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Designing a Bioeconomy-Based Sustainable Supply Chain Model in the Era of the Fourth Industrial Revolution (Case Study: Gas Industry)

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ABSTRACT

The primary objective of the present study was to design a bioeconomy-based sustainable supply chain model in the era of the Fourth Industrial Revolution for Iran's gas industry; a model capable of addressing the triple bottom line sustainability challenges (economic, environmental, and social) by leveraging two key global trends, namely the bioeconomy and the Fourth Industrial Revolution. The research approach was a combination of deductive and inductive reasoning. The research strategy was grounded in numerical data analysis and quantitative modeling. Data analysis indicated that, using a meta-synthesis approach, the global literature was systematically reviewed, leading to the extraction of 148 initial codes, 37 specialized concepts, and 7 overarching categories. These categories, which included (1) theoretical infrastructure, (2) strategic orientation, (3) environmental requirements, (4) operational instruments, and others, constituted the foundational components of the proposed model. The findings of the present study were classified into two main domains: thematic analysis (qualitative model) and network optimization (quantitative model), thereby providing the necessary foundations for proposing a comprehensive bioeconomy-based sustainable supply chain management (SSCM) model for the gas industry. The results of this research were obtained across two principal domains, namely the qualitative model (meta-synthesis) and the quantitative model (optimization). Interpreting these results through comparison with prior studies reveals both the alignment and the innovative contribution of the proposed model.

Keywords: Bioeconomy-based sustainable supply chain in the era of the Fourth Industrial Revolution.

Introduction

In recent years, the pursuit of sustainable development has fundamentally reshaped the logic of supply chain management, particularly in energy-intensive and resource-dependent industries. Traditional supply chain models, which have historically prioritized cost efficiency and operational performance, are increasingly criticized for their inability to respond to escalating environmental degradation, social inequities, and systemic risks. As a result, sustainable supply chain management (SSCM) has emerged as a dominant paradigm that integrates economic viability with environmental stewardship and social responsibility through the triple bottom line framework (1, 2). This paradigm shift is especially salient in the gas industry, where supply chains are complex, capital-intensive, and

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deeply intertwined with national development strategies, environmental commitments, and technological infrastructures.

Parallel to the rise of SSCM, the bioeconomy has gained prominence as a transformative economic model that emphasizes the sustainable use of biological resources, bio-based products, and renewable processes to reduce dependency on fossil-based systems. The bioeconomy is not merely a sectoral innovation but represents a systemic reconfiguration of production, consumption, and value creation across global supply chains (3, 4). In energy-related industries, the integration of bioeconomy principles—such as biomass utilization, circular resource flows, and low-carbon alternatives—offers a strategic pathway to reconcile energy security with sustainability imperatives (5, 6). However, despite its theoretical promise, the operationalization of the bioeconomy within large-scale energy supply chains remains fragmented and under-theorized, particularly in emerging economies.

The concept of the circular economy further reinforces the bioeconomy discourse by advocating closed-loop systems that minimize waste, extend product lifecycles, and regenerate natural capital. Circular economy principles have been widely recognized as complementary to SSCM, enabling supply chains to move beyond linear "take–make–dispose" models toward regenerative and restorative systems (7, 8). In the context of the gas industry, circular and bio-based approaches can support transitions toward biomethane, bio-based materials, and energy efficiency improvements, while simultaneously addressing environmental externalities and regulatory pressures (9). Nonetheless, integrating circular bioeconomy logics into existing gas supply chain infrastructures requires substantial strategic alignment, technological capability, and institutional support.

The Fourth Industrial Revolution, commonly referred to as Industry 4.0, introduces another critical layer of transformation. Digital technologies such as big data analytics, artificial intelligence, blockchain, and the Internet of Things (IoT) are reshaping how supply chains are designed, monitored, and governed. These technologies enhance transparency, traceability, and real-time decision-making, which are essential for achieving sustainability and resilience objectives in complex supply networks (10, 11). In sustainable and circular supply chains, Industry 4.0 technologies act as key enablers by facilitating resource optimization, emissions monitoring, and lifecycle assessment (12, 13). The convergence of digital transformation and sustainability thus represents a powerful opportunity to redesign energy supply chains for long-term value creation.

Despite growing scholarly attention to SSCM, the bioeconomy, and Industry 4.0 as separate domains, integrative models that systematically combine these three perspectives remain scarce. Existing studies often focus on individual dimensions, such as green supply chain practices and performance outcomes (14, 15), the role of digital technologies in circular supply chains (16, 17), or resilience and risk management under uncertainty (18, 19). While these contributions provide valuable insights, they frequently lack a holistic framework capable of capturing the interdependencies between sustainability dimensions, bioeconomy principles, and digital transformation within a unified supply chain model.

Risk and resilience considerations further complicate this landscape. Energy supply chains are increasingly exposed to environmental uncertainty, geopolitical volatility, regulatory shifts, and technological disruption. The COVID-19 pandemic and subsequent global shocks have underscored the vulnerability of conventional supply chain configurations and the urgent need for resilience-oriented design (2). Recent research highlights that resilience in sustainable supply chains is not solely a function of redundancy or flexibility but also depends on digital visibility, adaptive governance, and strategic alignment with sustainability goals (12, 18). In bioeconomy-oriented supply chains, additional layers of uncertainty arise from feedstock availability, technological maturity, and market acceptance, necessitating advanced risk modeling and decision-support mechanisms (20).

Performance evaluation and decision-making constitute another critical gap in the literature. Assessing sustainability, resilience, and bioeconomy integration requires multi-dimensional and often conflicting criteria. Multi-criteria decision-making (MCDM) approaches, including fuzzy methods, have been widely applied to address such complexity in sustainable and green supply chain contexts (21, 22). However, many studies remain sector-specific or methodologically isolated, limiting their generalizability and strategic relevance. There is a growing need for performance evaluation frameworks that are explicitly aligned with bioeconomy transitions and digitally enabled supply chain architectures (16, 23).

Governance and policy frameworks play a decisive role in shaping the feasibility and effectiveness of sustainable supply chain transformations. Regulatory incentives, institutional coordination, and national sustainability strategies influence how firms adopt green practices, invest in digital technologies, and integrate bio-based solutions (5, 24). In emerging economies, institutional pressures and policy coherence are particularly important, as firms often face resource constraints, infrastructural limitations, and regulatory uncertainty (15, 25). For the gas industry, which is typically characterized by strong state involvement and strategic importance, governance structures can either enable or hinder the transition toward sustainable and bioeconomy-based supply chains.

From a theoretical standpoint, supply chain evolution research emphasizes that contemporary supply chains must be understood as dynamic, adaptive systems rather than static linear structures (26). This perspective aligns closely with the integration of bioeconomy and Industry 4.0 principles, both of which require systemic thinking and cross-functional coordination. Recent studies in petrochemical and energy-related industries highlight that technological advancement alone is insufficient; organizational capabilities, strategic orientation, and policy alignment are equally critical for achieving sustainable and resilient supply chain expansion (23, 27).

Within this context, the gas industry represents a particularly relevant and underexplored empirical setting. As a cornerstone of national energy systems and a major contributor to greenhouse gas emissions, the gas sector faces mounting pressure to align with sustainability and low-carbon transition goals. At the same time, it possesses significant infrastructural assets, technological expertise, and strategic leverage that can support bioeconomy integration if appropriately harnessed (5, 9). However, existing research on sustainable supply chains in the gas industry tends to focus on isolated practices or environmental performance metrics, rather than comprehensive, integrative models that combine bioeconomy principles, digital transformation, resilience, and governance considerations (28, 29).

Moreover, much of the current literature is fragmented across disciplines, including operations management, environmental management, industrial engineering, and policy studies. This fragmentation hampers the development of coherent models that can guide both academic inquiry and managerial practice. Meta-analytic and integrative approaches are therefore essential to synthesize dispersed knowledge and translate it into actionable frameworks for complex industries such as gas and energy (9, 20). Combining qualitative synthesis with quantitative modeling offers a promising pathway to bridge theory and practice, enabling robust model development and empirical validation.

In light of these gaps, there is a clear need for a comprehensive and systematically validated model of sustainable supply chain management that explicitly incorporates bioeconomy and circular economy principles, leverages Industry 4.0 technologies, addresses resilience and risk, and accounts for governance and policy contexts within the gas industry. Such a model can contribute to the advancement of SSCM theory by integrating multiple transformative paradigms, while also providing practical guidance for policymakers and industry stakeholders seeking to navigate sustainability transitions in energy supply chains (16, 17, 27).

Accordingly, the aim of this study is to design and validate a comprehensive bioeconomy-based sustainable supply chain management model for the gas industry in the era of the Fourth Industrial Revolution.

Methods and Materials

This study adopted a mixed-methods research design grounded in a pragmatic philosophy, combining deductive and inductive reasoning to develop, evaluate, and validate a bioeconomy-based sustainable supply chain management model for the Iranian gas industry. The research design was structured in two sequential and complementary phases. The first phase consisted of a qualitative meta-synthesis aimed at integrating and reinterpreting findings from prior scholarly studies to construct a robust conceptual model. The second phase involved quantitative modeling and simulation to validate and operationalize the conceptual framework. The unit of analysis in the qualitative phase was peer-reviewed scientific articles and conference papers published in reputable national and international outlets, rather than individual human participants. These sources were selected to represent accumulated expert knowledge in the fields of sustainable supply chain management, bioeconomy, and Industry 4.0 within energy-related industries, particularly gas, oil, and petrochemicals. The quantitative phase did not involve human participants either; instead, it focused on abstracted network structures, parameters, and constraints representative of gas supply chain systems, enabling model validation through numerical experimentation and optimization.

Data collection in the qualitative phase was conducted through a systematic and structured literature search covering publications from 2012 to 2024 in English and from 2009 to 2024 in Persian. Multiple national and international scientific databases were explored to ensure comprehensive coverage of relevant studies. A transparent screening process was applied at the title, abstract, and full-text levels to identify studies aligned with the research objectives. The methodological quality of the selected studies was assessed using the Critical Appraisal Skills Programme (CASP) checklist to ensure rigor, credibility, and relevance. Only studies meeting acceptable quality thresholds were retained for synthesis. Qualitative data, including concepts, constructs, dimensions, and proposed frameworks, were extracted from the final corpus of studies and managed using MaxQDA software to facilitate systematic coding and categorization. In the quantitative phase, MATLAB software served as the primary data generation and processing environment. Numerical parameters, constraints, and objective functions derived from the conceptual model were encoded within MATLAB to enable simulation and optimization. Two metaheuristic algorithms—simulated annealing and genetic algorithms—were implemented as computational tools to explore the solution space, generate feasible solutions, and test the robustness and efficiency of the proposed supply chain model under different scenarios.

Data analysis followed a rigorous two-stage process aligned with the overall mixed-methods design. In the qualitative stage, a seven-step meta-synthesis procedure was applied to analyze and integrate prior research. This process involved formulating focused research questions, conducting a systematic review of the literature, selecting and appraising suitable models and studies, extracting relevant qualitative information, synthesizing and interpreting findings, performing quality control, and presenting integrated results. Through iterative coding and thematic analysis, a large set of initial codes was progressively condensed into higher-order concepts and overarching categories, revealing recurring patterns, relationships, and mechanisms underlying bioeconomy-based sustainable supply chain management. These synthesized themes formed the conceptual foundation of the proposed model. In the quantitative stage, the conceptual model was translated into a formal mathematical structure suitable for numerical analysis and optimization. MATLAB was used to implement network optimization models reflecting economic, environmental, and operational objectives. Simulated annealing was employed to avoid entrapment in local optima through probabilistic acceptance of suboptimal solutions, while genetic algorithms were used to perform global searches across complex solution spaces based on evolutionary principles. The performance of these algorithms was analyzed comparatively to assess convergence behavior, solution quality, and computational efficiency. The integration of qualitative meta-synthesis with quantitative optimization enabled comprehensive validation of the model, ensuring both theoretical coherence and practical applicability for sustainable supply chain management in the gas industry.

Findings and Results

The results of the qualitative meta-synthesis are summarized in Table 1, which presents the final concepts and their associated initial codes extracted from the reviewed literature.

Table 1. Concepts and Initial Codes of the Study

No.	Final Category / Concept	Initial Codes Extracted from the Literature
1	SSCM Foundations and Sustainability Dimensions	SSCM model framework; linkage between bioeconomy and circular economy in energy; systematic reviews of SSCM, sustainability indicators, and foresight studies; conceptual SSCM frameworks and foundational theories; triple bottom line (TBL) sustainability dimensions (social, economic, environmental); reviews of SSCM definitions and environmental practices
2	Bioeconomy and Circular Economy Axis	Bioeconomy development drivers, challenges, roadmaps, and multi-criteria evaluation; circular economy and sustainable business models with drivers and barriers; integration of biomass and gas infrastructure and bioenergy efficiency; bio–circular challenges and opportunities in oil and gas; risk assessment of adopting bio-based materials in chemical supply chains; structural analysis of factors influencing Iran’s energy bioeconomy development
3	Industry 4.0 Enablers	Digital transformation and integration of the bioeconomy into supply chains; blockchain as a technology for traceability and sustainability in gas supply chains; big data and Internet of Things (IoT) roles in sustainability and traceability; integration of Industry 4.0 and circular economy; role of advanced technologies (Industry 4.0) in gas supply chain sustainability; digital transformation frameworks in sustainable supply chain management
4	Resilience Management and Strategic Risk	Resilience-based sustainable SSCM models; sustainability risk assessment using fuzzy quantitative methods; resilient and sustainable network design and multi-objective optimization; modeling transition risks from gas infrastructure to biomethane economy; green supply chain management (GSCM) risk assessment in the gas industry; integrated risk modeling of gas supply chains under low-carbon constraints
5	Performance Evaluation and Modeling (MCDM)	Bio-based multi-criteria evaluation and fuzzy decision-making models (MCDM); performance evaluation of energy supply chains using DEA and fuzzy methods; performance metrics for energy-intensive supply chains; sustainability performance modeling of Iran’s energy supply chain using ANP; sustainable supplier selection in energy using fuzzy MCDM approaches; sustainability assessment frameworks for gas supply chains based on fuzzy MCDM
6	Implementation Strategies and Barriers	Drivers and barriers to implementing circular economy models; barriers to GSCM implementation in India’s oil industry and green logistics barriers in Iran’s oil and gas supply chain; implementation success factors and supply chain capabilities; role of green management and reverse logistics in emission reduction; modeling circular economy adoption in the oil and gas sector using TISM
7	Governance and Policymaking (Contextual Factors)	Policymaking and governance of transition toward the bioeconomy; effects of governmental policies and regulations on SSCM in emerging markets; role of regulatory institutions in evaluating energy supply chain sustainability; SSCM governance models in Iran’s oil industry; institutional mechanisms for implementing the circular economy in Iran; alignment of sustainability goals with operational performance of gas companies

Overall, the findings indicate that the bioeconomy-based sustainable supply chain management model for the gas industry is underpinned by seven interrelated and comprehensive conceptual categories. The meta-synthesis revealed that sustainability in gas supply chains is not limited to environmental considerations but is rooted in strong theoretical SSCM foundations, the integration of bioeconomy and circular economy principles, and the effective deployment of Industry 4.0 technologies. In addition, resilience and strategic risk management emerged as critical elements for ensuring long-term system stability under transition and low-carbon constraints. Performance evaluation using advanced multi-criteria decision-making and efficiency methods provides the analytical backbone for assessing sustainability outcomes, while implementation strategies highlight the importance of overcoming structural, logistical, and managerial barriers. Finally, governance and policymaking factors were identified as essential contextual enablers, emphasizing the decisive role of regulatory frameworks, institutional coordination, and policy alignment in operationalizing and sustaining the proposed model within the Iranian gas industry.

Table 2. Research Categories and Concepts

Major Category (Model Dimension)	Concepts (Constituent Components)
Theoretical Infrastructure and Model Structure	SSCM foundations and sustainability dimensions; theoretical structure and conceptual underpinnings; triple bottom line sustainability dimensions (economic, environmental, social)
Strategic Orientation and Innovation	Bioeconomy and circular economy axis; performance evaluation and modeling; supply chain risk and resilience management
Environmental and Institutional Requirements	Sustainable governance and policymaking; implementation strategies and barriers; governance and institutional structures
Operational and Transformative Instruments	Industry 4.0 enablers; performance evaluation and modeling (MCDM); operational strategies and barriers

The results summarized in Table 2 demonstrate that the proposed model is organized around four integrative and mutually reinforcing dimensions that collectively define the architecture of a bioeconomy-based sustainable supply chain in the gas industry. The theoretical infrastructure dimension establishes the conceptual and sustainability foundations of the model, ensuring coherence with SSCM principles and the triple bottom line. The strategic orientation and innovation dimension emphasizes the role of bioeconomy and circular economy integration, supported by performance assessment and resilience-oriented risk management to guide long-term strategic decisions. The environmental and institutional requirements dimension highlights the critical influence of governance, policymaking, and institutional arrangements in enabling or constraining sustainable supply chain implementation. Finally, the operational and transformative instruments dimension captures the practical mechanisms through which the model is realized, particularly through Industry 4.0 technologies, advanced performance evaluation methods, and targeted operational strategies that translate strategic sustainability objectives into actionable outcomes within the gas supply chain.

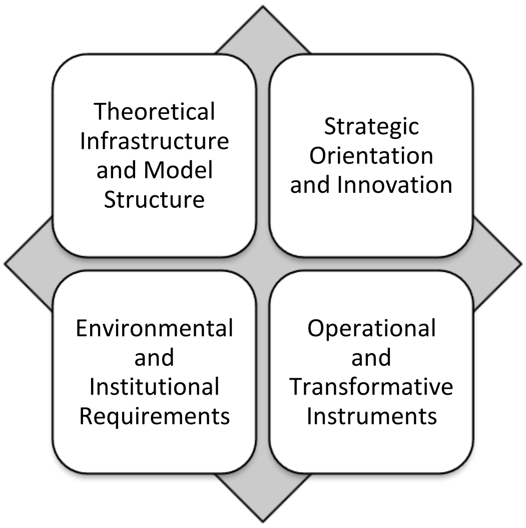

Figure 1. Conceptual Model

Discussion and Conclusion

The findings of this study provide a comprehensive and integrative understanding of how a bioeconomy-based sustainable supply chain management model can be conceptualized and operationalized in the gas industry under the conditions of the Fourth Industrial Revolution. The qualitative meta-synthesis revealed that sustainable supply chain performance in energy-intensive sectors is fundamentally grounded in strong theoretical foundations that integrate the triple bottom line with evolving notions of circularity and bio-based value creation. This result aligns with the broader SSCM literature, which emphasizes that sustainability-oriented supply chains must simultaneously address economic efficiency, environmental responsibility, and social legitimacy rather than privileging a single dimension (1, 2). The extracted categories demonstrate that bioeconomy principles do not operate in isolation but are deeply embedded within established SSCM frameworks, reinforcing prior arguments that sustainable transitions require incremental evolution rather than radical replacement of existing supply chain logics (3, 26).

A key contribution of the study lies in empirically synthesizing the bioeconomy and circular economy as a strategic axis within sustainable gas supply chains. The results indicate that bio-based and circular solutions—such as biomass integration, bioenergy efficiency, and circular material flows—are increasingly framed in the literature as viable pathways for reducing environmental footprints while maintaining industrial competitiveness. This finding corroborates earlier studies highlighting the circular bioeconomy as a unifying concept capable of reconciling economic growth with ecological constraints (7, 8). In the context of global energy supply chains, recent evidence also confirms that bioeconomy transitions extend beyond local production systems and generate sustainability implications along international value chains, thereby reinforcing the relevance of a supply chain–oriented analytical lens (5, 6). The present study advances this literature by positioning the bioeconomy not merely as an environmental add-on but as a core strategic driver of sustainable supply chain redesign in the gas industry.

The integration of Industry 4.0 technologies emerged as another central pillar of the proposed model, underscoring the enabling role of digital transformation in achieving sustainability and resilience objectives. The findings suggest that technologies such as big data analytics, IoT, artificial intelligence, and blockchain enhance supply chain transparency, traceability, and responsiveness, which are critical for monitoring bio-based inputs, managing emissions, and coordinating complex gas networks. These results are consistent with prior empirical and conceptual research demonstrating that Industry 4.0 technologies strengthen supply chain visibility and support sustainability-oriented decision-making (10, 11). Moreover, recent studies emphasize that digitalization amplifies the effectiveness of green and circular supply chain practices when aligned with strategic objectives and organizational capabilities (12, 16). The present findings extend this insight to the gas sector, illustrating how digital enablers function as transformative instruments that operationalize bioeconomy-based SSCM rather than acting as isolated technological upgrades.

Resilience and strategic risk management were identified as indispensable components of sustainable gas supply chains, particularly in the context of bioeconomy transitions and environmental uncertainty. The study's results indicate that resilience-oriented network design, multi-objective optimization, and risk modeling are increasingly emphasized in the literature as mechanisms for coping with supply disruptions, regulatory volatility, and technological uncertainty. This observation aligns with contemporary research arguing that sustainable supply chains must be resilient by design, integrating risk assessment and adaptive capacity into their structural configuration (18, 19). In bio-based and energy supply chains, uncertainty related to feedstock availability, technological maturity, and market acceptance further intensifies the need for robust risk management frameworks (20). By embedding resilience and risk management within the core structure of the proposed model, this study reinforces the view that sustainability and resilience are mutually reinforcing rather than competing objectives (2).

Performance evaluation and decision-support mechanisms constituted another significant dimension of the findings. The synthesis highlights the widespread application of multi-criteria decision-making and fuzzy modeling approaches to evaluate sustainability, efficiency, and risk in energy supply chains. This result reflects the inherent complexity of assessing bioeconomy-based SSCM, where economic, environmental, and social criteria often conflict and require systematic trade-off analysis (21, 22). Prior studies have demonstrated that advanced evaluation tools enhance the credibility and applicability of sustainability models by providing transparent and structured decision support (16, 23). The present study contributes to this stream of research by integrating performance evaluation not as a standalone analytical exercise but as a continuous feedback mechanism that informs strategic orientation, operational execution, and governance alignment in sustainable gas supply chains.

Governance and institutional factors emerged as critical contextual enablers influencing the feasibility and effectiveness of the proposed model. The findings indicate that policy coherence, regulatory support, and institutional coordination play a decisive role in shaping firms' capacity to adopt bioeconomy principles, invest in digital technologies, and implement sustainable supply chain practices. This result is strongly supported by existing literature, which highlights the moderating role of institutional pressure and policy frameworks in driving green supply chain adoption and sustainable performance, particularly in emerging economies (15, 24). In energy-intensive industries, governance structures often determine access to resources, technological pathways, and market incentives, thereby influencing the pace and direction of sustainability transitions (5, 27). By explicitly incorporating governance and policymaking into the model architecture, the study addresses a key gap in SSCM research, which has traditionally underemphasized the institutional dimension.

Taken together, the results demonstrate that a bioeconomy-based sustainable supply chain in the gas industry is a multidimensional and systemic construct that cannot be reduced to isolated practices or technologies. Instead, it emerges from the dynamic interaction between theoretical foundations, strategic orientation, technological enablers, resilience mechanisms, performance evaluation, and governance contexts. This integrative perspective is consistent with recent calls in the literature for holistic supply chain models that capture the interdependencies between sustainability, digitalization, and systemic risk (9, 17). By synthesizing dispersed strands of research into a coherent conceptual and analytical framework, the study contributes to advancing SSCM theory while offering a structured basis for empirical validation and practical application in the gas industry.

This study has several limitations that should be acknowledged. First, the qualitative phase relied on published academic literature, which may be subject to publication bias and may not fully capture tacit knowledge or emerging practices within the gas industry. Second, although the quantitative modeling provided validation of the conceptual framework, it was based on simulated data and abstracted network structures rather than real-time operational data from gas supply chains. Third, the focus on the gas industry, while theoretically and practically justified, limits the direct generalizability of the findings to other energy sectors or industrial contexts without further adaptation.

Future research could extend the present study in several directions. Empirical validation using real-world data from gas companies and national energy systems would strengthen the practical robustness of the proposed model. Comparative studies across different energy sectors or countries could also provide deeper insights into how institutional and regulatory contexts shape bioeconomy-based SSCM. In addition, future research may integrate dynamic system modeling or agent-based simulation to capture long-term transition pathways and feedback effects associated with bioeconomy and digital transformation in energy supply chains.

From a practical perspective, the findings offer several implications for managers and policymakers. Decision-makers in the gas industry can use the proposed model as a strategic roadmap for aligning sustainability objectives with digital transformation and bioeconomy initiatives. Policymakers may leverage the framework to design coherent regulatory and incentive structures that support sustainable supply chain transitions. Finally, supply chain managers can apply the model to assess current practices, identify capability gaps, and prioritize investments that enhance resilience, performance, and long-term sustainability.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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