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Analysis of Research Progress on Inventory Optimization in Green Supply Chain

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Abstract. Against the backdrop of the "dual carbon" strategy and global sustainable development goals, optimizing green supply chain inventory has gradually become an important research topic in both academia and industry. This article provides a systematic review and overview of relevant research in the past five years. Research has found that traditional inventory optimization models have gradually expanded from a single cost minimization objective to simultaneously consider multidimensional objectives such as carbon emissions and service levels. In terms of methodology, mathematical programming, intelligent optimization algorithms, and simulation have been widely applied, and the introduction of uncertainty handling, policies, and financial factors has made the model more practical. In terms of industry applications, the manufacturing industry focuses on closed-loop inventory and recycling strategies, while the e-commerce and fast-moving consumer goods industries rely on the Internet of Things, big data, and dynamic replenishment technology to achieve high turnover and low-carbon operations. Despite some progress, existing research still faces issues such as inconsistent carbon accounting standards, lack of consideration for social performance and institutional implementation costs, and incomplete incentive mechanisms upstream and downstream. Based on this, this article proposes that future research should strengthen interdisciplinary integration and real data verification, explore supply chain collaboration mechanisms, interpretability of deep optimization, and effective integration of policies and practices, in order to promote the further development of green supply chain management theory and practice.

Keywords: Green Supply Chain, Inventory Optimization, Carbon Emission.

1. Introduction

Climate change and resource constraints are profoundly altering the dynamics of global economic development, driving supply chains from a traditional efficiency-oriented approach to a low-carbon and sustainable one. As a crucial link connecting production, logistics, and consumption, supply chains account for a significant proportion of energy consumption and carbon emissions. Supply chains are estimated to generate around 60% of global carbon emissions. Even within the logistics sector, freight and warehousing activities contribute at least 7% of worldwide greenhouse gas emissions. These figures underscore the urgent need to decarbonize inventory and supply chain processes. Countries around the world are incorporating green supply chains into their policy frameworks for low-carbon transitions. For example, within the strategic context of its "dual carbon goal," China has successively issued policy documents, such as the "Green Supply Chain Management Guidelines," which require companies to comprehensively enhance green practices in raw material procurement, transportation, inventory, and recycling. Meanwhile, European and American countries have gradually embedded green standards into global trade rules through international systems such as the Paris Agreement and the Carbon Border Adjustment Mechanism (CBAM). Driven by both policy and market forces, green supply chains are rapidly expanding and have become a focus of both academia and industry.l

In the study of green supply chains, inventory optimization is a key component. While traditional inventory management aims to minimize holding costs and reduce stock-out risks, green inventory optimization also considers carbon emissions, energy efficiency, and recycling. In recent years, academic research has focused on achieving a balance between cost and carbon emission constraints, exploring the applicability of various optimization algorithms. This shows that inventory management has moved from a single economic goal to a dual goal of environmental and economic benefits [1]. However, existing literature focuses on quantitative models and theoretical algorithms, while the integration at the social level, institutional policies, and corporate practices is still insufficient. At the same time, the introduction of emerging technologies has provided breakthroughs for green inventory optimization. Artificial intelligence and big data have played an important role in demand forecasting, dynamic inventory adjustment and logistics path optimization, which can significantly reduce redundant inventory and reduce carbon emissions. This technology-driven path not only promotes the upgrading of management models but also strengthens the resilience of green supply chains in dealing with market uncertainties [2]. In the future, with the application of new technologies such as blockchain in carbon footprint tracking and green certification, the transparency and compliance of inventory optimization are expected to be further improved. At the international comparative level, foreign scholars generally emphasize the importance of institutional environment and technology synergy. Early reviews show that the research on green supply chain has formed a research framework with life cycle, reverse logistics, and environmental performance evaluation as the core, and the practice of European and American countries mainly relies on a sound policy mechanism and a mature market environment [3]. Chinese research emphasizes policy guidance and corporate adaptability. This difference shows that the development paths of green supply chains in China and abroad show different institutional logic and practice emphasis under the same trend. Despite this, existing research remains deficient. First, systematic research on environmental regulation and policy is relatively fragmented, lacking in-depth comparisons of institutional differences across countries. Second, while technological empowerment has received widespread attention, research on how technologies such as artificial intelligence, big data, and blockchain can collaboratively promote green inventory optimization remains insufficient. Finally, there is a disconnect between academia and industry, and the real-world validation and application of many models still require improvement. Regarding the inventory management segment, its carbon emissions mainly come from warehouse energy consumption, packaging materials, excess inventory handling, and transportation and distribution. According to the World Resources Institute, about 30% of the greenhouse gas emissions generated by global logistics and warehousing activities are directly or indirectly related to inventory holding and management. Especially in the fast-moving consumer goods and e-commerce industries, high inventory turnover and frequent replenishment further increase the carbon footprint per unit of product. Therefore, optimizing inventory structure and improving inventory turnover efficiency has become one of the key pathways for companies to achieve carbon reduction goals.

Based on these considerations, this paper aims to systematically review the research progress on green supply chain inventory optimization. This paper seeks to reveal the theoretical evolution and practical paths of green inventory optimization at the intersection of technology and policy. Furthermore, this paper aims to fill the gap between technology and policy research and provide a reference for future academic research and practical applications.

2. Technology-driven Path for Green Supply Chain Inventory Optimization

2.1. Artificial Intelligence and Big Data Analysis

With the digitization of supply chains and the widespread deployment of Internet of Things (IoT) devices, artificial intelligence and big data analysis have become one of the core technology paths to promote green supply chain inventory optimization. Compared with traditional static rules or simple statistical prediction methods, Artificial Intelligence (AI) technologies represented by machine learning (ML) and deep learning (DL) can learn complex nonlinear relationships from massive historical sales, sensor, and external environmental data, thereby bringing significant improvements in demand forecasting, inventory replenishment, and carbon emission estimation [4,5]. First, in demand forecasting and inventory strategy formulation, combined forecasting based on models such as Long Short-Term Memory (LSTM), random forest, and gradient boosting machine (GBM) can better capture the nonlinear impact of seasonality, promotion effects and external shocks on demand, thereby making order quantities and safety stock levels closer to the actual demand distribution and reducing the dual costs of excess inventory and stockouts [4]. At the same time, empirical and simulation studies have also shown that when the prediction accuracy is improved, the overall inventory holdings and the proportion of abandoned or unsold items will decrease significantly, which can effectively reduce the carbon footprint of the supply chain [4,5]. Second, the intelligent replenishment and dynamic pricing mechanism supported by AI and big data provides a feasible path for high-turnover e-commerce and instant delivery scenarios. By linking real-time sales flow, inventory levels, and transportation availability, the intelligent replenishment system can dynamically adjust multi-warehouse allocation and reordering strategies while ensuring service levels, reducing additional transportation emissions caused by multiple small-batch shipments [6]. In addition, by combining dynamic pricing with inventory control, companies can adjust demand peaks and valleys through price signals, reduce rush shipments and overtime deliveries during peak periods, and thus reduce energy consumption and carbon emissions [7].

At the same time, the carbon emission estimation and attribution capabilities brought by AI enable closed-loop management of inventory decisions and environmental performance. By jointly modeling energy consumption, transportation fuel consumption, equipment operation data, and production batch information collected by IoT, machine learning models can make more detailed estimates and predictions of the "chain carbon emissions" of each batch and each SKU, providing data support for differentiated inventory strategies [8].

Today, in the field of e-commerce warehousing and distribution, several large platforms have deployed hybrid ML models to improve replenishment frequency and warehouse distribution strategies by combining sales data, user search, and click behaviors with in-warehouse IoT data, thereby significantly reducing unsold and return rates [4,5]. In the manufacturing and wholesale industries, some companies use AI-driven carbon attribution models to evaluate supplier procurement alternatives and make inventory decisions to replace high-carbon raw materials with low-carbon raw materials, thereby reducing Scope-3 emissions without significantly increasing costs [8]. AI and big data provide full-chain technical capabilities for green inventory optimization, from prediction to execution. However, to be effective, they must meet prerequisites such as data quality, cross-enterprise data sharing, and model interpretability [4,5]. In addition, directly incorporating environmental goals (such as carbon emissions) into reinforcement learning reward functions or multi-objective optimization frameworks requires an appropriate trade-off between quantifiable carbon indicators and business performance, which is both a research hotspot and an engineering challenge [8].

Despite the strong potential of AI in inventory forecasting and carbon tracking, its integration with existing enterprise systems (such as ERP and WMS) still faces significant challenges. Many companies continue to use traditional architectures that lack support for real-time data processing and AI model interfaces. Furthermore, the "black box" nature of AI models reduces the transparency of decision-making processes, affecting their acceptability in environments with strict compliance requirements. Therefore, promoting deep integration of AI with inventory systems not only requires technological upgrades but also coordinated reforms in organizational processes, data governance, and personnel training.

Despite these advances, integrating AI with existing inventory management systems poses challenges. Legacy enterprise resource planning (ERP) and warehouse management systems (WMS) often lack the flexibility to absorb advanced AI modules without significant upgrades. High-quality, real-time data from all nodes in the supply chain is required, but data silos and quality issues are common. Organizations must also address change management and skills gaps to adopt AI-driven processes. However, successful deployments illustrate the potential gains. For example, Unilever’s ice cream division integrates AI-based demand forecasting (including weather and freezer inventory data) to better align production with consumer demand. This has improved forecast accuracy by about

10% and reduced production waste by roughly 10%. Such improvements in inventory alignment directly translate into reduced energy use and lower carbon emissions from excess production.

2.2. Blockchain Technology

Blockchain, with its decentralized, immutable, and traceable characteristics, provides a technical foundation for improving supply chain visibility, establishing credible carbon footprint records, and supporting green compliance [9]. In the green path of inventory optimization, blockchain mainly plays a role through three mechanisms: transparent and credible data sharing, carbon footprint on-chain to support auditable compliance, and smart contract-driven green incentives and financing. First, blockchain can solve the problem of a lack of trust and visibility of cross-enterprise data. Inventory management often relies on inventory and transportation information upstream and downstream of the supply chain, but in reality, data silos, falsification, and lags are common. Putting key events on-chain can provide all authorized nodes with consistent and immutable historical records, reducing overstocking or duplicate safety stocks caused by information asymmetry [9,10]. This is particularly important for cross-border e-commerce, multi-level distribution systems, and multi-supplier manufacturing companies. Second, blockchain provides a verifiable path for carbon footprint tracking and accounting. By uploading emission records of production batches and transportation batches, third-party audit results, etc., to the chain and combining them with IoT device data, enterprises and regulators can achieve a traceable carbon flow account from raw materials to finished products, thus providing enterprises with a solid accounting basis when formulating inventory strategies [11].

Finally, smart contracts can transform green compliance into an incentive or penalty mechanism that is automatically executed. For example, when the on-chain records show that a batch of products meets green production standards or is successfully recycled and reused, the smart contract can automatically trigger green credit discounts, accounts receivable discounts, or carbon credit rewards; on the contrary, if the upstream supplier's on-chain data does not meet the environmental protection threshold, it can automatically trigger warnings or binding procurement terms [9,10]. This mechanism closely couples green inventory management with financial incentives, reducing the financial resistance of enterprises to implement green transformation.

Blockchain provides a "trusted data layer" and an "automated compliance/incentive layer" in green inventory optimization, but its actual promotion still faces technical and organizational barriers, including authenticity issues before data is uploaded to the chain, sharing boundaries of privacy and commercially sensitive data, performance limitations of on-chain storage and query, and the lack of cross-enterprise governance and regulatory standards [10]. Therefore, blockchain is more likely to be a hybrid solution combined with IoT, big data, and traditional databases, rather than a single universal tool.

While blockchain enables trusted cross-enterprise carbon data sharing, it also faces challenges such as questions about the authenticity of data before it is recorded on the chain, system performance bottlenecks, and compatibility issues with existing databases. Especially in high-frequency transaction environments, the throughput and response speed of blockchain are still insufficient to support real-time inventory management across the entire chain. Therefore, future research should explore a 'on-chain off-chain' hybrid architecture and combine lightweight consensus mechanisms with privacy computing technologies to ensure data trustworthiness while enhancing system practicality.

For example, JD Logistics has deployed an AI-driven intelligent replenishment system, integrating sales forecasting with dynamic warehouse network scheduling, which has increased inventory turnover by over 20%, while also reducing resource waste and carbon emissions caused by unsold goods and returns. Additionally, Unilever has introduced AI forecasting models based on weather and sales data in its ice cream business, significantly reducing overproduction and energy consumption in cold chain storage, cutting annual carbon emissions by approximately 15%. These cases demonstrate that technology-enabled green inventory optimization not only provides environmental benefits but also delivers substantial economic returns.

In practice, blockchain integration also faces obstacles. For example, scalability and performance limitations can impede the recording of high-frequency inventory transactions, and companies must carefully manage privacy concerns and competitive data sharing. Cross-industry standards and governance must be established for multi-enterprise systems to function smoothly. Nonetheless, early adopters illustrate the potential: for instance, Carrefour, a French retail chain, has implemented blockchain tracking for food products and reported that items traced by blockchain saw boosted sales, as consumers gained trust from full traceability. Similarly, Walmart has piloted a Hyperledger-based blockchain for tracking pork and mango supply chains, reducing product traceability time from about seven days to just 2.2 seconds. These case studies demonstrate how blockchain transparency, combined with inventory management, can enhance sustainability and efficiency, even as widespread deployment still requires overcoming technical and organizational barriers.

3. The Impact of Environmental Regulations and Policies

3.1. International Policy Trends

Against the backdrop of accelerating global green transformation, environmental regulations and policies have become a key driving force for companies to implement green supply chain management. These policies not only redefine the conditions for supply chain operations but also directly affect the formulation and optimization of inventory strategies [12]. From the international carbon tariff mechanism to the internal carbon footprint disclosure requirements of enterprises, the multi-dimensional interaction of policies and regulations is profoundly affecting the theory and practice of green inventory management. At present, international environmental policies are showing a clear trend of shifting from voluntary initiatives to mandatory regulations, and from single-country actions to multilateral coordination mechanisms [13].

The Carbon Border Adjustment Mechanism, a key European Union (EU) policy, covers high-carbon-emitting industries such as cement, steel, and aluminum. It is expected to gradually expand to more sectors. This will force companies to include previously unaccounted carbon costs in their inventory decision models. CBAM will also prompt companies to re-select suppliers and restructure inventory networks. At the same time, it will incentivize investment in low-carbon warehousing technologies and green transportation.

At the same time, environmental, social and governance (ESG) information disclosure requirements are gradually being unified globally. Emissions from warehousing energy consumption, packaging waste and excess inventory handling generated during inventory management have become a focus of attention. Therefore, companies need to establish a full-life-cycle carbon accounting system, incorporate indicators such as inventory turnover rate and slow-moving inventory ratio into carbon efficiency assessments, and face the reality that green inventory performance is gradually becoming a threshold for financing and market access. This also further encourages companies to optimize inventory levels to reduce carbon footprints, and by building a closed-loop inventory system, strengthening return, recycling and remanufacturing processes, and reducing dependence on raw material procurement, thereby reducing overall emissions [14].

Furthermore, Green Public Procurement (GPP) policies and large-scale corporate green procurement standards require suppliers to meet low-carbon targets in aspects such as material selection, packaging design, and carbon labeling. These standards not only raise entry barriers at various stages of the supply chain but also force companies to adjust their procurement and inventory strategies, such as increasing safety stocks of environmentally friendly raw materials to cope with fluctuations in demand for green orders [15].

3.2. Enterprise Response Strategies

To cope with these increasingly stringent environmental regulations, companies are gradually making strategic adjustments. Carbon footprint accounting and disclosure have become fundamental to policy responses. Many companies have begun integrating Enterprise Resource Planning (ERP), Warehouse Management System (WMS), and carbon management software to establish systems that can link inventory changes and carbon emissions data in real time. Relying on international standards such as the Greenhouse Gas (GHG) Protocol and International Organization for Standardization (ISO) 14064, companies clearly account for inventory-related direct emissions, indirect emissions, and indirect emissions along the value chain, and use IoT sensors and blockchain technology to improve data accuracy and traceability [16]. These data provide reliable carbon cost parameters for inventory optimization, supporting dynamic adjustment of replenishment strategies to better balance service levels and carbon efficiency.

Green supply chain finance (GSCF) is another key strategy that links environmental performance with the financing conditions of enterprises, providing economic incentives for enterprises to implement green inventory strategies. Through trade financing linked to carbon performance, banks provide preferential interest rates based on indicators such as suppliers' inventory turnover rate and unit carbon emissions, directly incentivizing enterprises to reduce unsaleable inventory and high carbon dependence. Some enterprises also include carbon quotas and carbon credits in the scope of financing collateral, converting the carbon emission reduction benefits brought by inventory optimization into financial support, and further promoting green technology innovation and the application of intelligent warehousing systems. In terms of supply chain collaboration and contract design, enterprises strengthen transparency and cooperation with upstream and downstream partners on inventory carbon data by jointly building a carbon data sharing platform, thereby reducing excessive inventory and additional emissions caused by the "bullwhip effect". Some enterprises also carry out joint green technology investment, jointly build low-carbon warehousing, electric transport fleets and packaging recycling systems, reduce the implementation costs of individual enterprises through joint investment, and systematically evaluate cross-enterprise cost sharing and overall carbon benefits in the inventory model [17]. Overall, environmental regulations and policies are deeply embedded in the strategic framework of corporate inventory optimization. They are no longer merely external constraints, but have become a crucial force driving comprehensive carbon efficiency optimization and the restructuring of supply chain relationships. Through collaborative innovation in policies, technologies, and management models, green supply chain inventory optimization is expected to continue to evolve within a complex global regulatory environment, providing solid support for companies' low-carbon transitions.

To further promote the development of green supply chain inventory optimization, future research should focus on the following directions:Construct an interdisciplinary research framework.Integrate management, environmental science, data science, and policy studies to establish a multi-dimensional evaluation system, systematically analyze the synergistic mechanisms of carbon efficiency, economic performance, and social benefits; Strengthen technological collaboration and application depth.Explore integration paths for AI, blockchain, IoT, and other technologies to address key issues such as data silos, model interpretability, and system compatibility; Promote comparative research on international policies.Compare and analyze the impact mechanisms of carbon regulation policies (such as CBAM, ESG disclosure, green procurement) in different countries and regions on enterprise inventory strategies, providing differentiated response strategies for globalized supply chains; Establish industry-research collaborative platforms.Encourage academia and enterprises to jointly build open data platforms and experimental environments, promote the verification and iteration of theoretical models in real scenarios, and accelerate the practical application of green inventory innovative technologies.

4. Conclusion

This article systematically reviews research progress in green supply chain inventory optimization, focusing on two core themes: technology-driven approaches and policy influences. On the technical level, artificial intelligence and big data are transforming inventory management from an economic perspective to a dual-economy and environmental perspective by improving demand forecasting accuracy, optimizing dynamic replenishment strategies, and refining carbon emissions accounting. Blockchain, through trusted data sharing, carbon footprint traceability, and smart contract incentive mechanisms, provides technical support for cross-enterprise inventory collaboration and green compliance. On the policy level, international regulations such as the Carbon Border Adjustment Mechanism and ESG information disclosure have restructured corporate inventory decision-making processes, and companies have actively responded through strategies such as developing carbon accounting systems, applying green supply chain finance, and cross-stakeholder collaboration. Establish unified carbon accounting and reporting standards to reduce corporate compliance costs and enhance the comparability and credibility of carbon data. Design tiered fiscal and tax incentive policies to provide tax reductions or green credit support for enterprises adopting green warehousing technologies and implementing circular inventory models. Promote the development of public data platforms to support secure sharing of inventory and carbon data among upstream and downstream supply chain enterprises, breaking down 'information silos.' Strengthen international policy coordination, participate in the formulation of global green supply chain standards, and prevent trade barriers and carbon leakage caused by institutional differences.

The study also found that existing research suffers from fragmented policy research, unclear technical coordination mechanisms, and a disconnect between industry, academia, and research. Further in-depth exploration is needed by integrating multiple dimensions. Future research should transcend the limitations of single disciplines and construct a systematic analytical framework that integrates economics, environment, technology, and policy. This should focus on comparative studies of environmental regulations across countries to reveal the mechanisms that influence institutional differences on inventory optimization paths. On a technical level, it need to deepen the collaborative application of artificial intelligence, big data, and blockchain to address key challenges such as data sharing boundaries and model interpretability. On a practical level, it should promote deeper collaboration between academia and industry, establish open data platforms and case sharing mechanisms, and facilitate the transformation of theoretical models into practical solutions. Policymakers can improve green incentive policies and standards systems to provide clearer guidance for companies' green inventory transformation and promote the low-carbon and sustainable development of the global supply chain.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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