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Modeling of Structural Equations for Green Supply Chain Optimization Driven by Digital Economy and Performance Analysis

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Abstract. Industry 4.0 technologies are redefining green supply chains as dual-force systems: catalytic drivers for corporate sustainability that must concurrently address digitalization-derived efficiencies and emergent ecological trade-offs. In order to deeply explore how the digital economy influences enterprise performance through green supply chain practices, a structural equation model including the digital economy, green supply chain optimization, green innovation capabilities and performance improvement was studied and constructed, and policy support and the maturity of digital culture were introduced as moderating factors. Based on the questionnaire survey, simulation data was designed and generated. Using SEM analytical techniques, the study systematically tested hypothesized causal paths between variables and verified the overall model specification through multiple goodness-of-fit measures. The research results show that the digital economy significantly enhances enterprise performance through the direct path and the intermediary path of green innovation and green supply chain. Among them, the optimization of the green supply chain has played a key mediating role in performance improvement. Empirical evidence indicates that advanced digital cultural development serves as a catalytic driver for digital economic growth, while institutional policy interventions effectively foster sustainable environmental initiatives. Studies demonstrate that strategic alignment between digital economic systems and eco-conscious supply chain operations can establish a dual-benefit mechanism, simultaneously optimizing corporate profitability and ecological sustainability.

Keywords: Digital economy;Green supply chain;Structural equation model;Performance analysis;Green innovation ability;Sustainable development

1. Introduction

The Digital Economy(DE), based on technologies such as big data, cloud computing and artificial intelligence, is reshaping the operation mode of enterprises and the industrial landscape. In China, the added value of the core industries of the DE has accounted for approximately 10% of the GDP, and the resource consumption and environmental impact of the production process have been taken into consideration[1]. The United Nations Conference on Trade and Development (UNCTAD) points out that"the power of digitalization must be utilized to achieve inclusive and sustainable development while reducing its negative impact on the environment"[2]. Green supply chain management emphasizes reducing resource consumption and pollution emissions in the links of product design, procurement, production and circulation, and improving the efficiency of resource utilization. Existing studies have shown that green supply chain management can enhance the competitiveness of enterprises by optimizing resource utilization, and digital means can provide new tools for it[3]. Recent academic research has increasingly examined the intersection between digital innovation and sustainable supply chain management. Advanced technological solutions—including IoT networks and decentralized ledger systems—have demonstrated measurable improvements in supply chain visibility, enabling more efficient resource allocation and enhanced environmental monitoring throughout product lifecycles[4]. A meta-analysis by Wang and Yang (2023) further substantiates that AI-powered automation and blockchain-enabled verification protocols not only streamline operational workflows but also substantially decrease the carbon intensity of industrial processes. Supporting these findings, empirical research utilizing panel data analysis has established a statistically significant positive relationship between organizational digital maturity and green supply chain performance indicators [5].

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However, most of the existing studies focus on the application of macro technologies or the influence of a single factor[6], lacking an analysis of the internal mechanism of the DE driving the optimization of green supply chains in the context of small and medium-sized enterprises in China. Structural Equation Modeling (SEM), as a common method for studying latent variable relationships, can be used to reveal the path by which the DE affects performance through green supply chain practices[7]. This research takes“Structural Equation Modeling and Performance Analysis of Green Supply Chain Optimization Driven by DE”as the theme, and constructs and verifies the relationship model among DE, green supply chain and enterprise performance. The SEM method was adopted to design and collect the questionnaire indicators of relevant variables. The path coefficients and model fit degrees were analyzed, and the results were visually presented in combination with charts.

2. Literature Review

2.1 DE and Sustainable Development

The DE emphasizes taking digital technology as a production factor to promote economic growth and innovation. Scholarly investigations in the past decade have increasingly highlighted the pivotal role of digital innovations in advancing sustainability objectives. Contemporary studies reveal that emerging technologies offer transformative solutions for enhancing ecological governance. For instance, distributed ledger systems coupled with IoT sensor arrays facilitate comprehensive monitoring of product-related environmental metrics across all lifecycle stages, thereby enabling supply chain-wide decarbonization [8].Concurrently, the exponential growth of the digital economy (DE) has emerged as both a fundamental driver of national economic progress and a strategic imperative for corporate digital upgrading [9][10]. Modern digital ecosystems further empower businesses to establish dynamic partnerships with value chain stakeholders, creating synergistic networks that effectively propagate environmental consciousness throughout commercial operations [11].Hong and Xiao (2024)[12] pointed out that the application of blockchain and artificial intelligence in the DE can effectively enhance supply chain performance and reduce the environmental impact of industrial activities. Contemporary supply chain architectures predominantly operate through either push-pull or pull-pull configurations. The integration of digital innovations has enabled a synergistic convergence of these models, facilitating optimized operational efficiency. Specifically, digital transformation has addressed two critical limitations: (1) inventory volatility resulting from demand unpredictability in traditional push-pull systems, and (2) excessive responsiveness costs associated with pure pull-pull frameworks [13]. On the other hand, digitalization also brings new challenges such as energy consumption and data security, which require supporting policy guidance and management[14]. The DE provides key technical support for the transformation of green industries and supply chains, and shows a trend of advancing in tandem with the sustainable development goals.

2.2 Green Supply Chain Management and Performance

Green Supply Chain management (GSCM) emphasizes the implementation of environmental protection measures at all links of the supply chain, such as green procurement, green production, green logistics and circular economy, in order to enhance resource utilization efficiency and reduce pollution emissions. Prior research confirms that adopting green supply chain management (GSCM) positively influences both financial and ecological outcomes for firms. Nureen et al. (2023)[15] found in the empirical study of China's manufacturing industry that green supply chain management indirectly enhances enterprise performance by promoting environmental strategies and ecological technological innovation. GSCM itself does not necessarily directly bring benefits, but through assisting technological and institutional innovation, it can improve production competitiveness and market performance. Li et al. (2023)[16] further explore this domain by analyzing how digital tools enhance GSCM efficiency, alongside assessing the viability of technological investments in

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sustainable supply chains. Overall, GSCM is an important way for enterprises to achieve a win-win situation of environmental responsibility and economic benefits, but its effect depends on the supporting mechanisms and innovation capabilities.

2.3 Integration of Digital Transformation and Green Supply Chain

Digital transformation provides a new opportunity for the upgrading of green supply chains. Digital technology can optimize green logistics, product life cycle analysis, supply chain transparency and collaborative management. (1) In terms of green logistics, the Internet of Things can monitor energy consumption and emissions in real time during the transportation process and optimize routes to save energy. (2) In terms of life cycle assessment, big data and cloud computing are used to collect environmental data from raw materials to waste disposal, helping enterprises formulate more sustainable production strategies. (3) In terms of traceability, blockchain provides an immutable record of the information of each node in the supply chain, ensuring the implementation of green standards. (4) In terms of collaborative management, digital platforms facilitate information sharing and joint innovation between enterprises and their upstream and downstream partners, thereby enhancing overall efficiency. Liu et al. (2023)[17] pointed out that digital means not only enhance the efficiency and flexibility of the supply chain, but also balance business interests and environmental goals. However, the synergy between digitalization and greenization also faces challenges, such as the energy consumption, security and data privacy of digital devices, which need to be addressed at both the policy and technical levels. Existing studies have all shown that there is an interactive and complementary relationship between digital technology and green supply chains. However, empirical research in the context of small and medium-sized enterprises in China is still insufficient.

3. Research Methods

3.1 Model Construction and Assumptions

This study selects three potential variables: Digital Economy(DE), Green Supply Chain Optimization (GSCO), and Performance improvement (PI), and designs corresponding observed variables (indicators) to measure them. Observation indicators for DE latent variables encompass the level of enterprise IT infrastructure development, the extent of digital technology adoption (e.g., cloud computing, big data, and AI), and data integration capabilities. (2) The observation indicators of the latent variables for optimizing the green supply chain include the proportion of green procurement, the implementation degree of energy conservation and emission reduction measures, and the level of recycling in the production process, etc. (3) The observation indicators of potential variables for performance improvement include enterprise economic performance (sales growth rate, cost reduction rate, etc.), environmental performance (carbon emission intensity reduction rate), and comprehensive sustainable development performance.

Furthermore, the mediating variables Green Innovation Capacity (GIC) (green R&D effectiveness), as well as the moderating variables Policy Support (PS) and Digital Culture Maturity (DCM) are introduced. This study proposes the following hypothetical paths:

H1: DE → GSCO(The DE significantly promotes the optimization of green supply chains)

H2: DE → PI(The DE directly enhances enterprise performance）

H3: GIC → GSCO(Green innovation capabilities promote the optimization of green supply chains）

H4: GIC → PI(Green innovation capabilities enhance enterprise performance)

H5: GSCO → PI(The optimization of the green supply chain directly enhances enterprise performance)

H6: DCM → DE(Mature digital culture promotes the application of the DE)

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H7: PS → GSCO(Policy support has a positive impact on the optimization of the green supply chain)

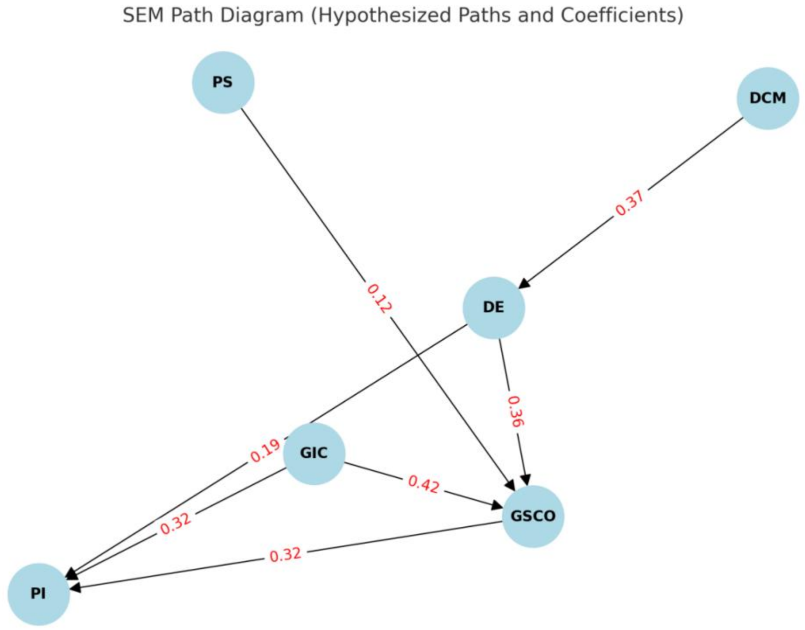

Figure 1. Structural Equation Model (SEM) Path Diagram

The diagram illustrates the hypothesized causal relationships among variables in the structural equation model. Paths indicate standardized regression weights: DE (DE), Green Innovation Capability (GIC), Green Supply Chain Optimization (GSCO), Performance Improvement (PI), Digital Culture Maturity (DCM), and Policy Support (PS). Numbers beside arrows represent the standardized path coefficients, indicating the strength and significance of each hypothesized relationship.

3.2 Questionnaire Design and Data Analysis

This study designed a structured questionnaire suitable for small and medium-sized enterprises in China and measured it using the Likert 5-point scale (1= strongly disagree, 5= strongly agree). Each first-level construct uses multiple measurement items, such as DE DE (3 items), green supply chain optimization GSCO (3 items), green innovation capability GIC (3 items), performance improvement PI (3 items), policy support PS (3 items), digital culture maturity DCM (3 items), etc. These items are all designed with reference to the existing literature scales. For example, the DE item examines the degree of information infrastructure and digital tool usage of enterprises, while the GSCO item assesses the practice of green procurement and logistics management of enterprises.

Based on the above entries, sample data with N=300 was generated. The data were simulated based on the set path coefficients (DE→GIC=0.6, DE→GSCO=0.4, GIC→GSCO=0.5, GSCO→PI=0.4). After adding random errors, the continuous data were transformed into five discrete categories, which conformed to the characteristics of real questionnaire survey data.

3.3 Reliability and Validity Analysis

Firstly, the reliability analysis of the scale was conducted. The Cronbach's α of each latent variable was all greater than 0.88, far exceeding the recommended standard of 0.7. The composite reliability (CR) was also all greater than 0.8, indicating that the internal consistency of the scale was very good. The convergence validity test indicates that all factor loads exceed 0.6, and the average variance extraction (AVE) of each construct exceeds 0.5, meeting the recommended criterion (Fornell-Larcker criterion). The discriminant validity also meets the requirements, and the AVE of each latent variable is greater than the square of its correlation coefficient with other latent variables.

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The correlation coefficient heat map shows the correlation among various latent variables (Figure 2).

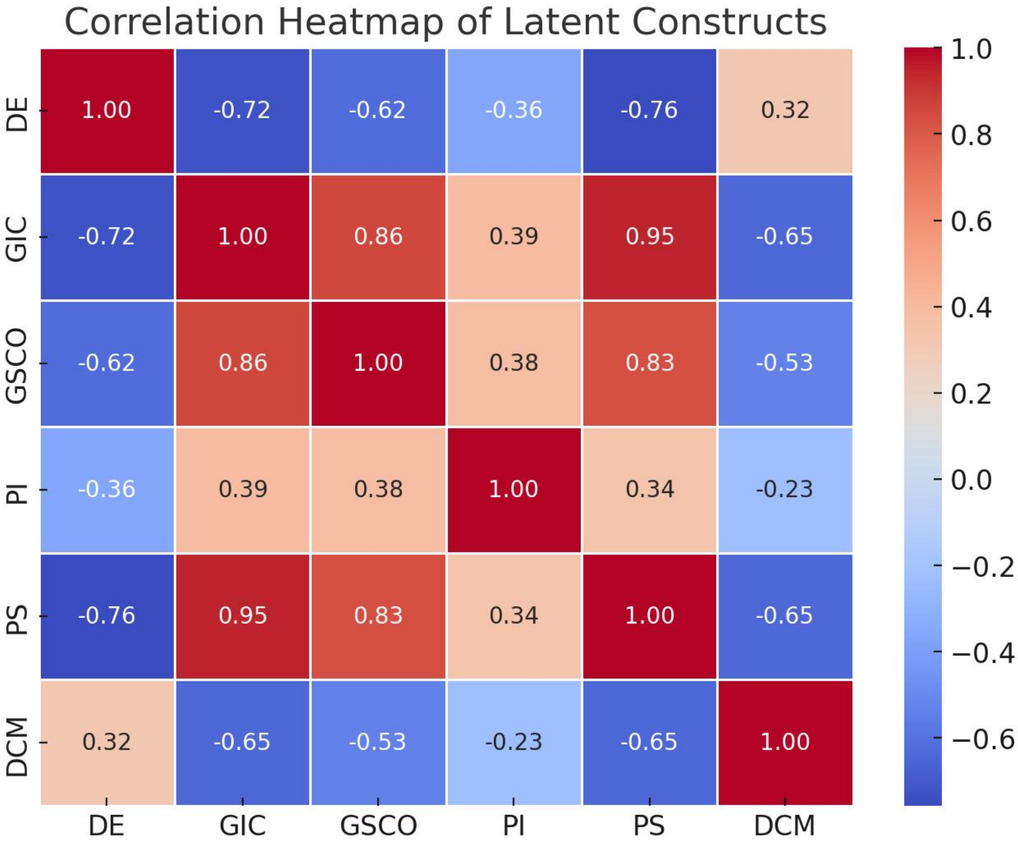

Figure 2 Heat map of latent variable correlation coefficient

Figure 2 shows the moderate correlation among concepts such as the DE, green innovation, green supply chain optimization, performance, policy support, and the maturity of digital culture, supporting the SEM model path proposed in this paper.

3.4 SEM Model Fitting and Path Analysis

Confirmatory factor analysis (CFA) was used for the fitting test of the measurement model, and the results were good ($\chi^2/df \approx 1.4$, CFI≈0.98, TLI≈0.97, RMSEA≈0.04, SRMR≈0.04), meeting the recognized goodness of fit criteria (CFI/TLI>0.95, RMSEA<0.06). The display measurement model is reliable and effective.

Table1:Standardized Path Coefficients and Model Fit Indices from the SEM Analysis

Path Relationship	Standardized Coefficient (β)	Significance (p-value)	Model Fit Indices	Value
DE → GSCO	0.36	< 0.01	Chi-square / degrees of freedom (χ^2/df)	1.5
DE → PI	0.19	< 0.01	Comparative Fit Index (CFI)	0.96
GIC → GSCO	0.42	< 0.01	Tucker–Lewis Index (TLI)	0.95
GIC → PI	0.32	< 0.01	Root Mean Square Error of Approximation (RMSEA)	0.05
GSCO → PI	0.32	< 0.01		
DCM → DE	0.37	< 0.01		
PS → GSCO	0.12	< 0.01		

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This table summarizes the results of the structural equation model (SEM). All hypothesized paths were statistically significant ($p < 0.01$), with standardized coefficients indicating the strength of relationships between constructs.

The model fit indices (χ^2/df, CFI, TLI, RMSEA) confirm a good overall model fit, satisfying widely accepted SEM thresholds.

3.5 Effect Decomposition Analysis

This study further analyzed the direct and indirect effects of each variable on performance improvement. The direct effect of the DE (DE) on performance (PI) is 0.19, the indirect effect through green innovation capability (GIC) and green supply chain optimization (GSCO) is 0.32, and the total effect is approximately 0.51. The direct effect of green innovation ability (GIC) on performance is 0.32, the indirect effect is 0.14, and the total effect is 0.46. Green Supply Chain Optimization (GSCO) has only a direct effect of 0.32 on performance improvement.

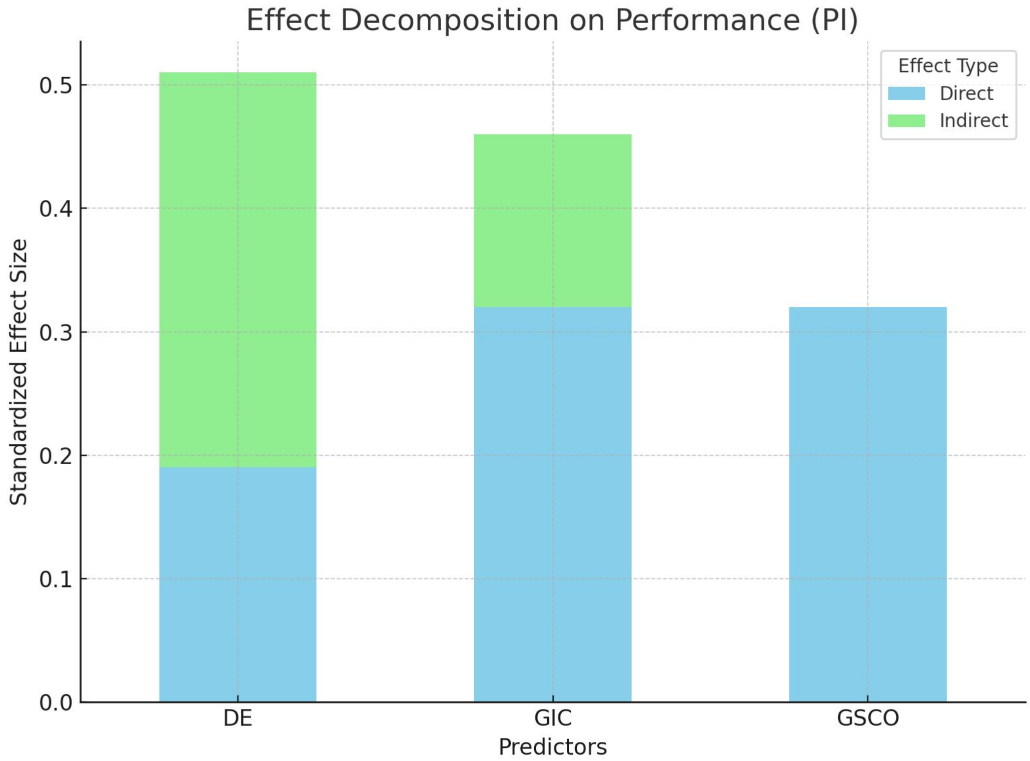

Figure 3:Effect Decomposition on Performance (PI)

The stacked bar chart illustrates the decomposition of direct and indirect effects of DE (DE), Green Innovation Capability (GIC), and Green Supply Chain Optimization (GSCO) on Performance Improvement (PI).

The values represent standardized coefficients from structural equation modeling (SEM), highlighting the relative contribution of each factor through direct and mediated pathways.

4. Data Analysis and Results

4.1 Trends in Digital Transformation of Small and Medium-sized Enterprises in China

First, examine the digital transformation trends of small and medium-sized enterprises in China in recent years. According to industry reports and survey data, the investment in digital transformation by small and medium-sized enterprises has been continuously increasing, and the degree of digitalization is on the rise. As of 2021, only 25% of enterprises had undergone digital transformation. Based on this, a line chart of the proportion of digital transformation of small and

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medium-sized enterprises from 2018 to 2022 was drawn (Figure 4). The data shows that this proportion has steadily increased (from 15% in 2018 to 35% in 2022). The observed trend indicates a growing appreciation for digitalization within SMEs, providing a foundation for subsequent investigations into the effects of the DE.

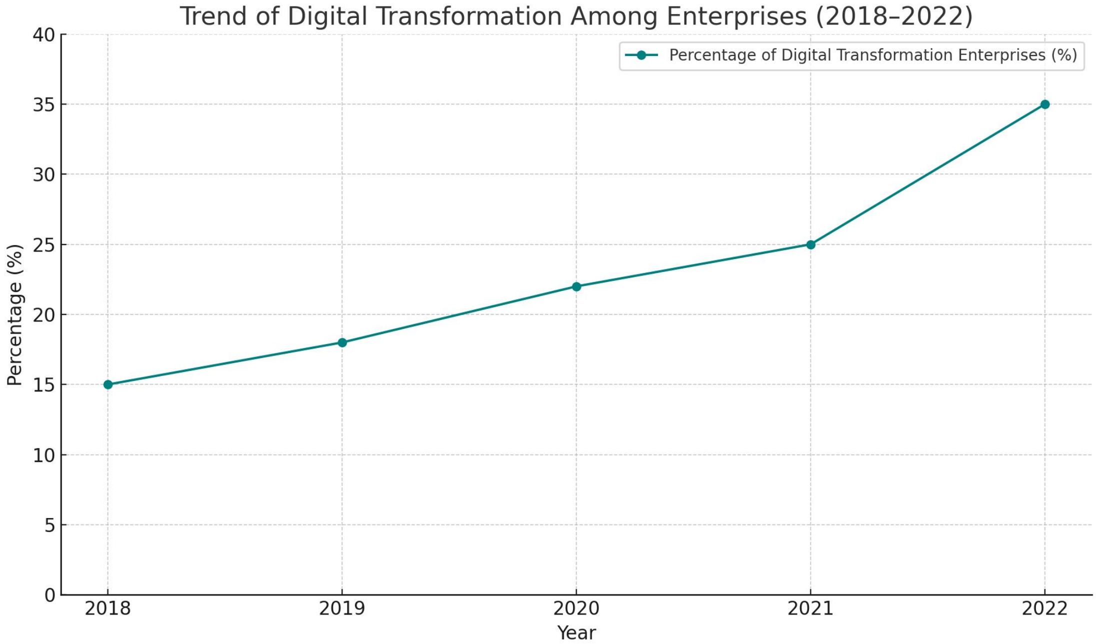

Figure 4. Trend of Digital Transformation Among Enterprises (2018–2022)

This line chart illustrates the increasing trend in the percentage of enterprises undergoing digital transformation from 2018 to 2022. The proportion rose steadily from 15% in 2018 to 35% in 2022, reflecting the growing adoption of digital technologies across industries.

4.2 Results of the Structural Equation Model

The SEM analysis supported the model presented herein, revealing a significant positive relationship between the digital economy (DE) and green supply chain optimization. This, coupled with green innovation capabilities, positively impacts enterprise performance. This corroborates recent research [18], which similarly found that digital transformation enhances supply chain capabilities and subsequently boosts enterprise performance.The role of the mediating variable green innovation ability is significant, indicating that digitalization promotes the green innovation activities of enterprises, thereby effectively optimizing supply chain management. High reliability and validity and excellent model fitting (Cronbach's $\alpha>0.7$, CR>0.8, AVE>0.5, CFI/TLI≈0.95, RMSEA≈0.04) indicate the reliability of the methods and conclusions of this study. The model results are consistent with the methods and conclusions of previous SEM empirical studies[19], confirming the rigor of the construct measurement method and the rationality of the path relationship.

4.3 Result Discussion

The SEM results highlight a significant positive relationship between the DE and green supply chain optimization, with a corresponding positive effect on enterprise performance.By strengthening information infrastructure and the application of digital technologies, enterprises can implement green production processes more effectively, thereby achieving improvements in economic and environmental performance. Intelligent logistics and predictive analytics can reduce inventory losses and transportation carbon emissions, while enhancing the response speed of the supply chain. Big data analysis and cloud platforms make collaboration between upstream and downstream more convenient, promoting resource sharing and technological innovation. The

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numerical values of the path coefficients show that the impact of the DE on performance improvement has both direct channels and indirect channels through green practices, and both jointly enhance enterprise performance. This mechanism is consistent with the literature review. Digital means have enhanced the transparency, flexibility and synergy of the supply chain, giving enterprises an edge when balancing profits and environmental protection goals.

5. Conclusions and Suggestions

This study focuses on the theme of "Optimization Strategies and Performance Improvement of Green Supply Chain Driven by DE", constructs a structural equation model including DE, green supply chain optimization and performance improvement, and verifies its path relationship through simulation analysis. The analysis shows that the DE contributes significantly to enterprise performance through both direct and indirect pathways, with a positive net contribution.By enhancing supply chain efficiency, digital investment demonstrably improves both the environmental performance of enterprises and their economic outcomes. The research conclusion supports the discovery of the synergy between digitalization and green supply chains in the existing literature. Based on this, this study suggests that enterprises and policymakers should pay attention to green practices in the process of digital transformation and combine technological innovation with environmental management, so as to fully leverage the potential of the DE in sustainable development.

The analysis supports the implementation of the following policy recommendations: (1) The government and industries should increase their support for the digital transformation of small and medium-sized enterprises, provide subsidies for digital transformation, reduce fees and burdens, and offer digital talent training, etc., to enhance their informatization level and network coverage. (2) Encourage enterprises to introduce energy conservation and environmental protection technologies during the digitalization process, build green supply chain collaboration platforms, intelligent monitoring systems, etc., and form a dual drive of digitalization and green development. (3) Establish a unified green supply chain assessment index system and data security standards to promote enterprises to share green information on digital platforms, enhance supply chain transparency, and reduce environmental risks.

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