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Research on the challenges and countermeasures of applying artificial intelligence in green supply chain management

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Abstract: The global proliferation of sustainable development principles has elevated Green Supply Chain Management (GSCM) to a critical position within corporate environmental governance and strategic management frameworks. Concurrently, the accelerated advancement of artificial intelligence (AI) technologies has emerged as a transformative catalyst for supply chain digitalization. The integration of AI in GSCM demonstrates significant potential for enhancing environmental performance, optimizing resource utilization efficiency, and facilitating carbon neutrality objectives. Nevertheless, this technological convergence presents substantial implementation challenges across multiple dimensions. This study conducts a comprehensive examination of the principal barriers hindering AI adoption in GSCM through data, technology, organization, and ethics, while proposing targeted mitigation strategies and optimization approaches. The research outcomes aim to contribute both theoretical foundations and practical implementation guidelines for enterprises pursuing sustainable transformation and intelligent supply chain modernization.

Keywords: Artificial Intelligence; Green Supply Chain Management; challenges; Countermeasures

1. Introduction

With the growing emphasis on global sustainable development goals, Green Supply Chain Management (GSCM) has become a critical strategic direction for enterprises (Chatzoudes and Chatzoglou, 2022). GSCM encompasses not only internal environmental management but also supplier selection, production process optimization, and product recycling, aiming to reduce resource consumption, minimize environmental pollution, and enhance corporate sustainability (Gawusu et al., 2022). Artificial Intelligence enables machines to mimic the human cognitive actions of perceiving, learning, problem-solving, interacting, and reasoning across various organizational fields (Arrieta et al., 2020). These features have enabled AI to revolutionize the operation of making it possible for businesses to streamline operations, reduce costs, and enhance customer experience (Kumar et al., 2022). AI-powered predictive analytics can help businesses make data-driven decisions, forecast demand, and identify trends (Nozari, 2024). AI’s ability to analyze massive amounts of data, understand relationships, provide visibility into operations, and support better decision-making makes AI a potential game-changer (Belhadi et al., 2024). However, with all these descriptions, companies should take organized steps towards fully exploiting AI and not just settle for using a part of it. One of the most important applications of AI is analyzing big data and optimizing all kinds of transformational and distribution processes in the supply chain, which can contribute to the supply chain's green-ness (Susithra and Vasantha, 2024). GSCM is a complicated process without good management and planning, the whole system cannot produce the intended results. Data gathering from each stage of the process is needed to obtain critical information, Smart technologies for data collecting can be deployed, and further AI can be leveraged for sustainable supply chain

system planning and control. In a modern, data-driven environment, multimodal AI can provide more comprehensive and in-depth insights to support a variety of supply chain decisions and operations (Sharma et al. 2022). In addition, AI can also help enterprises optimize resource allocation and use (Maghsoudi et al. 2023). However, AI also faces many challenges in its actual application in GSCM, which restricts its sustainable development and comprehensive implementation. This paper aims to systematically sort out the main challenges of AI in GSCM and propose corresponding solutions.

2. The overview of AI and GSCM

2.1. The Concept of AI

Artificial intelligence (AI) refers to a collection of technologies that simulate human intelligent behavior by computers or systems, covering core capabilities such as learning, reasoning, perception, language processing, and autonomous decision-making (Zhai et al., 2021). The development of AI began in the 1950s. With the continuous advancement of computing power and algorithm technology, it has gradually moved from theoretical conception to practical application (Pournader et al., 2021). The current AI mainly belongs to "weak artificial intelligence" or "narrow domain AI", that is, systems that focus on specific tasks, such as image recognition, natural language processing, recommendation systems, etc., and are widely used in manufacturing, finance, medical care, transportation and other industries. In contrast, "strong artificial intelligence" or "general AI" is still in the exploratory stage, referring to systems with generalized cognition and self-awareness like humans, which has not yet been realized. In terms of technical architecture, AI mainly relies on machine learning and deep learning methods. The former emphasizes automatic modeling from data, while the latter is centered on neural networks, especially in big data environments. It shows excellent performance.

AI is not only a technical tool, but also a manifestation of systematic thinking. It significantly improves organizational efficiency and reduces operating costs by building data-driven prediction and decision-making models, especially showing unique advantages in processing unstructured data, executing complex processes, and coping with uncertain environments (Tang et al., 2022). At the same time, the rapid popularization of AI has also aroused widespread concern about issues such as privacy security, algorithmic bias, and ethical responsibility. In academia and industry, AI is not only regarded as a key force in promoting a new round of industrial revolution, but is also increasingly becoming an important part of public governance and sustainable development strategies. With the integration of AI and other cutting-edge technologies (such as the Internet of Things, big data, and blockchain), its application prospects in green supply chains, smart cities, precision medicine, and other fields are becoming increasingly broad, pushing the world into a new era of "intelligent drive."

2.2. Green Supply Chain Management Description

Green Supply Chain Management (GSCM) represents an advanced paradigm that integrates environmental sustainability into conventional supply chain operations. As global environmental regulations tighten and stakeholder expectations evolve, GSCM has emerged as a strategic approach for organizations to achieve both ecological and economic objectives. This concept extends beyond traditional efficiency-focused supply chain models by incorporating environmental considerations across all stages, including green design, sustainable sourcing, eco-friendly production, low-carbon logistics, and reverse logistics for product recovery and recycling.

The theoretical foundation of GSCM draws from multiple disciplines, combining operations management with environmental science and corporate sustainability principles. Key practices include environmental supplier assessment, which evaluates partners based on their carbon footprint and resource efficiency; cleaner production

techniques that minimize waste and emissions; and closed-loop systems that facilitate material reuse. A distinctive feature of GSCM is its emphasis on lifecycle thinking, requiring companies to assess and mitigate environmental impacts throughout a product's entire value chain. This holistic perspective differentiates GSCM from conventional approaches that often focus narrowly on cost reduction and operational efficiency.

Implementation of GSCM presents both opportunities and challenges. On one hand, it enables firms to achieve regulatory compliance, enhance brand reputation, and realize cost savings through improved resource productivity. Many leading corporations have demonstrated that GSCM can drive innovation while creating competitive advantages in increasingly eco-conscious markets. On the other hand, barriers such as higher short-term costs, complex supplier coordination, and measurement difficulties for sustainability performance persist. The development of digital technologies, particularly AI and big data analytics, is helping overcome these obstacles by enabling smarter environmental impact assessment and more efficient green operations.

3. The role of AI in GSCM

3.1. Smart Procurement

In the smart procurement process, artificial intelligence technology has been widely used in demand forecasting, supplier selection, price negotiation, market analysis and contract management, significantly improving the scientific nature of procurement decisions and the level of green management. First, AI can accurately predict product market demand through comprehensive analysis of historical procurement data, market dynamics and corporate operating conditions, which helps to formulate more scientific procurement, production and sales plans, thereby reducing resource waste and inventory backlogs. Secondly, with the help of natural language processing and machine learning technology, AI can efficiently process a large amount of price information and procurement standards, achieve intelligent price comparison and green procurement matching, improve procurement efficiency and reduce costs. At the same time, AI can also use big data to evaluate the production history, delivery capabilities and environmental performance of suppliers, assist enterprises in selecting the best partners, avoid potential risks, and build stable and sustainable supply relationships. Finally, enterprises can use AI to build a visual procurement and supply chain management platform to achieve multi-source data integration and dynamic monitoring, provide real-time and visual risk assessment and operational feedback for green procurement decisions, comprehensively improve the efficiency and resilience of green supply chain management, and help enterprises achieve green transformation and sustainable development goals.

3.2. Smart storage

In the warehousing link of green supply chain management, artificial intelligence technology plays a key role, significantly improving the scientific nature of warehousing decisions and the intelligent level of operations. Taking warehouse site selection as an example, AI can build a multi-dimensional logistics model that integrates factory construction costs, business layout, urban development policies and corporate strategies, thereby providing a better site selection plan and avoiding subjective bias in human decision-making. In terms of intelligent warehousing construction, AI can deeply analyze the storage characteristics and transportation requirements of different goods, optimize warehouse design and space layout, effectively improve the efficiency of goods circulation and storage utilization, and promote the visualization and automation management of the warehousing process. At the same time, the application of AI in inventory management is also becoming more and more mature. Through the integration with big data and Internet of Things technologies, enterprises can realize dynamic monitoring and refined classification of goods information, optimize inventory structure with the help of intelligent algorithms, and comprehensively balance ordering costs, warehousing costs and out-of-stock risks, thereby improving the accuracy

of inventory decisions and reducing operating costs. Furthermore, with the help of radio frequency identification (RFID) and intelligent warehousing systems, AI can also realize the automated management of cargo tracking, storage allocation and operation processes, and combine historical sales and logistics data to assist enterprises in inventory warning and intelligent replenishment to prevent inventory backlogs and logistics bottlenecks. Overall, the deep integration of AI in the warehousing process has not only promoted the green transformation of warehousing operations, but also provided strong support for the efficient and sustainable development of the entire green supply chain system.

3.3. Smart Transportation

The transportation link is the core of green supply chain management, which determines the construction level and core competitiveness of the green supply chain of enterprises. Artificial intelligence technology is widely used in smart transportation. Supply chain transportation mainly includes water, road, aviation and railway, each with its own advantages and disadvantages. Artificial intelligence can collect data such as actual traffic conditions, road information and transportation costs in various places, optimize transportation models through intelligent calculations, and formulate the most optimized transportation combination strategy according to different destinations, cargo conditions and delivery time, so as to reduce transportation losses and environmental pollution and achieve the goal of reducing costs and increasing efficiency. By using artificial intelligence and machine learning, enterprises can realize automatic driving of logistics vehicles in logistics parks. This not only ensures the safety and efficiency of vehicle driving, but also saves manpower and time costs, and improves the effectiveness of green supply chain management.

3.4. Construction of intelligent supply chain information platform

The construction of an intelligent green supply chain information platform is an important part of supply chain logistics and an important guarantee for achieving green and high-quality services. Artificial intelligence plays an important role in "intelligent decision-making" in the construction of an intelligent supply chain information platform, effectively improving the information processing and decision-making capabilities of enterprises and improving service efficiency. Using computer vision technology, you only need to stick a barcode on the goods, and artificial intelligence visual recognition technology can quickly identify, upload, track and verify the goods information, avoid manual operation errors, and improve the service efficiency of the platform. After the intelligent supply chain information platform is built, a large amount of logistics information data will be generated, including order information, inventory status and transportation status. Artificial intelligence can help enterprises achieve real-time insights by organizing and analyzing these data, building an integrated supply chain information management network, and formulating automated logistics processing plans to connect various links, automatically execute contract terms, trigger payments, plan routes and vehicle scheduling, and maximize transportation efficiency. The wide application of artificial intelligence technology in green supply chain management has not only improved the efficiency of each link, but also promoted enterprises to achieve green transformation and sustainable development.

4. Challenges of artificial intelligence in green supply chain management

4.1. Data quality and acquisition barriers

Data quality and data acquisition issues are one of the most basic and difficult challenges for AI in GSCM. The essence of AI technology relies on a large amount of high-quality data for training and reasoning, but in the context

of green supply chains, companies often face problems such as uneven distribution of environmental data, inconsistent formats, and lack of standards. For example, in the procurement process, whether the supplier's raw materials meet environmental standards, in the transportation process, whether carbon emission data is traceable, and in the production process, whether indicators such as wastewater and exhaust gas are accurately reported, all involve a large amount of structured and unstructured data. However, many small and medium-sized enterprises have not yet established a complete green information system, and even lack awareness of the collection of environmental data. This makes it difficult for AI systems to "cook without rice" at the data level and build effective models. In addition, there are concerns about data security and privacy between different companies, which makes it difficult to share green performance-related data between upstream and downstream of the supply chain, further hindering the collaborative application of AI.

4.2. Model Black Box and Explainability Dilemma

The "black box" nature of AI models has raised issues of credibility and explainability in GSCM. Although current algorithms such as deep learning and neural networks have achieved remarkable results in prediction and optimization, the problems of complex internal operating mechanisms and unexplainable results have not been fundamentally solved. In the actual application of green supply chain management, companies not only need AI to come up with the "optimal" solution, but also need to understand why the model comes to this conclusion to evaluate whether it matches the company's sustainable development strategy. For example, when AI recommends a certain mode of transportation that can reduce overall logistics costs, but this method may be accompanied by higher carbon emissions, the company needs to weigh the pros and cons and provide reasonable explanations to regulators and stakeholders. At this time, if the AI model cannot provide a clear logical path or influencing factors, it will be questioned as a "decision-making black box", which will affect its adoption within the company.

4.3. High costs and technical barriers

The high cost of technology deployment and the complexity of green supply chain applications have also become obstacles to the implementation of AI. On the one hand, the construction of AI systems involves data collection terminals, algorithm development, computing resource investment, and professional talent recruitment, which is a heavy burden for companies with limited resources, especially small and medium-sized enterprises. On the other hand, the green supply chain itself has the characteristics of complex processes, many participants, and difficulty in coordination. AI models are often difficult to "adapt with one click" and need to be customized according to different industries, enterprise scales, regional policies, etc., which further increases the time and economic cost of technology deployment. In addition, AI technology is constantly updated and iterated, which puts higher requirements on the company's technical maintenance capabilities, which also makes some companies worry about their sustainable investment.

3.4. Talent cross-border and organizational coordination barriers

The effective application of AI in GSCM is also affected by organizational management and talent structure. The green supply chain requires cross-departmental collaboration and cross-functional integration, and the operation of the AI system also relies on multidisciplinary cross-knowledge such as information technology, operational optimization, and environmental management. However, AI developers may lack an understanding of green performance indicators and carbon neutrality strategies, while environmental managers may be unfamiliar with algorithm modeling, data logic, and other content, resulting in communication barriers between the technical team and the business department, making it difficult to form effective collaboration. In addition, some companies lack

experience in the use of AI and training mechanisms, and employees are resistant to new systems, which affects the frequency of use and decision-making weight of the AI system, weakening its value release in green management.

3.5. Moral and ethical issues

AI technology has also triggered many ethical challenges in this process, mainly including data privacy and security, algorithmic bias and unfair decision-making, and unclear decision-making responsibilities. First, AI systems are highly dependent on massive data support, including enterprise operation information, supplier carbon emission records, product life cycle data, and even sensitive information such as consumer behaviour and geographic location. In the process of cross-organizational or cross-border data sharing, if there is a lack of strict permission control and data encryption mechanism, it may lead to the leakage of user privacy or business secrets, especially when AI collects and uses data without the user's knowledge or authorization, it is more likely to violate basic data ethics principles. Secondly, the decision-making basis of AI models often comes from historical data, and these data may have structural biases themselves, which are then amplified in green procurement, supplier evaluation and other links, resulting in some AI systems favouring large enterprises, thereby forming unfair treatment for small and medium-sized enterprises or emerging market players. This "technological discrimination" violates the concept of environmental fairness and win-win cooperation emphasized by GSCM. In addition, AI-led key decisions in the supply chain, such as raw material selection, production scheduling or waste disposal methods, are also likely to lead to unclear responsibility issues. Once they lead to environmental pollution, delivery delays or negative social impacts, the traditional responsibility division mechanism will find it difficult to clearly define the responsible party, which will not only easily lead to legal disputes, but may also undermine the credibility of companies in fulfilling their social responsibilities.

5. AI coping strategies in GSCM

5.1. Building a green data infrastructure

First, at the data level, a unified green data standard system should be established to clarify the definition and collection methods of core indicators such as carbon emissions, energy consumption, and water resource use. This will not only help improve the accuracy and consistency of data, but also ensure that data between different enterprises and supply chain links can be effectively connected and shared. At present, the caliber and statistical methods of green indicators are not unified, resulting in uneven data quality, making it difficult to provide stable and reliable support for AI models. Therefore, promoting industry associations, government regulatory agencies and enterprises to cooperate to formulate green data specifications that meet international standards has become the basic work for realizing the digital transformation of green supply chains.

At the same time, building a unified sharing platform or formulating unified data interface specifications is also key. Through the data sharing platform, different supply chain nodes can exchange environmental performance data in real time, promote the coordinated optimization of the supply chain and improve the overall green benefits. The introduction of blockchain technology provides strong support for improving the transparency and security of data. Blockchain can ensure that data cannot be tampered with and the entire process is traceable, reduce the risk of data falsification and concealment, and enhance the credibility of green supply chain data. In addition, smart contract technology can also automatically perform environmental compliance inspections and carbon trading settlements, further promoting the automation and intelligence of green governance.

Finally, Internet of Things (IoT) devices play an irreplaceable role in the green supply chain. By deploying sensors

at key nodes such as factory production lines, storage facilities and transport vehicles, companies can achieve real-time collection and monitoring of environmental data, such as energy consumption, exhaust emissions, temperature and humidity changes, etc. High-frequency and real-time data input not only improves the dynamic response capability of the AI model, enabling it to quickly capture environmental fluctuations, but also supports timely early warning and intervention of potential risks, helping companies to adjust production plans and logistics arrangements in a timely manner, and further reduce resource waste and environmental load. In summary, the integration of data standardization, sharing mechanism, blockchain technology and IoT devices provides a solid data foundation and technical guarantee for the efficient application of AI in green supply chain management.

5.2. Adopting explainable AI technology and human-machine collaboration mechanism

In terms of model design and selection, algorithms with good interpretability should be given priority, which is particularly important for decision transparency and responsibility traceability in green supply chain management. Specifically, rule-based expert systems or shallow decision tree models can be used first. These models have clear structures, are easy to understand and verify, and can enable managers to clearly understand the basis of each decision and avoid the uncertainty caused by the "black box" effect. In addition, with the development of artificial intelligence technology, the introduction of explainable AI (XAI) technology has become an effective means to solve the complexity of deep learning models. Through XAI technology, the decision-making process of complex models such as deep neural networks can be visualized and explained, helping users understand how the model draws conclusions, thereby improving trust and acceptance.

At the same time, the human-machine collaborative model is also an important way to improve the application effect of the model. In this mode, the AI system is responsible for providing preliminary analysis and suggestions based on data, while the final decision is made by manual decision makers with practical experience. This method can not only give full play to the advantages of AI in data processing and pattern recognition, but also combine human comprehensive judgment and industry experience to effectively avoid the risk of misjudgment caused by relying solely on algorithms. Through the combination of man and machine, the scientific nature of decision-making is guaranteed, and the flexibility and reliability of green supply chain management are improved.

5.3. Lowering deployment thresholds and promoting intelligent services

In terms of cost and deployment, the main challenge faced by enterprises is the large initial investment in artificial intelligence technology, especially the expenditure on hardware equipment, software development and maintenance. To this end, cloud computing platforms and AI-as-a-Service (AIaaS) models can be fully utilized to achieve on-demand use and elastic expansion with the help of cloud resources, greatly reducing the one-time investment pressure on enterprises in infrastructure construction. At the same time, cloud platforms usually have high-performance computing capabilities and a rich AI tool library, which can speed up model training and deployment and improve the efficiency of green supply chain management. The support of the government and industry associations is also crucial. Through multi-dimensional measures such as financial subsidies, tax exemptions, technical guidance and talent training, enterprises can overcome the threshold of technology introduction, reduce operational risks, and promote the popularization of green intelligent systems. It is worth noting that leading enterprises in the industry can be encouraged to take the lead in carrying out pilot projects of AI in the green supply chain and accumulate practical experience and application cases. After the mature solutions and successful experiences have formed a demonstration effect, they will be gradually promoted to small and medium-sized enterprises and the entire industry, and the "point-to-surface" strategy will be used to achieve the widespread popularization and application of technology and promote the overall upgrading and transformation of

the green supply chain.

5.4. Promoting interdisciplinary talent training and organizational integration

To facilitate the effective integration of artificial intelligence in green supply chain management, it is essential to strengthen interdisciplinary talent development by enhancing supply chain managers' mastery of green supply chain knowledge alongside their understanding of AI fundamentals and applications, ensuring a comprehensive awareness of AI's potential and limitations. Simultaneously, IT teams should deepen their comprehension of sustainable management principles to align technological development closely with environmental objectives, achieving an organic integration of technology and environmental protection. To this end, enterprises can establish "green intelligence officers" or hybrid roles combining technical and managerial expertise to bridge communication gaps between supply chain management and technical teams, fostering cross-departmental collaboration and resource integration. Moreover, continuous employee training and cultural development are critical; regular AI application training, green supply chain seminars, and innovation-sharing sessions can cultivate a positive, open learning environment, enhance employees' acceptance and engagement with AI systems, and promote the smooth implementation and deep integration of technology into daily operations, thereby advancing the intelligent capabilities and overall competitiveness of the green supply chain.

5.5. Improving the technical system

In order to cope with the ethical challenges faced by artificial intelligence (AI) in the application of green supply chain management (GSCM), enterprises and policymakers need to promote system governance from multiple dimensions such as institutional construction, technical specifications and cultural guidance to ensure the safety, transparency and fairness of AI in the green transformation. First, the data governance mechanism should be improved, the permissions for data collection, storage, processing and sharing should be clarified, encryption, access control and anonymization technologies should be used to ensure information security, and data use should be transparent, the principle of "informed consent" should be followed, and the information rights and interests of all parties should be respected. Secondly, the fairness and interpretability of algorithms should be strengthened, and models should be trained with diverse and representative data to avoid systematic bias against specific regions or enterprises. At the same time, explainable AI technology should be promoted to improve decision-making transparency and supervision efficiency, and reduce the risk of "black box decision-making". In addition, an ethical assessment and accountability mechanism should be established, a systematic ethical risk review should be carried out, the legal and moral responsibilities of all parties should be clarified, and a cross-departmental ethics committee should be established to supervise AI decisions to ensure compliance with environmental and social responsibility requirements. Finally, the internalization of green ethical culture should be promoted, and the organizational culture with sustainable development as the core should be strengthened through employee training and value shaping. In summary, only by combining institutional guarantees and technical means can we realize the green empowerment of AI in GSCM and promote the coordinated improvement of environmental performance and social responsibility.

6. Conclusion

The integration of Artificial Intelligence (AI) into Green Supply Chain Management (GSCM) represents a transformative shift toward sustainability and operational efficiency. AI enhances key GSCM processes, including smart procurement, warehousing, transportation, and information platform construction, by optimizing resource allocation, reducing environmental impact, and improving decision-making through data-driven insights. However,

challenges such as data quality issues, model explainability, high implementation costs, interdisciplinary talent gaps, and ethical concerns hinder its full potential. To address these barriers, strategies such as establishing green data standards, adopting explainable AI, leveraging cloud-based solutions, fostering cross-disciplinary collaboration, and implementing robust ethical frameworks are essential. Future research should focus on scalable AI solutions, industry-specific applications, and policy support to ensure equitable and sustainable adoption. Ultimately, AI-powered GSCM can drive the transition toward a circular economy, balancing economic growth with environmental stewardship.

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