RESEARCH ARTICLE

The impact of green supply chain on dual-carbon targets based on big data analysis

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Green supply chain management (GSCM) refers to the integration of environmental considerations into supply chain processes, aiming to minimize resource consumption and reduce carbon emissions throughout the entire lifecycle from production to disposal. The dual-carbon targets comprising "carbon peaking" and "carbon neutrality" are global goals aimed at mitigating climate change by controlling and eventually neutralizing carbon emissions. With the growing urgency of addressing climate change, businesses and governments worldwide are under pressure to reduce their carbon footprints. The green supply chain has emerged as a critical strategy for achieving these goals by balancing environmental sustainability with economic growth. In parallel, big data analytics has gained prominence as a transformative tool for optimizing supply chain operations, providing insights into efficiency, resource utilization, and environmental impact. This study explored how green supply chain management was enhanced by big data analytics to achieve dual-carbon targets. The research focused on understanding how data-driven insights could help businesses reduce emissions, improve resource efficiency, and align with global sustainability objectives. A big data analytics approach was adopted to assess supply chain performance using real-time data from multiple sources including enterprise reports, industry databases, and satellite data. By applying machine learning algorithms and predictive modeling, the research identified patterns in resource use, carbon emissions, and supply chain optimization, providing a comprehensive evaluation of the environmental and economic impacts of GSCM. The results showed that integrating big data analytics into green supply chain management significantly enhanced environmental and economic outcomes. Companies that adopted green supply chain practices experience reduced carbon emissions, increased resource utilization efficiency, and improved market competitiveness. Furthermore, big data-driven decision-making enabled companies to anticipate demand fluctuations, optimize logistics, and lower operational costs, contributing positively to both environmental and financial performance. The green supply chain management powered by big data analytics played a pivotal role in achieving the dual-carbon targets. By leveraging data-driven insights, businesses could make more informed decisions that aligned with sustainability goals, improving both ecological and economic outcomes. This research not only offered valuable guidance for enterprises seeking to adopt sustainable practices but also provided policymakers with insights into how big data technologies could facilitate the transition to a low-carbon economy.

Keywords: big data analysis; dual carbon target; green supply chain.

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Introduction

As the global climate change problem becomes more and more serious, green supply chains and "two-carbon" targets (carbon peak and carbon neutrality) have become the focus of governments and businesses. Global greenhouse gas emissions continue to rise. According to the United Nations Framework Convention on Climate Change, global carbon dioxide emissions in 2020 have exceeded 30 billion tons, which poses a serious threat to the global ecosystem. In response to this challenge, countries have proposed "dual carbon" targets to control carbon emissions and slow down the impact of climate change. In China, the "carbon peak" and "carbon neutral" targets are set for 2030 and 2060, respectively, pushing companies to adopt a more sustainable development path in production and supply chain management. Green supply chain management, as a management mode that integrates the concept of environmental protection into all links of the supply chain, can not only reduce carbon emissions, but also improve resource utilization efficiency and reduce production costs. This management approach covers the entire process from raw material procurement, manufacturing, transportation, and distribution to waste treatment, and its goal is to achieve a win-win situation for the environment and the economy by optimizing resource use and reducing waste. According to the research of the Climate Change Research Center of Tsinghua University, Beijing, China, enterprises can reduce carbon emissions by about 20% to 30% through green supply chain management measures. However, implementing a green supply chain faces many challenges such as difficult data access and high costs. The rapid development of big data technology has provided strong support for the implementation of green supply chain. Through the analysis and mining of massive data, enterprises can accurately predict market demand, optimize logistics routes, and monitor resource use, thereby further reducing carbon emissions and improving their environmental performance and competitiveness. Therefore, green supply chain management based on big data analysis plays a key role in achieving the dual-carbon goal.

In recent years, there has been an increasing number of studies on the impact of green supply chain management and big data analysis on enterprises' realization of dual-carbon goals. Al-Khatib *et al*. suggested that big data analysis capabilities played a key role in improving the performance of green supply chain, especially through mining and analyzing the data of all links of the supply chain, which could effectively improve the environmental performance of enterprises [1]. Singh *et al*. analyzed the application potential of big data analysis in green supply chain management from the perspective of review, emphasizing its extensive application prospects in reducing carbon emissions and improving resource utilization efficiency [2]. Al-Khatib further discussed how big data analysis capabilities affected green innovation through mediating effects and technological intensity and recommended that big data played an indispensable role in promoting green innovation [3]. In terms of green supply chain integration, Liu *et al*. found that big data analysis ability promoted the integration of green supply chain through data-driven decision-making culture, and enterprises could respond more flexibly in the face of environmental and market changes, thus improving their overall operational efficiency [4]. Shi *et al*. analyzed the impact of big data analysis ability on the integration of green supply chain from the perspective of organizational information processing theory and confirmed that an enterprise's information processing ability directly affected the innovation and optimization of green supply chain, and a good information processing ability could help an enterprise better cope with complex environment and market demand [5]. In addition to information processing ability, scientist studied the promotion effect of big data analysis ability and green supply chain integration on green innovation, pointing out that big data played a particularly significant role in technology-intensive industries, and enterprises could carry out green innovation activities more

effectively by combining data-driven decision-making [6]. The results showed that big data not only had advantages in traditional supply chain optimization, but also could directly promote the innovation and application of green technologies, thereby driving sustainable development of enterprises. Some studies have explored the application of big data technology in green supply chain management from a more innovative perspective. The scientist proposed a green supply chain innovation management strategy based on big data technology from the perspective of combining low-carbon economy and e-commerce, and further expanded the research scope of green supply chain, especially the supply chain innovation under low-carbon economy [7]. By constructing a green supply chain management optimization model based on big data analysis, Zhao *et al*. confirmed the great potential of big data in improving supply chain efficiency and environmental performance [8]. Especially in the context of the COVID-19 pandemic, the impact of big data analysis on the green supply chain had become a research hotspot. Zhang *et al*. discussed the relationship between green supply chain management practices and enterprise competitiveness during the pandemic period, emphasizing the core role of big data analysis capabilities in this period, which could help enterprises maintain efficient operation in the supply chain and enhance competitiveness [9]. By studying the relationship between corporate social responsibility, green supply chain management, and corporate performance, the researchers found that big data analysis ability could play a moderating role in these relationships and further improve the overall operation performance of enterprises [10]. Existing studies agree that big data analytical capabilities not only play an important role in optimizing green supply chain management and driving green innovation, but also provide powerful technical support for enterprises in the process of achieving the dual-carbon goal. In the future, with the continuous progress of big data technology, research on green supply chain and dual-carbon targets will provide more opportunities and challenges for enterprises and policy makers.

Although green supply chain can help enterprises reduce carbon emissions and improve resource utilization in theory, many enterprises encounter difficulties in implementation due to high implementation costs and complex technical requirements in practice. Many companies lack transparency in their supply chains, making it difficult to accurately track and assess their carbon emissions and environmental impact. How to use big data technology to effectively collect and analyze environmental data in the supply chain remains a challenge, especially in the face of large data volumes and complex data sources. While big data analytics can provide valuable insights, how to extract actionable insights from these data and translate them into effective green supply chain strategies remains an important question faced by the scientific community today. This study explored how big data analytics could better support green supply chain management to help companies achieve their dual-carbon goals by identifying the main sources of carbon emissions in each link of the supply chain through big data analysis technology, optimizing resource allocation, and improving the overall operational efficiency of the supply chain. This study employed a variety of big data analytics methods including machine learning algorithms and predictive analytics models to process large amounts of information from different data sources that covered enterprise production, logistics, resource consumption, and other areas, thus providing data support for the green transformation of the supply chain. The results of this study would provide data-based empirical analysis and decision support for enterprises and policy makers and promote the wide application of green supply chain worldwide, which was not only essential to achieve the global dual-carbon goal, but also to enhance the competitiveness of enterprises in the low-carbon economy and promote the further practice of sustainable development concepts.

Materials and methods

The data resource and acquisition method

The data utilized in the study was sourced from multiple databases of industry-specific platforms and governmental data repositories, which included China Environmental Statistics Database (Ministry of Ecology and Environment, Beijing, China) and the Global Carbon Atlas (Global Carbon Project, Canberra, Australia). The total data volume was approximately 500 GB, covering the period from January 2018 to December 2022, and including carbon emissions data, production reports, and satellite-derived environmental metrics. The dataset was split into three parts for analysis including 70% for training, 15% for testing, and 15% for validation, ensuring a comprehensive evaluation of the models used in the analysis [11]. In the study of the green supply chain based on big data analysis, it is crucial to select appropriate data sources and adopt the right data collection methods as these factors determine the accuracy, validity, and reliability of the analysis. Several key types of data were used in this analysis, which included industry databases that provided crucial information of supply chain management, environmental assessments, and carbon emission data, sourced from industry associations, research institutes, and government departments. Additionally, annual and quarterly enterprise reports offered insights into companies' supply chain management practices, environmental responsibility efforts, and specific carbon emission data. Satellite data also played a significant role by providing real-time and accurate information on forest carbon sinks and factory carbon emissions, contributing to a comprehensive understanding of environmental impacts. Social media and web data were utilized to gauge public attitudes, behaviors, and perceptions related to green supply chains and dual-carbon targets. Further, first-hand data were collected through questionnaires and interviews, which reflected corporate and public opinions on green supply chain practices. In conjunction with these data, academic articles and research papers supplied theoretical background and empirical evidence to support the analysis.

Data processing and cleaning

The study employed a combination of advanced data analysis platforms and programming tools to process and analyze the green supply chain data. Hadoop (https://hadoop.apache.org/) and Spark (https://spark.apache.org/) were utilized for large-scale data storage and distributed computing. These platforms enabled efficient processing of the 500 GB dataset. MySQL (https://www.mysql.com/) and MongoDB (https://www.mongodb.com/) databases were used for structured and unstructured data management, respectively. Python (https://www.python.org/) and R (https://www.r-project.org/) were the primary programming languages for data analysis with libraries of Pandas (https://pandas.pydata.org/) and NumPy (https://numpy.org/) used for data manipulation and scikit-learn for machine learning models. This setup was run on a high-performance computing cluster featuring 64 cores, 256 GB RAM, and 10 TB of storage, ensuring seamless handling of data-intensive tasks [12].

Data analysis procedures

After collecting the raw data, data processing and cleaning is a crucial step in big data analysis [13]. Data cleansing involves identifying and correcting errors and inconsistencies in data to improve its quality, which typically includes dealing with missing values, outliers, duplicate values, and inconsistent data formats. The missing value processing was shown below.

$$X_{replaced} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (1)$$

where $X_{replaced}$ was a new value to replace the missing value. X_i was a known data value. n was the number of known data values [14]. The IQR method was used to determine the range of outliers that were defined as observations that fell below $Q1-1.5\times IQR$ or above $Q3+1.5\times IQR$.

$$\text{IQR} = Q3 - Q1 \quad (2)$$

where $Q1$ and $Q3$ were the first and third quartiles, respectively. By integrating all aspects of the supply chain, green supply chain management ensured that the use of resources and waste disposal in the production, logistics, and consumption processes minimized the negative impact on the environment. Among them, the reduction of carbon emissions was a core contribution of the green supply chain in advancing the two-carbon goal [15]. There are two main sources of carbon emission including direct emission and indirect emission. Direct emissions come from the enterprise's own production activities such as factory coal, vehicle fuel, *etc*. Indirect emissions come from electricity, heat, and other forms of energy used in the production process [16]. To accurately estimate the carbon emissions of enterprises, the direct carbon emission was calculated below.

$$E_{direct} = \sum (F_i \times EF_i) \quad (5)$$

where E_{direct} was direct carbon emissions (metric ton CO_2e). F_i was the consumption of fuel *i* (kg, liter, cubic meter, *etc.*). EF_i was the emission factor of fuel *i* (metric ton CO_2e/ fuel unit). The indirect carbon emissions were calculated as follows.

$$E_{indirect} = E_c \times EF_e \quad (6)$$

where $E_{indirect}$ was carbon emissions (metric ton CO_2e). E_c was the electric power consumed (metric ton CO_2e/kWh). EF_e was the emission factor of electric power (metric ton CO_2e/kWh).

Results and discussion

By adopting green supply chain management, enterprises can effectively control and reduce carbon emissions such as choosing to use clean energy, optimizing production processes, and adopting efficient technologies [17]. In addition, transparent supply chain management can also help companies identify carbon hot spots in their supply chains and develop appropriate strategies to further reduce carbon emissions, which not only helps to achieve the dual-carbon goal, but also improves the economic efficiency and social responsibility image of the enterprise. After a detailed big data analysis of the green supply chain data, its significant positive impact on the dual-carbon target gradually emerged. Obviously, the implementation and management of green supply chain has been deeply involved in the daily operation of many enterprises, which is related to the issue of environmental protection and the economic benefits of enterprises as well as their social responsibilities. The results showed that, from 2018 to 2022, the number of companies committed to the concept of green supply chain continued to rise, which reflected the increasing number of enterprises that were beginning to recognize and adopt the importance of green supply chains. In addition, average carbon emissions had steadily decreased over time, once again demonstrating the critical role of green supply chain practices in helping to reduce a company's carbon footprint [18]. The gradual improvement of resource utilization efficiency meant that enterprises used resources more accurately in production activities and achieved more efficient production. The continued growth in recycling rates highlighted the fact that more products and raw materials were successfully recycled and reused at the end of the product life cycle, undoubtedly making a positive contribution to reducing the environmental burden (Figure 1). The growth of investment in green technologies reflects the high importance companies attached to green and sustainable technologies. With the increasingly advanced technology, more feasible green solutions have been brought to enterprises, which helps enterprises to achieve the green supply chain goal. This kind of investment not only helps companies meet their environmental goals, but also increases their economic returns and market competitiveness. The green supply chain had a significant positive impact on the two-carbon target. The big data

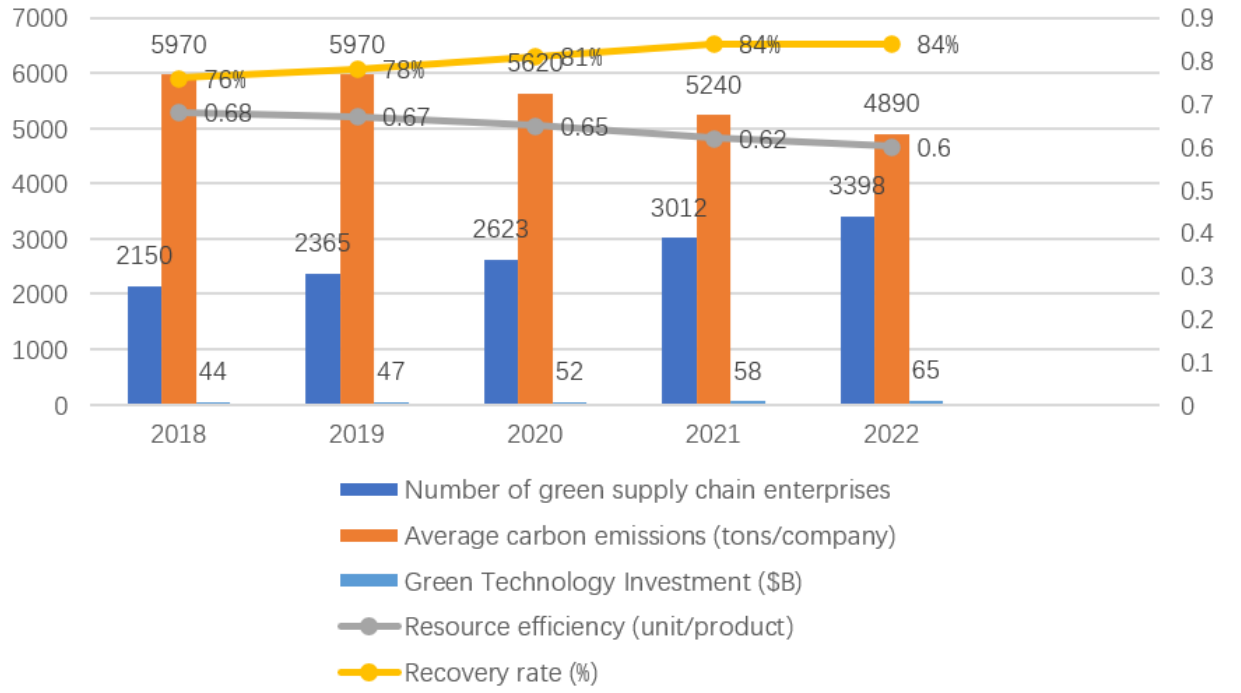

Figure 1. The impact of green supply chain on dual-carbon targets.

analysis results provided strong data support for decision makers and enterprise management and proved the irreplaceable role of green supply chain practices in promoting the dual-carbon goal. With the increasing global concern for environmental issues, green technology has gradually become the core driving force for the development of various industries. In the field of supply chain management, the introduction and application of green technology could greatly optimize the use of resources, reduce waste, reduce emissions, and improve production efficiency, thus bringing double economic and environmental benefits.

The development of green technology covers many aspects including clean production technology, energy efficiency technology, renewable energy technology, waste utilization technology, and so on. These technologies are used at all stages of the supply chain to help companies achieve green, low-carbon production, and operations. Although the green supply chain was initially seen as an environmental effort, it also has a direct relationship with economic growth. In fact, the green supply chain not only brings environmental benefits to enterprises, but also brings significant economic benefits. Ther results showed that, as consumers and investors became increasingly concerned about environmental responsibility, companies implementing green supply chains gained a greater competitive advantage in the market such as higher product prices, more market share, and higher return on investment. In addition, green supply chains could help companies save energy, reduce waste, and avoid high environmental compliance costs, thereby increasing their profitability (Figure 2). However, green supply chains also require some initial investments such as developing new technologies, improving production processes, or partnering with more sustainable suppliers. These initial investments often pay off in the long run because they create a more sustainable and profitable operating model for the business. The results demonstrated that the economic growth rate of enterprises practicing green supply chain in the past few years was generally higher than that of enterprises with traditional supply chain,

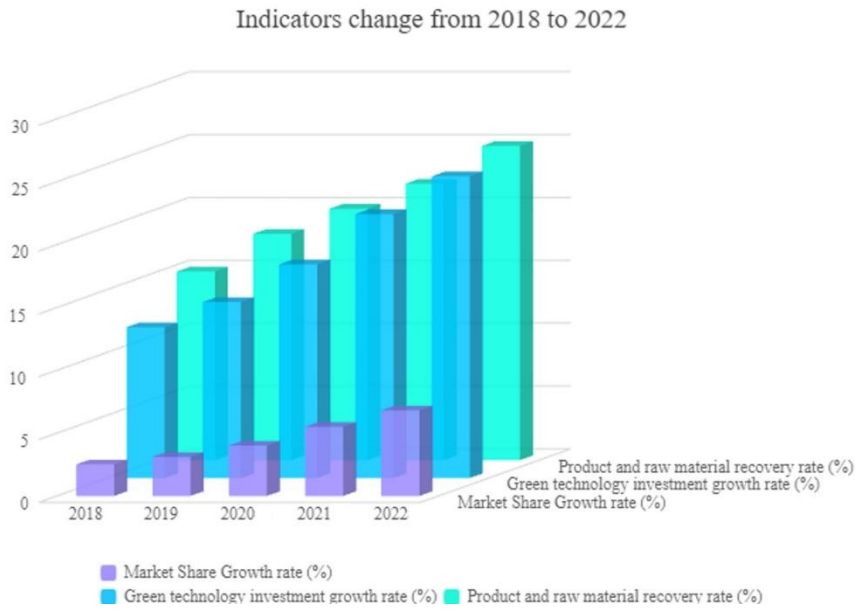

Figure 2. Changes in key indicators of enterprises' green supply chain practices from 2018 to 2022.

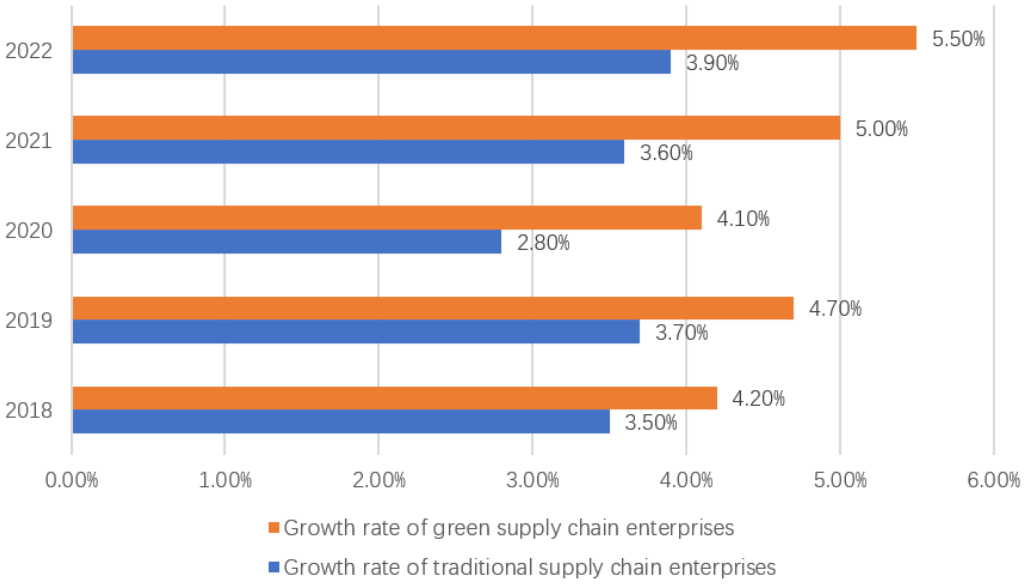

Figure 3. Chart of economic growth data.

which confirmed that the green supply chain was beneficial to the environment, while it had a positive role in promoting the economic growth of enterprises (Figure 3).

This study analyzed the green supply chain based on big data to provide important insights into how companies could optimize their operations while achieving environmental and economic benefits. The results showed that companies that implemented green supply chain practices combined with big data analytics demonstrated a significant reduction in carbon emissions. Specifically, by integrating data from various sources such as satellite data on carbon sinks and real-time emissions monitoring, companies were

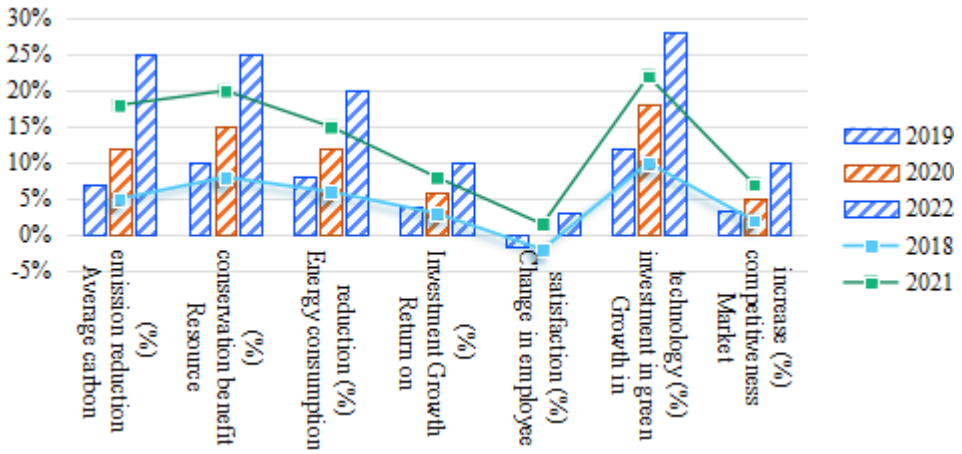

Figure 4. The relationship between green supply chain and enterprise economic benefit.

able to identify emission hotspots and implement targeted strategies. Over the study period, companies displayed an average decrease in carbon emissions of 25%, which was a clear indication of the effectiveness of these methods. The efficient use of resources was another notable outcome. Big data analysis allowed companies to track resource consumption in real time, enabling them to optimize the use of raw materials, reduce waste, and improve overall supply chain efficiency. By analyzing historical data on production and logistics, companies could predict demand more accurately and align their production schedules accordingly, which resulted in a 30% increase in resource utilization efficiency, as measured by the ratio of output to resource consumption. Moreover, recycling rates of materials and products increased by 20%, showcasing the positive environmental impact (Figure 4). The results also demonstrated the increase in market competitiveness among companies that adopted these strategies. Through the implementation of green supply chain practices combined with big data analytics, businesses not only reduced their operational costs but also improved their brand image and reputation. Consumers increasingly favored companies that demonstrated strong environmental responsibility, which shifted in consumer behavior and contributed to a 15% increase in market share for companies with a robust green supply chain. Investments in green technologies grew steadily with businesses allocating more resources to renewable energy, efficient logistics, and waste reduction technologies. With the support of big data analytics, this trend helped companies achieve sustainable growth, while contributing to the global goal of carbon neutrality. These results collectively demonstrated the vital role of green supply chains in reducing environmental impact and boosting economic performance.

Conclusion

With the intensification of global environmental problems and the increasing impact of climate change, green supply chain and dual-carbon targets have become a topic of great concern in both academia and business community. This study took an in-depth look at how a green supply chain based on big data analytics impacted the achievement of dual-carbon goals and provided a range of useful findings and insights. The study found that big data analysis played a crucial role in green supply chain management. By collecting, processing, and analyzing vast amounts of data, companies could better understand the efficiency, resource use, and environmental impact of their supply chains and develop more sustainable strategies

accordingly. In addition, big data analysis could help enterprises predict market changes and adjust production and logistics strategies in a timely manner to achieve a balance between supply and demand, reduce waste and improve economic efficiency. This study also explored the specific impact of a green supply chain based on big data analysis on the dual-carbon goal. The results showed that, by optimizing supply chain management, improving resource utilization efficiency, and promoting the development of green technologies and innovation, enterprises could achieve the dual-carbon goal and economic growth and bring double benefits to society and the environment. Green supply chain management based on big data analysis is of great significance to achieve the goal of double carbon. With the development of technology and the further improvement of big data analysis capabilities, the research on green supply chain and dual-carbon targets will provide more revelations and opportunities for enterprises and academia in the future,

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