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PAPER

# How Sustainable Supply Chain Operation Management Enhances Enterprise Perceived Low-Carbon Development Efficiency: Evidence from Manufacturing Enterprises

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## Abstract

This study examines how sustainable supply chain operation management enhances enterprise perceived low-carbon development efficiency in manufacturing enterprises. A quantitative survey design was adopted. Data were collected from 384 respondents, including supply chain managers, production managers, operations managers, logistics managers, ESG or environmental officers, and senior administrative staff. Structural equation modelling was used to test the effects of five supply chain operation practices on four low-carbon development outcomes. The results show that green procurement, green production, green logistics, supply chain collaboration, and green information sharing positively predict enterprise perceived low-carbon development efficiency. Green production shows the strongest effect on carbon reduction efficiency, while supply chain collaboration and green information sharing are particularly important for low-carbon competitive performance. This study extends sustainable supply chain management research by examining multiple operational dimensions and multiple low-carbon efficiency outcomes simultaneously.

**Key words:** Sustainable supply chain operation management, low-carbon development efficiency, green procurement, green production, structural equation modelling

## Introduction

Global climate change and the transition toward low-carbon development have increased the pressure on enterprises to reduce carbon emissions, improve resource efficiency, and integrate environmental responsibility into daily operations (Gao et al., 2022; Qu et al.,2022). In this context, supply chains have become an important arena for low-carbon transformation because procurement, production, logistics, collaboration, and information sharing are closely connected with energy consumption, material flows, and carbon emissions. Sustainable supply chain management emphasizes the coordinated management of material, information, and capital flows while incorporating economic, environmental, and social objectives across supply chain members (Seuring & Müller, 2008). Therefore, supply chain operation management should not be understood merely as a logistics function, but as an integrated operational system that may shape enterprise perceived low-carbon development efficiency.

Manufacturing enterprises are especially relevant to this issue because their operational processes often involve intensive energy use, resource consumption, production emissions, and complex upstream and downstream relationships. Prior research has shown that green supply chain management practices can improve environmental and economic performance among manufacturing enterprises (Zhu & Sarkis, 2004). Other empirical studies also indicate that green supply chain management practices are associated with improvements in environmental, economic, and operational performance (Green et al., 2012). These findings suggest that sustainable supply chain operation management may provide an important pathway for enterprises to improve energy utilization, reduce carbon emissions, optimize resource use, and strengthen low-carbon competitiveness.

Although the relationship between green or sustainable supply chain management and firm performance has been widely discussed, several research gaps remain. First, many studies have treated green supply chain management as a broad or aggregated construct, with less attention to the distinct roles of specific operational dimensions such as green procurement, green production, green logistics, supply chain collaboration, and green information sharing. Second, existing studies often examine general outcomes such as firm performance, environmental performance, or economic performance, while enterprise perceived low-carbon development efficiency has received less focused attention. Third, relatively limited research has examined how different supply chain operation dimensions independently relate to different low-carbon efficiency outcomes, such as energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. As meta-analytic evidence suggests, the effects of environmentally sustainable supply chain practices may vary across performance dimensions, which makes a more refined empirical framework necessary (Golicic & Smith, 2013).

To address these gaps, this study examines how five dimensions of sustainable supply chain operation management, green procurement, green production, green logistics, supply chain collaboration, and green information sharing, are associated with four outcomes of enterprise perceived low-carbon development efficiency: energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. This study makes three contributions. First, it extends sustainable supply chain operation management research by decomposing it into specific operational dimensions. Second, it enriches the measurement of enterprise perceived low-carbon development efficiency by treating it as a multidimensional outcome rather than a single environmental performance indicator. Third, it provides empirical evidence for manufacturing enterprises seeking to improve low-carbon development through more systematic supply chain operation practices.

## Conceptual Framing and Hypothesis Development

Sustainable supply chain operation management refers to the integration of environmental responsibility, resource efficiency, and low-carbon objectives into enterprise operations across procurement, production, logistics, collaboration, and information sharing (Liu et al., 2024; Lu & Liao, 2025). It extends traditional supply chain management beyond cost reduction and delivery efficiency by emphasizing the environmental consequences of operational decisions across the whole supply chain. From this perspective, firms are not only expected to improve their internal production efficiency, but also to coordinate suppliers, customers, logistics partners, and information systems toward low-carbon and resource-efficient goals. Sustainable supply chain management therefore provides a useful theoretical foundation for understanding how firms can combine economic value creation with environmental responsibility through integrated supply chain practices (Seuring & Müller, 2008). More specifically, this study conceptualizes sustainable supply chain operation management through five dimensions: green procurement, green production, green logistics, supply chain collaboration, and green information sharing.

Enterprise perceived low-carbon development efficiency refers to the ability of a firm to achieve economic and operational value while improving energy utilization, reducing carbon emissions, optimizing resource use, and developing low-carbon competitive advantages. Compared with general environmental performance, perceived low-carbon development efficiency places stronger emphasis on the balance between business output and carbon/resource efficiency. In this study, it is reflected through four outcomes: energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. These four outcomes represent different but related aspects of low-carbon transformation. Energy utilization efficiency reflects whether firms can use energy more effectively in operations; carbon reduction efficiency captures the effectiveness of reducing emissions; resource utilization efficiency concerns the improved use of materials and other inputs; and low-carbon competitive performance reflects whether low-carbon practices help firms gain reputation, market recognition, or strategic advantage.

Green procurement is expected to improve enterprise perceived low-carbon development efficiency because procurement decisions shape the environmental quality of materials, components, technologies, and suppliers entering the production system. When firms prioritize low-carbon materials, environmentally responsible suppliers, recyclable inputs, and supplier environmental certification, they can reduce environmental burdens at the upstream stage of the supply chain. Green procurement may also encourage suppliers to adopt cleaner production and environmental standards, thereby extending low-carbon responsibility beyond the focal firm. Prior research has shown that green supply chain practices, including environmentally oriented purchasing and supplier management, are associated with better environmental and economic performance in manufacturing firms (Zhu & Sarkis, 2004; Green et al., 2012). Therefore, this study proposes the following hypothesis:

**H1a: Green procurement positively predicts enterprise perceived low-carbon development efficiency outcomes.**

Green production is one of the most direct operational pathways for improving perceived low-carbon development efficiency. It includes cleaner production processes, energy-saving equipment, emission reduction technologies, waste reduction, recycling practices, and production process optimization. These practices can directly improve energy utilization efficiency and carbon reduction efficiency by reducing unnecessary energy use and lowering emissions generated during manufacturing activities. Green production may also enhance resource utilization efficiency by reducing material waste and increasing circular use of inputs. In addition, cleaner and more efficient production may strengthen low-carbon competitive performance by improving product quality, regulatory compliance, and environmental reputation. Empirical studies suggest that internal environmental management and green operational practices are positively related to environmental and operational performance (Zhu & Sarkis, 2004; Green et al., 2012). Therefore, this study proposes:

**H1b: Green production positively predicts enterprise perceived low-carbon development efficiency outcomes.**

Green logistics may also contribute to enterprise perceived low-carbon development efficiency because logistics activities are closely related to transportation emissions, fuel use, packaging waste, warehousing energy consumption, and distribution efficiency. Through route optimization, green packaging, energy-efficient warehousing, low-carbon delivery, and reverse logistics, firms can reduce carbon emissions and resource waste in the movement and storage of goods. Green logistics can also support low-carbon competitive performance by improving firms' environmental image and meeting customers' increasing sustainability requirements. Research has indicated that logistics-related environmental practices are connected with sustainability performance and environmental accountability in the logistics sector (Karaman et al., 2020). Therefore, this study proposes:

**H1c: Green logistics positively predicts enterprise perceived low-carbon development efficiency outcomes.**

Supply chain collaboration is important because low-carbon transformation cannot be achieved by a single enterprise alone. Carbon emissions and resource consumption are distributed across suppliers, manufacturers, logistics providers, and customers. Therefore, firms need to work with supply chain partners to set common low-carbon goals, share resources, coordinate emission reduction activities, and develop joint solutions. Collaboration with suppliers may improve material selection and production planning, while collaboration with customers may support low-carbon product design and demand coordination. Vachon and Klassen (2008) found that environmental collaboration in the supply chain is related to manufacturing and environmental performance, suggesting that cooperative practices can support sustainability-oriented operational outcomes. Therefore, this study proposes:

**H1d: Supply chain collaboration positively predicts enterprise perceived low-carbon development efficiency outcomes.**

Green information sharing refers to the exchange of environmental, carbon-related, and sustainability-related information among supply chain partners. It includes sharing information on energy use, carbon emissions, supplier environmental performance, product environmental attributes, recycling requirements, and sustainability standards. Such information sharing can improve perceived low-carbon development efficiency by increasing transparency, reducing information asymmetry, and supporting better decision-making in procurement, production, logistics, and resource allocation. When firms have access to accurate environmental and carbon-related information, they can identify inefficiencies, monitor emissions, and coordinate low-carbon actions more effectively. Previous research suggests that information sharing and green information systems can support environmental performance by improving the availability and use of sustainability-related information in supply chain management (Meacham et al., 2013). Therefore, this study proposes:

**H1e: Green information sharing positively predicts enterprise perceived low-carbon development efficiency outcomes.**

Several firm characteristics may influence enterprise perceived low-carbon development efficiency and therefore need to be controlled in the empirical

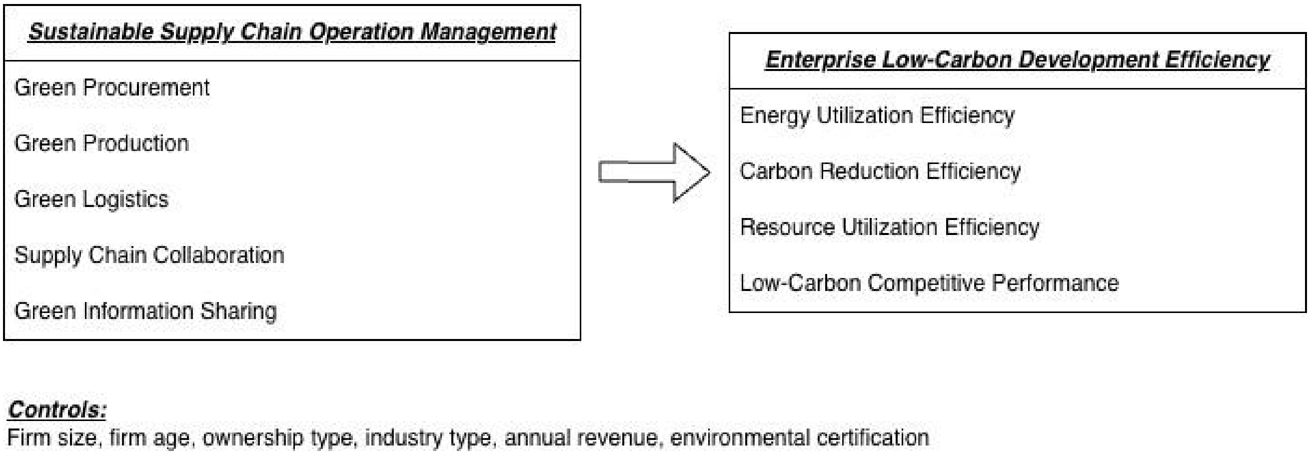


**Fig. 1. Hypothesised Model**

model. Firm size may affect low-carbon development because larger firms usually have more financial resources, technical capabilities, and managerial capacity to implement sustainable supply chain practices. Firm age may reflect accumulated operational experience and established supply chain relationships, although older firms may also face challenges in transforming traditional production systems. Ownership type may influence access to resources, environmental pressure, and strategic priorities. Industry type is important because energy consumption, carbon intensity, and regulatory pressure vary across sectors. Annual revenue reflects firms' economic capacity to invest in environmental management and low-carbon technologies. Environmental certification may indicate a stronger formal commitment to environmental management. Therefore, this study controls for firm size, firm age, ownership type, industry type, annual revenue, and environmental certification when testing the hypothesized relationships.

Overall, this study examines five sustainable supply chain operation management factors—green procurement, green production, green logistics, supply chain collaboration, and green information sharing—in relation to four enterprise perceived low-carbon development efficiency outcomes: energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. Structural equation modelling is used to test the hypothesized relationships while controlling for relevant firm characteristics. The proposed framework is shown in Figure 1.

## Method

This study adopted a cross-sectional quantitative survey design to examine the relationships between sustainable supply chain operation management factors and enterprise perceived low-carbon development efficiency outcomes (Gupta et al., 2025; Sánchez-García et al., 2025; Liu et al., 2024). The target population consisted of manufacturing enterprises and supply-chain-related enterprises in China, particularly firms involved in procurement, production, logistics, energy-related operations, and other supply-chain activities. The survey was conducted among enterprises located in major industrial and supply-chain regions, where manufacturing production, logistics distribution, and low-carbon transformation practices are relatively active. The industry scope included manufacturing, logistics, energy-related industries, and other supply-chain-related industries. Respondents were required to have sufficient knowledge of their firms' supply chain management and low-carbon operational practices. Therefore, the questionnaire was distributed to supply chain managers, production managers, operations managers, logistics managers, ESG or environmental management officers, and senior administrative staff.

Data were collected through a structured questionnaire using both online and offline distribution channels. Before completing the questionnaire, respondents were informed of the academic purpose of the study, the voluntary nature of participation, and the confidentiality of their responses. To improve data quality, the questionnaire included screening questions to ensure that respondents were familiar with their firms' supply chain practices and low-carbon operations. After data collection, incomplete responses, repeated submissions, responses with excessive missing values, and responses showing obvious straight-line answering patterns were removed. The final valid sample was then used for subsequent statistical analysis.

All core constructs were measured using a seven-point Likert scale ranging from 1 = strongly disagree to 7 = strongly agree. The use of multi-item Likert-type scales is appropriate for measuring managerial perceptions and organizational practices because it allows latent constructs to be represented through multiple observable indicators (Churchill, 1979). The measurement items were adapted from prior studies on green supply chain management, sustainable operations, environmental management, and firm performance, with wording adjusted to fit the context of enterprise low-carbon development. To ensure content relevance, the items were reviewed to confirm that they reflected the operational meaning of each construct.

Green procurement was measured by items assessing whether the firm prioritizes environmentally responsible suppliers, low-carbon materials, supplier environmental certification, and green purchasing standards. Green production was measured by items related to cleaner production processes, energy-saving equipment, emission reduction technologies, waste reduction, and production process optimization. Green logistics was measured by items assessing transportation route optimization, green packaging, energy-efficient warehousing, low-carbon delivery, and reverse logistics. Supply chain collaboration was measured by items reflecting joint low-carbon goal setting, environmental cooperation with suppliers and customers, shared resource use, and collaborative problem solving. Green information sharing was measured by items related to the exchange of environmental data, carbon-related information, supplier environmental performance, and sustainability standards across supply chain partners.

Enterprise perceived low-carbon development efficiency was measured through four outcome dimensions. Energy utilization efficiency was measured by items assessing whether the firm has improved energy use in production and operations. Carbon reduction efficiency was measured by items reflecting the firm's ability to reduce carbon emissions and carbon intensity. Resource utilization efficiency was measured by items related to reducing material waste, improving resource productivity, and increasing circular use of inputs. Low-carbon competitive performance was measured by items assessing whether low-carbon practices have improved the firm's environmental reputation,

**Table 1. Respondent and Firm Profile**

| Variable | Category | Frequency | Percentage |
|---|---|---|---|
| Respondent position | Supply chain manager | 82 | 21.35% |
| | Production manager | 76 | 19.79% |
| | Operations manager | 68 | 17.71% |
| | Logistics manager | 54 | 14.06% |
| | ESG/environmental officer | 49 | 12.76% |
| | Senior administrative staff | 55 | 14.32% |
| Total | | 384 | 100.00% |
| Firm size | Small enterprise | 91 | 23.70% |
| | Medium enterprise | 173 | 45.05% |
| | Large enterprise | 120 | 31.25% |
| Total | | 384 | 100.00% |
| Firm age | Less than 5 years | 67 | 17.45% |
| | 5–10 years | 139 | 36.20% |
| | More than 10 years | 178 | 46.35% |
| Total | | 384 | 100.00% |
| Ownership type | State-owned enterprise | 78 | 20.31% |
| | Private enterprise | 198 | 51.56% |
| | Foreign-invested enterprise | 57 | 14.84% |
| | Joint venture | 51 | 13.28% |
| Total | | 384 | 100.00% |
| Industry type | Manufacturing | 236 | 61.46% |
| | Logistics | 58 | 15.10% |
| | Energy-related industry | 45 | 11.72% |
| | Other supply-chain-related industry | 45 | 11.72% |
| Total | | 384 | 100.00% |

market competitiveness, customer recognition, and long-term strategic advantage.

Several firm-level control variables were included in the analysis because enterprise perceived low-carbon development efficiency may differ across firms with different backgrounds and resources. Firm size was measured according to the number of employees or annual revenue category. Firm age was measured by the number of years since establishment. Ownership type was coded according to whether the firm was state-owned, private, foreign-invested, or a joint venture. Industry type was coded according to the main business sector of the firm. Annual revenue was measured using categorical revenue groups. Environmental certification was measured as a binary variable indicating whether the firm had obtained ISO 14001 or other recognized environmental management certification. These variables were controlled to reduce the possibility that the observed relationships between sustainable supply chain operation management and perceived low-carbon development efficiency were caused by firm background differences rather than the focal supply chain practices.

The data analysis proceeded in several steps. First, data screening was conducted to examine missing values, outliers, normality, and common method bias. Since the study relied on questionnaire responses, common method bias was assessed following recommendations in survey-based behavioral and management research (Podsakoff et al., 2003). Second, confirmatory factor analysis was conducted to examine whether the measurement model fit the data. Following the two-step approach to structural equation modelling, the measurement model was assessed before testing the structural paths (Anderson & Gerbing, 1988). Third, reliability and validity were assessed using Cronbach's alpha, composite reliability, average variance extracted, and standardized factor loadings. Convergent and discriminant validity were evaluated based on established criteria for latent construct measurement (Fornell & Larcker, 1981). Fourth, latent correlations among the substantive factors were calculated to examine preliminary associations among the constructs. Finally, structural equation modelling was used to test the hypothesized relationships between the five sustainable supply chain operation management factors and the four enterprise perceived low-carbon development efficiency outcomes while controlling for firm characteristics. All statistical analyses were conducted using IBM SPSS Statistics 26.0 and AMOS 24.0. SPSS was used for data screening, descriptive statistics, reliability analysis, normality assessment, and common method bias testing. AMOS was used to conduct confirmatory factor analysis and covariance-based structural equation modelling. The maximum likelihood estimation method was adopted because the data did not show serious deviations from normality and the study aimed to test a theory-driven covariance-based SEM model.

## Results

### Data Screening and Common Method Bias

Before hypothesis testing, the dataset was screened for missing values, outliers, normality, and common method bias. A total of 412 questionnaires were initially collected. In the first stage of data screening, 16 questionnaires were removed because they were incomplete, repeated, or showed obvious straight-line answering patterns, leaving 396 responses for further screening. In the second stage, multivariate outliers were examined using Mahalanobis distance, and 12 abnormal responses were removed. Therefore, 384 valid questionnaires remained for final analysis. The proportion of missing values in the retained dataset was low, ranging from 0.00% to 1.82%, and missing data were handled using mean replacement because the missing proportion was below the commonly accepted threshold. Skewness values ranged from −0.84 to 0.71, and kurtosis values ranged from −0.96 to 1.22, indicating that the data did not seriously violate normality assumptions.

Common method bias was examined because all major variables were collected through self-reported questionnaires. Harman's single-factor test showed that the first unrotated factor explained 32.46% of the total variance, which was below the 50% threshold. In addition, a common latent factor test was conducted by comparing the baseline measurement model with a model including a common latent factor. The change in model fit was small, suggesting that common method bias was not a serious concern in this study.

**Table 2. Measurement Items and Construct Sources**

| Construct | Dimension | Number of items | Sample item | Source |
|---|---|---|---|---|
| Sustainable Supply Chain Operation Management | Green procurement | 4 | GP1. Our firm gives priority to suppliers with strong environmental standards. GP2. Our firm considers suppliers' environmental certification when making procurement decisions. GP3. Our firm gives preference to low-carbon or environmentally friendly materials. GP4. Our firm has established green purchasing standards for major procurement activities. | Adapted from Zhu & Sarkis (2004); Green et al. (2012) |
| | Green production | 4 | GPR1. Our firm adopts cleaner production processes to reduce energy use and emissions. GPR2. Our firm uses energy-saving equipment or technologies in production. GPR3. Our firm implements emission reduction technologies during production. GPR4. Our firm continuously optimizes production processes to reduce waste and resource consumption. | Adapted from Zhu & Sarkis (2004); Green et al. (2012) |
| | Green logistics | 4 | GL1. Our firm optimizes transportation routes to reduce fuel use and carbon emissions. GL2. Our firm uses green packaging to reduce environmental impact. GL3. Our firm improves warehousing efficiency to reduce energy consumption. GL4. Our firm promotes low-carbon delivery and reverse logistics practices. | Adapted from Karaman et al. (2020) |
| | Supply chain collaboration | 4 | SCC1. Our firm works with suppliers and customers to achieve low-carbon operational goals. SCC2. Our firm collaborates with supply chain partners to solve environmental problems. SCC3. Our firm shares resources with supply chain partners to improve low-carbon operations. SCC4. Our firm jointly develops environmental improvement plans with suppliers or customers. | Adapted from Vachon & Klassen (2008) |
| | Green information sharing | 4 | GIS1. Our firm shares environmental and carbon-related information with supply chain partners. GIS2. Our firm exchanges information on supplier environmental performance. GIS3. Our firm communicates sustainability standards and requirements to supply chain partners. GIS4. Our firm uses green information to support supply chain decision-making. | Adapted from Meacham et al. (2013) |
| Enterprise perceived low-carbon development efficiency | Energy utilization efficiency | 3 | EUE1. Our firm has improved the efficiency of energy use in operations. EUE2. Our firm has reduced unnecessary energy consumption in production and operational processes. EUE3. Our firm uses energy more efficiently than before through low-carbon management practices. | Adapted from Green et al. (2012); Golicic & Smith (2013) |
| | Carbon reduction efficiency | 3 | CRE1. Our firm has effectively reduced carbon emissions per unit of output. CRE2. Our firm has improved its ability to control and reduce operational carbon emissions. CRE3. Our firm's low-carbon practices have contributed to lower carbon intensity. | Adapted from Green et al. (2012); Golicic & Smith (2013) |
| | Resource utilization efficiency | 3 | RUE1. Our firm uses materials and resources more efficiently than before. RUE2. Our firm has reduced material waste in production and operational activities. RUE3. Our firm has improved the circular or repeated use of resources. | Adapted from Green et al. (2012); Golicic & Smith (2013) |
| | Low-carbon competitive performance | 3 | LCCP1. Our firm has gained competitive advantages through low-carbon development. LCCP2. Our firm's low-carbon practices have improved its environmental reputation. LCCP3. Our firm's low-carbon development has increased customer recognition and long-term strategic value. | Adapted from Green et al. (2012); Golicic & Smith (2013) |

**Table 3. Data Screening and Common Method Bias Results**

| Test item | Result | Recommended criterion | Conclusion |
|---|---|---|---|
| Initial questionnaires collected | 412 | — | — |
| Invalid questionnaires removed | 28 | — | Removed |
| Final valid sample | 384 | > 300 recommended for SEM | Acceptable |
| Missing values | 0.00%–1.82% | < 5% | Acceptable |
| Multivariate outliers | 12 cases removed | Based on Mahalanobis distance | Acceptable |
| Skewness | −0.84 to 0.71 | Within ±2 | Acceptable |
| Kurtosis | −0.96 to 1.22 | Within ±2 | Acceptable |
| Harman's single-factor variance | 32.46% | < 50% | No serious concern |
| Common latent factor test | $\Delta CFI = 0.006$ | < 0.010 | No serious concern |

**Table 4.** Reliability, Convergent Validity, and Standardized CFA Factor Loadings

| Construct | Item | Standardized loading | Cronbach's alpha | CR | AVE |
|---|---|---|---|---|---|
| Green Procurement | GP1 | 0.71 | 0.84 | 0.85 | 0.59 |
| | GP2 | 0.78 | | | |
| | GP3 | 0.82 | | | |
| | GP4 | 0.84 | | | |
| Green Production | GPR1 | 0.74 | 0.88 | 0.88 | 0.65 |
| | GPR2 | 0.81 | | | |
| | GPR3 | 0.86 | | | |
| | GPR4 | 0.87 | | | |
| Green Logistics | GL1 | 0.7 | 0.85 | 0.86 | 0.61 |
| | GL2 | 0.78 | | | |
| | GL3 | 0.82 | | | |
| | GL4 | 0.85 | | | |
| Supply Chain Collaboration | SCC1 | 0.73 | 0.87 | 0.87 | 0.63 |
| | SCC2 | 0.8 | | | |
| | SCC3 | 0.84 | | | |
| | SCC4 | 0.86 | | | |
| Green Information Sharing | GIS1 | 0.72 | 0.86 | 0.86 | 0.6 |
| | GIS2 | 0.79 | | | |
| | GIS3 | 0.83 | | | |
| | GIS4 | 0.85 | | | |
| Energy Utilization Efficiency | EUE1 | 0.77 | 0.89 | 0.89 | 0.69 |
| | EUE2 | 0.85 | | | |
| | EUE3 | 0.89 | | | |
| Carbon Reduction Efficiency | CRE1 | 0.79 | 0.91 | 0.91 | 0.72 |
| | CRE2 | 0.87 | | | |
| | CRE3 | 0.89 | | | |
| Resource Utilization Efficiency | RUE1 | 0.74 | 0.87 | 0.87 | 0.63 |
| | RUE2 | 0.8 | | | |
| | RUE3 | 0.86 | | | |
| Low-Carbon Competitive Performance | LCCP1 | 0.68 | 0.82 | 0.83 | 0.56 |
| | LCCP2 | 0.78 | | | |
| | LCCP3 | 0.82 | | | |

## Reliability, Descriptive Statistics, and CFA Factor Loadings

Reliability, descriptive statistics, and factor loadings were then examined for all constructs. As shown in Table 4, Cronbach's alpha values ranged from 0.82 to 0.91, indicating satisfactory internal consistency. The mean scores ranged from 4.86 to 5.43, suggesting that respondents generally perceived a moderate-to-high level of sustainable supply chain operation management and perceived low-carbon development efficiency in their firms. The standard deviations ranged from 0.78 to 0.95, indicating acceptable variation among responses. Standardized factor loadings ranged from 0.68 to 0.89, exceeding the minimum recommended level of 0.60. These results suggest that the measurement items were reliable and suitable for further analysis.

## Measurement Model Fit and Validity

Confirmatory factor analysis was conducted to evaluate the measurement model. The results showed that the model achieved acceptable fit: $\chi^2$/df = 1.91, CFI = 0.947, TLI = 0.938, RMSEA = 0.049, and SRMR = 0.041. These values met the recommended criteria for an acceptable measurement model. Composite reliability values ranged from 0.83 to 0.91, exceeding the threshold of 0.70. Average variance extracted values ranged from 0.56 to 0.72, exceeding the recommended threshold of 0.50. These results indicate that the constructs demonstrated satisfactory convergent validity.

## Latent Correlations among Substantive Factors

Latent correlations among the substantive factors are presented in Table 6. The five sustainable supply chain operation management factors were positively correlated with the four perceived low-carbon development efficiency outcomes. Green production showed relatively strong correlations with energy utilization efficiency and carbon reduction efficiency, while supply chain collaboration and green information sharing showed stronger correlations with low-carbon competitive performance. The correlation coefficients were all below 0.80, suggesting that multicollinearity was not a serious concern. Overall, the correlation results provided preliminary support for the hypothesized relationships.

## Structural Equation Modelling Results

Structural equation modelling was conducted to test the hypothesized relationships between sustainable supply chain operation management factors and enterprise perceived low-carbon development efficiency outcomes. The structural model showed acceptable fit: $\chi^2$/df = 2.04, CFI = 0.939, TLI = 0.928, RMSEA = 0.052, and SRMR = 0.046. As shown in Table 7, green procurement positively predicted energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance, although the strongest effect was observed for resource utilization efficiency. Green production showed significant positive effects on all four outcomes, with the strongest effect on carbon reduction efficiency. Green logistics significantly predicted all four outcomes, especially carbon reduction efficiency and resource utilization efficiency.

Supply chain collaboration was positively associated with all four perceived low-carbon development efficiency outcomes, with the strongest effect on low-carbon competitive performance. Green information sharing also showed significant positive effects on all four outcomes, particularly resource utilization efficiency and low-carbon competitive performance.

**Table 5. Measurement Model Fit and Validity Results**

| Indicator / Construct | | Value |
|---|---|---|
| $\chi^2$/df | | 1.91 |
| CFI | | 0.947 |
| TLI | | 0.938 |
| RMSEA | | 0.049 |
| SRMR | | 0.041 |
| CR range | | 0.83–0.91 |
| AVE range | | 0.56–0.72 |
| **Construct** | **CR** | **AVE** |
| Green Procurement | 0.85 | 0.59 |
| Green Production | 0.88 | 0.65 |
| Green Logistics | 0.86 | 0.61 |
| Supply Chain Collaboration | 0.87 | 0.63 |
| Green Information Sharing | 0.86 | 0.6 |
| Energy Utilization Efficiency | 0.89 | 0.69 |
| Carbon Reduction Efficiency | 0.91 | 0.72 |
| Resource Utilization Efficiency | 0.87 | 0.63 |
| Low-Carbon Competitive Performance | 0.83 | 0.56 |

**Table 6. Latent Correlations among Substantive Factors**

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1. Green Procurement | 1 | | | | | | | | |
| 2. Green Production | .56** | 1 | | | | | | | |
| 3. Green Logistics | .48** | .52** | 1 | | | | | | |
| 4. Supply Chain Collaboration | .51** | .57** | .55** | 1 | | | | | |
| 5. Green Information Sharing | .46** | .50** | .53** | .61** | 1 | | | | |
| 6. Energy Utilization Efficiency | .49** | .60** | .45** | .43** | .48** | 1 | | | |
| 7. Carbon Reduction Efficiency | .44** | .63** | .54** | .47** | .50** | .66** | 1 | | |
| 8. Resource Utilization Efficiency | .52** | .55** | .50** | .53** | .56** | .61** | .64** | 1 | |
| 9. Low-Carbon Competitive Performance | .41** | .48** | .46** | .62** | .60** | .50** | .53** | .58** | 1 |

Note. **p < .01.

**Table 7. Standardised Path Estimates from Structural Equation Modelling**

| Predictor | Energy Utilization Efficiency | Carbon Reduction Efficiency | Resource Utilization Efficiency | Low-Carbon Competitive Performance |
|---|---|---|---|---|
| Green Procurement | .22** | .18* | .25** | .16* |
| Green Production | .31*** | .36*** | .27*** | .21** |
| Green Logistics | .18* | .29*** | .22** | .19* |
| Supply Chain Collaboration | .15* | .17* | .21** | .33*** |
| Green Information Sharing | .24** | .20** | .26*** | .30*** |
| Firm size | .14* | .12* | 0.1 | .16* |
| Firm age | 0.06 | 0.04 | 0.07 | 0.05 |
| Ownership type | 0.08 | 0.09 | 0.06 | 0.11 |
| Industry type | .13* | .15* | .12* | 0.1 |
| Annual revenue | .17** | .16** | .14* | .18** |
| Environmental certification | .20** | .22** | .19** | .17* |
| $R^2$ | 0.46 | 0.52 | 0.49 | 0.48 |

Note. *p < .05, **p < .01, ***p < .001.

Among the control variables, firm size, annual revenue, and environmental certification showed relatively consistent positive associations with several low-carbon development outcomes, suggesting that firms with stronger resource capacity and formal environmental systems may perform better in low-carbon transformation.

## Summary of Hypothesis Testing

The hypothesis testing results are summarized in Table 8. Overall, all five hypotheses were supported. Green procurement, green production, green logistics, supply chain collaboration, and green information sharing all positively predicted enterprise perceived low-carbon development efficiency outcomes. However, the strength of the relationships differed across outcomes. Green production had the strongest effect on carbon reduction efficiency, while supply chain collaboration and green information sharing had stronger effects

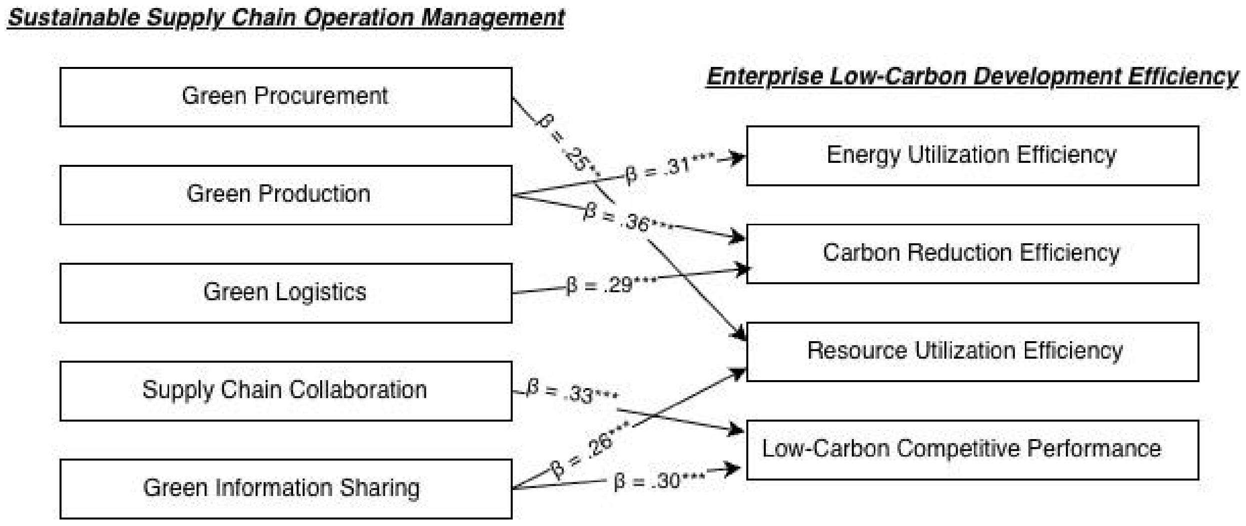


**Fig. 2. Results from Structural Equation Model**

**Table 8. Summary of Hypothesis Testing**

| Hypothesis | Path | Result |
|---|---|---|
| H1a | Green procurement positively predicts enterprise perceived low-carbon development efficiency outcomes. | Supported |
| H1b | Green production positively predicts enterprise perceived low-carbon development efficiency outcomes. | Supported |
| H1c | Green logistics positively predicts enterprise perceived low-carbon development efficiency outcomes. | Supported |
| H1d | Supply chain collaboration positively predicts enterprise perceived low-carbon development efficiency outcomes. | Supported |
| H1e | Green information sharing positively predicts enterprise perceived low-carbon development efficiency outcomes. | Supported |

on low-carbon competitive performance. These findings indicate that different sustainable supply chain operation management factors contribute to different aspects of enterprise perceived low-carbon development efficiency.

## Discussion

The findings suggest that green procurement is an important upstream practice for improving enterprise perceived low-carbon development efficiency. By selecting environmentally responsible suppliers, low-carbon materials, recyclable inputs, and certified partners, firms can reduce environmental burdens before production begins. This may explain why green procurement contributes to energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. Procurement decisions influence the quality and environmental characteristics of resources entering the firm, so stronger green procurement standards can help enterprises reduce inefficient material use and improve the environmental reliability of their supply base. This result is consistent with previous green supply chain research showing that environmentally oriented purchasing and supplier management are associated with improved environmental and economic outcomes (Green et al., 2012; Zhu & Sarkis, 2004). However, compared with green production, the effect of green procurement may be less direct because procurement works mainly through supplier selection and input control rather than through immediate changes in internal energy use or emission processes. This suggests that green procurement mainly works as a preventive and boundary-setting mechanism. Its contribution lies in reducing environmental risks at the source and improving the low-carbon quality of inputs before they enter the firm's production system. Therefore, green procurement should be interpreted not only as a purchasing activity, but also as an upstream governance mechanism that extends low-carbon responsibility to suppliers.

Green production appears to be one of the most central pathways through which enterprises improve perceived low-carbon development efficiency. This is reasonable because production is the stage where energy consumption, resource transformation, waste generation, and carbon emissions occur most directly. Cleaner production processes, energy-saving equipment, emission reduction technologies, and waste minimization practices can directly reduce unnecessary energy use and improve carbon reduction efficiency. At the same time, green production can improve resource utilization efficiency by reducing material loss and encouraging recycling or circular use of inputs. Its relationship with low-carbon competitive performance also suggests that firms may transform cleaner production into strategic value, such as stronger environmental reputation, better compliance with regulation, and improved customer recognition. This supports the idea that internal environmental management and green operational practices are important drivers of both environmental and operational performance (Green et al., 2012). The strong role of green production also indicates that low-carbon transformation cannot rely only on external supply chain coordination; it must be embedded in the firm's core production system. In other words, green production functions as the technical core of low-carbon efficiency because it directly changes how energy, materials, technologies, and emissions are managed inside the enterprise.

Green logistics also plays a meaningful role in enterprise perceived low-carbon development efficiency. Logistics activities are often treated as supporting activities, but they are closely linked to fuel consumption, transportation emissions, packaging waste, warehousing energy use, and distribution efficiency. Therefore, improvements in route planning, vehicle utilization, green packaging, warehouse energy management, and reverse logistics can reduce carbon emissions beyond the production floor. The effect of green logistics on carbon reduction and resource utilization is particularly understandable because logistics directly affects the movement, storage, and recovery of materials and products. Moreover, green logistics can help firms respond to customers' sustainability expectations and improve environmental accountability. This finding is aligned with research suggesting that green logistics performance is connected with sustainability reporting and environmental responsibility in logistics-related sectors (Karaman et al., 2020). This result also shows that low-carbon efficiency is not limited to the production stage. Emissions and resource losses may occur throughout the movement, storage, delivery, and recovery of products. Green logistics therefore extends the low-carbon logic from internal production processes to the broader circulation process of the supply chain.

Supply chain collaboration contributes to perceived low-carbon development efficiency because enterprise low-carbon transformation cannot be achieved by a single firm alone. Carbon emissions and resource consumption are distributed across multiple actors, including suppliers, manufacturers, logistics providers, distributors, and customers. When firms collaborate with supply chain partners, they are better able to set common environmental goals, coordinate production and delivery schedules, reduce duplicated activities, share low-carbon technologies, and solve environmental problems collectively. The strong relationship between supply chain collaboration and low-carbon competitive performance is especially important. It suggests that collaboration not only improves operational efficiency, but also helps firms build stronger partnerships, respond to green market demands, and create strategic advantages. This finding supports previous evidence that environmental collaboration in the supply chain is associated with manufacturing and environmental performance (Vachon & Klassen, 2008). The stronger effect of collaboration on low-carbon competitive performance suggests that competitive advantage in low-carbon development is increasingly relational rather than purely internal. Firms gain strategic value not only by improving their own operations, but also by building coordinated low-carbon capabilities with suppliers, customers, and logistics partners.

Green information sharing is another important factor in perceived low-carbon development efficiency. Low-carbon management depends heavily on accurate and timely information about energy use, carbon emissions, supplier environmental performance, product attributes, resource consumption, and sustainability standards. When firms share environmental and carbon-related information with supply chain partners, they can improve transparency, reduce information asymmetry, and support better decision-making across procurement, production, logistics, and resource allocation. The relationship between green information sharing and low-carbon competitive performance indicates that information transparency can also become a source of trust and market advantage. Firms that can collect, disclose, and use green information effectively may be better positioned to satisfy customers, regulators, investors, and supply chain partners. This is consistent with previous research showing that information sharing and green information systems can support environmental performance by improving the availability and use of sustainability-related information (Meacham et al., 2013). This finding highlights the informational foundation of low-carbon supply chain management. Without reliable environmental and carbon-related information, firms may find it difficult to identify inefficiencies, coordinate partner actions, or convert green practices into credible market signals. Green information sharing therefore acts as a cognitive and decision-support mechanism within sustainable supply chain operations.

Theoretically, this study makes a deeper contribution to the sustainable supply chain management literature by explaining how low-carbon development efficiency is generated through different operational mechanisms within the supply chain. Rather than viewing sustainable supply chain management as a general environmental practice, the findings suggest that low-carbon efficiency is produced through a staged and functionally differentiated process. Green procurement represents an upstream input-control mechanism because it influences the environmental quality of suppliers, materials, and purchasing standards before production begins. Green production represents an internal process-optimization mechanism because it directly affects energy consumption, emission reduction, and resource transformation within the firm. Green logistics represents a flow-efficiency mechanism because it reduces carbon burdens in transportation, packaging, warehousing, distribution, and reverse logistics. Supply chain collaboration represents an inter-organizational coordination mechanism because it enables firms to align environmental goals, resources, and problem-solving activities with external partners. Green information sharing represents a data-transparency mechanism because it improves the visibility and use of carbon-related information across supply chain actors. Therefore, the theoretical value of this study is not only that it divides sustainable supply chain operation management into five dimensions, but also that it clarifies the distinct mechanisms through which each dimension contributes to enterprise low-carbon transformation.

This study also advances the theoretical understanding of low-carbon development efficiency by linking operational practices to multiple forms of efficiency creation. Previous studies often examined environmental performance or firm performance as broad outcomes, which may obscure the different ways in which sustainable supply chain practices create value. The present findings show that low-carbon development efficiency should be understood as a multidimensional construct involving operational efficiency, environmental efficiency, resource efficiency, and strategic efficiency. Energy utilization efficiency reflects the firm's ability to reduce energy waste; carbon reduction efficiency reflects the firm's ability to lower emission intensity; resource utilization efficiency reflects the firm's ability to improve material productivity and circular resource use; and low-carbon competitive performance reflects the transformation of environmental practices into market reputation and strategic advantage. This provides a more integrated theoretical explanation of how sustainable supply chain management connects environmental responsibility with operational and competitive outcomes.

More importantly, the results indicate that different sustainable supply chain practices do not contribute to low-carbon development efficiency in the same way. Green production shows a stronger connection with carbon reduction efficiency because production activities are directly associated with energy use, emissions, and process-level environmental control. In contrast, supply chain collaboration and green information sharing are more strongly associated with low-carbon competitive performance because reputation, customer recognition, and long-term strategic advantage depend not only on internal environmental improvement, but also on external coordination, transparency, and stakeholder trust. This finding enriches sustainable supply chain theory by suggesting a differentiated effect logic: internally oriented practices are more closely related to technical and operational efficiency, whereas externally oriented practices are more closely related to relational and strategic low-carbon value. In this sense, the study moves beyond a simple "green practice–performance" relationship and provides a more precise theoretical explanation of how different supply chain practices generate different types of low-carbon outcomes.

The practical implications are also clear. Enterprises should strengthen green procurement standards by evaluating suppliers not only according to cost, quality, and delivery, but also according to environmental certification, carbon performance, material sustainability, and willingness to cooperate in low-carbon initiatives. Firms should also promote cleaner production and energy-saving technologies, because production remains one of the most direct sources of energy consumption and carbon emissions. In addition, enterprises should optimize green logistics through transportation route planning, energy-efficient warehousing, green packaging, low-carbon delivery, and reverse logistics systems. Supply chain collaboration should be strengthened by building shared low-carbon goals with suppliers, customers, and logistics partners. Finally, firms should establish green information sharing and carbon data management mechanisms. Digital platforms, environmental reporting systems, supplier evaluation databases, and carbon monitoring tools can help enterprises improve transparency and make more accurate low-carbon decisions.

Overall, the discussion indicates that sustainable supply chain operation management is not a single action, but a coordinated system of operational, relational, and informational practices. Green procurement controls environmental impact at the input stage, green production improves internal operational efficiency, green logistics reduces emissions in movement and storage, supply chain collaboration enhances inter-organizational coordination, and green information sharing improves transparency and decision quality. Together, these practices form a supply-chain-based low-carbon capability system. This means that enterprises can improve perceived low-carbon development efficiency not only by adopting isolated green practices, but also by integrating upstream supplier control, internal process improvement, downstream logistics optimization, partner collaboration, and carbon-related information sharing into a coherent operational strategy. This integrated explanation strengthens the theoretical argument that low-carbon development efficiency is a systemic outcome of sustainable supply chain operation management rather than the result of any single green practice.

## Limitations and Future Directions

Although this study provides useful evidence on the relationship between sustainable supply chain operation management and enterprise perceived low-carbon development efficiency, several limitations should be acknowledged. First, the study uses a cross-sectional research design, which means that the data were collected at one point in time. Therefore, the findings can show associations among green procurement, green production, green logistics, supply chain collaboration, green information sharing, and perceived low-carbon development efficiency outcomes, but they cannot fully confirm causal relationships. For example, firms with higher perceived low-carbon development efficiency may also be more likely to adopt sustainable supply chain practices. Future research should use longitudinal designs to examine whether changes in sustainable supply chain operation management lead to later improvements in energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. Longitudinal data would also help clarify the direction and stability of these relationships over time.

Second, this study relies on questionnaire data, which may involve subjective bias. Although managerial perceptions are useful for understanding organizational practices, respondents may overestimate their firm's green supply chain practices or low-carbon performance due to social desirability, organizational image concerns, or limited access to complete firm-level information. This is a common concern in survey-based management research, especially when independent and dependent variables are collected from similar respondents (Podsakoff et al., 2003). Future studies could reduce this limitation by combining survey data with objective indicators, such as actual carbon emissions, energy consumption records, resource productivity data, ESG ratings, environmental penalties, carbon disclosure quality, or third-party sustainability reports.

Third, the sample may be concentrated in manufacturing and supply-chain-related enterprises. Although this focus is appropriate because manufacturing firms are strongly connected with procurement, production, logistics, and emissions, it may limit the generalizability of the findings to other sectors. Service industries, technology firms, retail companies, and energy- intensive industries may have different low-carbon transformation pathways. For example, green logistics may be more important in distribution- intensive industries, while green production may be more central in heavy manufacturing. Future research should compare different industries to determine whether the effects of sustainable supply chain operation management vary across sectoral contexts.

Fourth, enterprise perceived low-carbon development efficiency in this study is measured through perceived outcomes, including energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. This multidimensional measurement is useful for capturing managerial perceptions of low-carbon transformation, but it may not fully reflect objective low-carbon efficiency. Future research could combine perceived measures with quantitative efficiency methods, such as carbon intensity analysis, green total factor productivity, data envelopment analysis, or undesirable-output efficiency models. Such approaches would provide a stronger assessment of whether sustainable supply chain practices truly improve low-carbon efficiency in measurable operational terms.

Future research can further extend this study in several directions. First, researchers may use longitudinal or panel data to examine the dynamic effects of sustainable supply chain operation management. Low- carbon transformation is not a short-term process; it requires continuous investment, technology adjustment, supplier coordination, and organizational learning. A longitudinal design would make it possible to examine whether early investments in green procurement, green production, green logistics, collaboration, and information sharing generate stronger low-carbon outcomes over time.

Second, future studies may integrate objective enterprise data, including carbon emissions, energy consumption, green patent applications, ESG performance, and environmental disclosure information. Combining subjective survey responses with archival data would improve measurement accuracy and reduce common method bias. It would also allow researchers to examine whether firms' reported sustainable supply chain practices are consistent with their actual carbon and environmental performance.

Third, future research can compare different industries, regions, and ownership types. The effect of sustainable supply chain operation management may differ between state-owned and private firms, between large and small firms, and between high-carbon and low-carbon industries. Such comparative research would help identify the conditions under which sustainable supply chain practices are most effective.

Finally, future studies can introduce additional mechanisms and boundary conditions. For example, green technological innovation may explain how sustainable supply chain operation management improves perceived low-carbon development efficiency, while digital transformation may strengthen the effect of supply chain practices by improving data monitoring, carbon tracking, and information sharing. Environmental regulation, market pressure, and organizational learning capability could also be examined as moderators. By incorporating mediating and moderating variables, future research can further explain not only whether sustainable supply chain operation management affects perceived low-carbon development efficiency, but also how and under what conditions this effect occurs.

## Conclusion

This study examined the influence of sustainable supply chain operation management on enterprise perceived low-carbon development efficiency. Specifically, it investigated how green procurement, green production, green logistics, supply chain collaboration, and green information sharing are related to four low-carbon development outcomes: energy utilization efficiency, carbon reduction efficiency, resource utilization efficiency, and low-carbon competitive performance. By adopting a multidimensional framework and using structural equation modelling, this study provides a clearer understanding of how different supply chain operation practices contribute to different aspects of low-carbon development.

Overall, the findings suggest that sustainable supply chain operation management is an important pathway for manufacturing enterprises to improve perceived low-carbon development efficiency. Green procurement helps control environmental impacts from the input stage, green production directly improves energy and emission performance, green logistics reduces carbon burdens in transportation and distribution, supply chain collaboration strengthens coordinated low-carbon action, and green information sharing supports transparent and data-driven decision-making. These results provide both theoretical and practical insights for enterprises seeking to achieve low-carbon transformation through more systematic and sustainable supply chain operations.

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