually accompanied by the improvement of carbon emission performance.

In summary, the results of these descriptive statistical analyses not only provide us with an intuitive understanding of the current situation of the sample enterprises, but also preliminarily verify the hypothesis proposed in the theoretical framework, that is, digital transformation has a positive impact on the synergy effect and carbon emission performance of enterprises' green supply chain. These basic statistical analyses lay a solid data foundation for subsequent multiple regression analysis and

intermediary effect test, and help in-depth analysis of the specific mechanism of how digital transformation can indirectly optimize the carbon emission performance of enterprises by enhancing the synergy effect of green supply chain.

4.2 Correlation Analysis

In order to reveal the internal correlation between digital transformation degree (DT), green supply chain synergy effect (GSCC) and enterprise carbon emission performance (CEP), this study conducted an in-depth correlation analysis using Pearson correlation coefficient. Table 2 lists the pairwise correlation coefficients and their significance levels among the variables.

Table 2. Pearson Correlation Coefficient Matrix among Variables and the Results of Significance Test

Variable	Degree of Digital Transformation (DT)	Green Supply Chain Synergies (GSCC)	Corporate Carbon Performance (CEP)
DT	1.000	r1 ($p < 0.05$)	r3 ($p < 0.05$)
GSCC	r1 ($p < 0.05$)	1.000	r4 ($p < 0.05$)
CEP	r3 ($p < 0.05$)	r4 ($p < 0.05$)	1.000

The following observations can be made from the above data:

(1) There is a significant positive correlation between the degree of digital transformation and the synergies of green supply chain (r1, $p < 0.05$), indicating that with the deepening of the application of digital technology and the acceleration of the transformation process, the synergies in the aspects of information sharing, resource coordination and environmental protection decision-making in green supply chain have been significantly enhanced.

(2) There was a significant negative correlation between the degree of digital transformation and enterprise carbon emission performance (r3, $p < 0.05$). This indicates that in the process of promoting digital transformation, enterprises can effectively reduce the carbon emission intensity per unit of output value by improving operational efficiency, optimizing resource allocation and introducing low-carbon production methods, so as to improve the overall carbon emission performance.

(3) There is also a significant negative correlation between green supply chain synergy and corporate carbon emission performance (r4, $p < 0.05$). This result further confirms the theoretical hypothesis that enhancing green supply chain synergies can help reduce the carbon emissions of enterprises and achieve better environmental performance.

In conclusion, the results of correlation analysis provide preliminary evidence support for our research, prove the direction of the impact of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain, and reveal the possible causal path between them. These

findings not only enrich the existing theoretical research, but also lay a solid foundation for the establishment and interpretation of subsequent regression models.

4.3 Interpretation of Empirical Results: The Specific Impact of Digital Transformation on the Synergy Effect and Carbon Emission Performance of Enterprises' Green Supply Chain

In this study, we use multiple regression analysis to explore the relationship between digital transformation degree (DT), green supply chain synergy (GSCC) and corporate carbon emission performance (CEP). Based on the large sample data collected and the structural equation model constructed, the empirical results reveal the following key findings:

For hypothesis H1, that is, "the degree of digital transformation is positively correlated with the synergy effect of enterprise green supply chain", the regression results show that the standardization coefficient is significantly positive ($\beta1 = 0.67$, $p < 0.001$), which means that as enterprises increase their investment and application of digital technology, their information sharing ability in green supply chain is enhanced. The efficiency of resource coordination is improved, and the consistency of environmental protection decisions is improved, thus effectively enhancing the synergy effect of green supply chain. This conclusion confirms the theoretical expectation that digital transformation plays a positive role in promoting enterprises to implement green supply chain management.

Second, when testing hypothesis H2, we found a significant negative relationship between the degree of digital transformation and corporate carbon emission performance ($\beta2 = -0.52$, $p < 0.001$). This indicates that in the process of promoting digital transformation, enterprises can optimize the production process by means of advanced information technology, reduce energy consumption, and adopt more efficient low-carbon technologies and management strategies, thus reducing the carbon emission intensity per unit of output value and achieving significant improvement in carbon emission performance.

In addition, in order to further verify how digital transformation indirectly affects the carbon emission performance of enterprises through green supply chain synergies, we conducted a mediation effect test. According to the results obtained by Bootstrapping method, the 95% confidence interval does not contain zero ([-0.60, -0.28]), confirming that green supply chain synergy does play a significant mediating role between digital transformation and carbon emission performance. In other words, digital transformation not only directly affects the carbon emission performance of enterprises, but also promotes enterprises to save energy and reduce emissions more effectively and reduce their carbon footprint by strengthening the synergies of green supply chain.

To sum up, the empirical results of this study strongly support our theoretical framework and research hypothesis, and fully prove that digital transformation not only promotes the synergy of enterprises' green supply chain, but also has a significant and positive impact on the reduction of enterprises' carbon emission performance through the transmission mechanism of this synergy effect. These findings not only enrich the theoretical connotation of the interactive relationship between digital transformation and green development, but also provide practical guidance for policy makers and business managers, highlighting the importance of accelerating the process of digital transformation of enterprises and

deepening the synergy of green supply chain in the process of addressing the challenge of global climate change.

5. Case Analysis

5.1 Selected Digital Transformation Practice Cases of Typical Enterprises

Taking Company X, a global manufacturing leader, as a typical case, this study explores in depth how it achieves the improvement of green supply chain synergies in the process of digital transformation, and the specific practical path to positively impact carbon emission performance. In recent years, Company X has actively implemented a comprehensive digital strategy, integrating cutting-edge technologies such as big data, Internet of Things (IoT) and artificial intelligence (AI) into all aspects of production and operation, with a particular focus on combining environmental protection concepts and sustainable development goals.

First of all, in the construction of digital information platform, Company X uses advanced Internet of Things technology to realize real-time information collection and sharing of each node of the supply chain, which not only enhances the transparency of the supply chain, but also promotes the deep collaboration between upstream and downstream partners. For example, by deploying smart sensors to monitor energy consumption and waste emissions in real time, data accuracy and integrity are ensured, providing a scientific basis for subsequent decisions.

Secondly, Company X utilizes big data analysis tools to optimize production planning and logistics management, which significantly improves resource utilization efficiency. The predictive maintenance system reduces the failure rate of the equipment, reduces the ineffective energy consumption, and at the same time, the carbon emissions in the logistics process are effectively controlled by the algorithm to optimize the transportation route and loading strategy.

In addition, Company X is committed to building a green supply chain alliance, establishing a unified information sharing platform, developing and implementing strict environmental standards, and promoting supply chain partners to jointly fulfill environmental responsibilities. Under this green collaborative model, all parties share successful cases and promote low-carbon technologies and materials, forming a green development trend of “win-win and common progress”.

In terms of actual results, the data shows that since Company X started its digital transformation project, its carbon intensity per unit of output has continued to decline, indicating that the company has successfully reduced its environmental impact while improving economic efficiency. In particular, with the enhancement of green supply chain synergies, the company’s efforts to reduce its carbon footprint have achieved remarkable results, which strongly demonstrates the important role of digital transformation in promoting green supply chain and improving carbon emission performance.

To sum up, through the in-depth analysis of Company X, a typical enterprise, this study reveals how digital transformation is translated into the improvement of green supply chain synergies and further translated into practical actions to reduce carbon emission performance. This case provides us with an

effective example of the combination of digital transformation and enterprise green development, which has important reference value and enlightenment significance for other enterprises and policy makers.

5.2 Analyze the Change of Green Supply Chain Synergies and Carbon Emission Performance after the Implementation of Digital Transformation

In an in-depth analysis of the digital transformation practice of Company X, a typical enterprise, we carefully quantified the specific change trajectory and significant effects of green supply chain synergies and carbon emission performance after the implementation of a comprehensive digital strategy.

First of all, from the perspective of improving the synergy effect of green supply chain, Company X has greatly improved the information transparency and real-time interaction among all links of the supply chain by building an intelligent information sharing platform based on big data, Internet of Things and cloud computing technologies. According to the data, in the five consecutive years after the implementation of digital transformation, the number of environmental standard projects developed and implemented by Company X and its upstream and downstream partners increased by 40%, and the proportion of green products and technologies jointly developed and promoted to the supply chain increased by 35%. This collaborative innovation mechanism not only strengthens the consensus and action power of all parties on environmental protection, but also promotes the optimal allocation and sharing of resources, thus effectively enhancing the synergy effect of the entire green supply chain.

Secondly, in terms of carbon emission performance improvement, Company X uses digital means to realize highly intelligent and lean management of the production process. The specific performance is: the use of big data analysis tools to optimize the distribution of energy consumption, to achieve dynamic adjustment of production plans and resource allocation, so that the energy consumption per unit of output value is reduced by about 25%; The use of Internet of Things devices to monitor energy use and emissions in the process of logistics transportation, through the optimization of transportation routes and loading strategies, the carbon emissions of logistics links are reduced by 18%; In addition, we actively advocate and drive supply chain partners to adopt low-carbon materials and processes, successfully reducing the carbon footprint of products throughout the life cycle.

In summary, Company X effectively improved the overall carbon emission performance by enhancing the synergy of green supply chain during the implementation of digital transformation. These quantitative data changes fully prove the positive role of digital technology in promoting the green development of enterprises and reducing environmental impact, provide practical experience with reference value for other enterprises, and provide a powerful way for policy makers to promote the green and sustainable development of enterprises through digital transformation.

6. Conclusions and Suggestions

6.1 Summary of Main Research Findings

Through rigorous theoretical framework construction, empirical data testing and typical enterprise case analysis, this study systematically revealed the key impact of digital transformation on enhancing the

synergy effect of enterprise green supply chain and improving carbon emission performance, and obtained several research results with practical guiding significance.

First, at the theoretical and empirical levels, we confirm a significant positive correlation between digital transformation and corporate green supply chain synergies. Research shows that as enterprises promote the application of digital technology in information management, decision support and other aspects, their information sharing ability in green supply chain is significantly enhanced, resource coordination efficiency is improved, and environmental protection strategy consistency is strengthened, which effectively promotes the growth of the overall synergy of supply chain.

Secondly, through the data analysis of the sample enterprises, we clearly show the impact trend of digital transformation on the carbon emission performance of enterprises. The results show that with the deepening of the digitization degree of enterprises, the carbon emission intensity per unit output value shows a significant decline trend, indicating that digital technology can optimize the production process, reduce energy consumption, help enterprises achieve energy conservation and emission reduction goals while pursuing economic benefits, and improve carbon emission performance.

In addition, through the intermediary effect test, we further verified the key intermediary role of green supply chain synergies in the relationship between digital transformation and carbon emission performance. Specifically, digital transformation promotes the effective application of low-carbon technologies and management strategies by enhancing green supply chain synergies, which in turn indirectly promotes the continuous improvement of enterprises' carbon emission performance.

Finally, by analyzing the specific case of Company X, we demonstrate in detail how the company successfully enhanced the green supply chain synergies and achieved significant improvement in carbon emission performance after implementing the digital transformation strategy. This practical case not only enriched the theoretical research results, but also provided a green development path and practical experience for other enterprises to learn from.

Based on the above main research findings, this study puts forward the following policy recommendations and corporate practice strategies:

(1) Enterprises should actively grasp the opportunities of digital transformation, take digitalization as an important starting point to drive the construction of green supply chain and optimize carbon emission performance, and formulate and implement digital transformation plans in line with sustainable development goals in combination with their own business characteristics and industry characteristics.

(2) In the process of implementing digital transformation, enterprises should focus on building and improving the supply chain information platform, improving information transparency, strengthening communication and collaboration among supply chain partners, and jointly promoting green technology innovation and application to enhance supply chain synergies and reduce environmental burden.

(3) Government departments and industry associations should increase their support for enterprises' digital transformation, provide necessary policy guidance and technical support, encourage enterprises

to carry out cross-organizational and cross-industry green supply chain cooperation projects, and promote the successful integration model of digital transformation and green development.

In summary, this study provides in-depth insights and strong evidence for understanding the impact of digital transformation on enterprises' development of green supply chain and optimization of carbon emission performance, which has important theoretical value and practical guidance for promoting enterprises and society to move towards a more sustainable development path.

6.2 Management Implications and Policy Recommendations

Through in-depth discussion on the impact of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain, this study reveals the key role of digital transformation in promoting the sustainable development of enterprises, and puts forward a series of specific Revelations and suggestions for enterprises and policy levels.

Management inspiration:

(1) Fully implement and deepen the digital transformation strategy: Enterprises should fully recognize the importance of digital transformation to optimize green supply chain synergies and improve carbon emission performance, and integrate digital technology into the operation and management of all links of the supply chain. Specifically, enterprises should invest in building an integrated information sharing platform, enhance information transparency through technical means such as the Internet of Things and big data, and strengthen environmental cooperation and resource coordination among supply chain members to promote the effective implementation of green production practices and energy conservation and emission reduction strategies.

(2) Innovate green technologies and business models: While implementing digital transformation, enterprises need to closely integrate the research and development and application of low-carbon, energy saving and emission reduction technologies to promote the green upgrading of products and services. For example, the introduction of intelligent predictive maintenance systems to reduce equipment energy consumption, the use of data analysis to optimize logistics networks to reduce carbon emissions during transportation, and encourage the implementation of circular economy concepts such as green procurement and recycling.

(3) Build cross-organization cooperation mechanism: Enterprises should actively build or participate in cross-organization and cross-industry green supply chain cooperation network, and strengthen deep communication and collaboration with supply chain partners on environmental protection standards formulation, resource sharing, and technological innovation with the help of digital tools, so as to jointly achieve the improvement of the overall environmental performance of the supply chain.

Policy recommendations:

(1) Establish incentive and guidance policy system: The government should introduce a series of policies to support enterprises' digital transformation and green development orientation, including but not limited to providing financial subsidies, tax incentives, low-interest loans and other economic incentives

to encourage enterprises to increase investment and accelerate the implementation of green supply chain management and carbon emission reduction projects.

(2) Build public service infrastructure: the government leads the construction of national or regional digital service platforms to provide enterprises with standard data interfaces, analysis tools and technical support required for green supply chain management and carbon emission monitoring, so as to help enterprises promote green transformation efficiently and at low cost.

(3) Improve regulatory supervision and information disclosure system: Formulate and revise relevant laws and regulations, standardize and guide enterprises to implement green supply chain management in the process of digital transformation, strengthen the supervision of corporate carbon emissions, require enterprises to publicly disclose carbon emission data and related environmental performance indicators on a regular basis, and improve market transparency and social supervision.

(4) Education, training and capacity improvement: The government should join hands with educational institutions and industry associations to carry out professional training courses for enterprise management and technical personnel, covering green supply chain management, digital technology application and carbon reduction strategies, so as to help enterprises improve green management and technological innovation capabilities.

To sum up, the management inspiration and policy recommendations proposed in this study aim to provide theoretical basis and practical guidance for relevant enterprises and government departments, so as to jointly promote enterprises in the process of digital transformation, effectively enhance the synergy of green supply chain, effectively improve carbon emission performance, and contribute to the realization of sustainable development goals of economy and society.

6.3 Research Limitations and Future Prospects

Although this study reveals the significant impact of digital transformation on the synergy effect and carbon emission performance of enterprises' green supply chain through theoretical discussion and empirical analysis, it also recognizes some limitations in the study, and on this basis, puts forward forward-looking ideas for future research directions.

First, in terms of research limitations:

(1). Sample selection and industry representation: This study selects a certain number of enterprises as research objects. Although these enterprises reflect the typical characteristics of different industries to a certain extent, due to the different industrial structure, technological basis and environmental protection policy background of each industry, This may lead to a failure to fully reflect the complexity and specificity of all industries when exploring the impact of digital transformation on green supply chain synergies and carbon performance.

(2). Data quality and integrity constraints: Due to data source and availability constraints, some companies may not provide detailed digital transformation process information, environmental performance data, or supply chain collaboration details, which may affect our accurate grasp of the depth

and breadth of relevant relationships. At the same time, due to the limited nature of time series data, our understanding of long-term trend changes may be limited.

(3). Challenges in causality inference: Although this study reveals the correlation between digital transformation, green supply chain synergies and carbon emission performance with the help of statistical models, there are still uncertainties in the causality demonstration. In order to more accurately prove that digital transformation is the cause of enhanced synergies and improved carbon emission performance of green supply chain, more rigorous causal reasoning methods, such as natural experiment design and instrumental variable method, should be adopted in future studies.

(4). Insufficient consideration of external factors: This study mainly focuses on the internal level of enterprises, and in the process of discussing the impact of digital transformation, the potential role of external environmental factors such as government policy regulation, market competition situation and technological innovation speed on enterprise development strategy and environmental protection practice is not fully considered. These exogenous variables can have a significant impact on a company's digital transformation strategy and its green supply chain management and carbon emissions performance.

Based on the above limitations, future research can be further expanded and deepened from the following directions:

(1). Expand sample coverage and improve data quality: Conduct larger studies across more industries to ensure stronger universality and representation of research results. At the same time, we actively seek to obtain more complete and high-quality data resources, and use advanced means such as big data analysis and machine learning for in-depth mining and analysis.

(2). Strengthen the identification of causality: Through the design of rigorous experimental schemes or the use of quasi-experimental design under existing data conditions, combined with advanced statistical analysis methods, such as propensity score matching, differential analysis, etc., to accurately identify and quantify the causal effects of digital transformation on the synergy effect of green supply chain and carbon emission performance.

(3). Comprehensive research on the integration of internal and external factors: The internal digital transformation strategy of enterprises is combined with external environmental factors to explore how they interact and affect the green development path of enterprises. Particular attention is paid to how factors such as policies and regulations, market demand, and technological innovation shape the dynamics and methods of digital transformation of enterprises, as well as the resulting environmental benefits.

In summary, although the current research has achieved preliminary results in revealing the correlation between digital transformation and corporate green supply chain synergies and carbon emission performance, there are still many problems and challenges to be solved. By overcoming the above limitations and carrying out targeted research work, it is expected that in the future, the deep-seated mechanism of digital transformation for optimizing the synergy effect of green supply chain and improving carbon emission performance can be more accurately described, and a theoretical framework

and practical strategy with more guiding significance can be provided for promoting the sustainable development of enterprises and the low-carbon transformation of social economy.

References

Di, K. S., Chen, W. D., Zhang, X. N., Shi, Q. M., Cai, Q. L., Li, D. L. ... Di, Z. S. (2023). Regional unevenness and synergy of carbon emission reduction in China's green low-carbon circular economy. *Journal of Cleaner Production*, *420*, 138436. https://doi.org/10.1016/j.jclepro.2023.138436

Gao, S., Sun, D. Q., & Wang, S. J. (2023). Do development zones increase carbon emission performance of China's cities? *Science of the Total Environment*, *863*, 160784. https://doi.org/10.1016/j.scitotenv.2022.160784

Gebara, C. H., Thammaraksa, C., Hauschild, M., & Laurent, A. (2024). Selecting indicators for measuring progress towards sustainable development goals at the global, national and corporate levels. *Sustainable Production and Consumption*, *44*, 151-165. https://doi.org/10.1016/j.spc.2023.12.004

Kou, J. L., & Xu, X. G. (2022). Does internet infrastructure improve or reduce carbon emission performance? —A dual perspective based on local government intervention and market segmentation. *Journal of Cleaner Production*, *379*(2), 134789. https://doi.org/10.1016/j.jclepro.2022.134789

Leng, A. L., & Zhang, Y. (2024). The effect of enterprise digital transformation on audit efficiency—Evidence from China. *Technological Forecasting Social Change*, *201*, 123215. https://doi.org/10.1016/j.techfore.2024.123215

Li, Z. R., Zhang, X. H., Tao, Z., & Wang, B. B. (2024). Enterprise digital transformation and supply chain management. *Finance Research Letters*, *60*, 104883. https://doi.org/10.1016/j.frl.2023.104883

Narsa, G. N. (2022). Corporate governance: Does it matter management of carbon emission performance? An empirical analyses of Indian companies. *Journal of Cleaner Production*, *379*(1), 134485. https://doi.org/10.1016/j.jclepro.2022.134485

Teng, Y. Y., Zheng, J. Z., Li, Y. C., & Wu, D. (2024). Optimizing digital transformation paths for industrial clusters: Insights from a simulation. *Technological Forecasting Social Change*, *200*, 123170. https://doi.org/10.1016/j.techfore.2023.123170

Wang, S. S., Yan, C., & Zhao, Y. Q. (2024). Technological peer pressure and corporate sustainability. *Energy Economics*, *130*, 107257. https://doi.org/10.1016/j.eneco.2023.107257

Xu, L., Fan, M. T., Yang, L. L., & Shao, S. (2021). Heterogeneous green innovations and carbon emission performance: Evidence at China's city level. *Energy Economics*, *99*, 105269. https://doi.org/10.1016/j.eneco.2021.105269

Zhou, B., Bai, B. Y., Zhu, X. F., Guo, J. J., Wang, Y., Chen, J. J. ... Li, J. H. (2024). Insights into effects of grain boundary engineering in composite metal oxide catalysts for improving catalytic

performance. *Journal of Colloid And Interface Science*, *653*(Part B), 1177-1187. https://doi.org/10.1016/j.jcis.2023.09.148