Sustainable supply chain modeling: a review based on the application of the system dynamics approach

Julia Kurniasih[1,2], Zuraida Abal Abas[1], Siti Azirah Asmai[1], Agung Budhi Wibowo[3]
[1]Department of Intelligent Computing and Analytics, Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Department of Informatics, Universitas Sarjanawiyata Tamansiswa, Yogyakarta, Indonesia
[3]School of Vocational, Universitas Gadjah Mada, Yogyakarta, Indonesia

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ABSTRACT

Sustainable supply chains, evolving with supply chain 5.0 revolution, are crucial for achieving sustainable development goals (SDGs) by balancing economic growth, environmental protection, and social responsibility. They help reduce environmental impacts, promote ethical labor practices, and ensure financial viability. Sustainable supply chains involve complex interactions and external influences. The system dynamics approach effectively captures these intricate interactions through feedback loops and non-linear relationships. This review seeks to identify issues in modeling sustainable supply chains using system dynamics and offer insights for developing sustainable, flexible, responsive, and resilient models. This paper reviews literature from 2020 to 2023 using thematic analysis. It examines dynamics, behaviors, management, sustainability strategies, decision-making, and future directions for sustainable supply chain modeling. The findings suggest that a comprehensive framework can enhance management practices, support policymaking, and promote sustainability. Integrated risk management is essential for resilient, adaptable supply chains, while financial viability and scalability are essential for the widespread adoption of sustainability practices. Understanding the roles of various actors and integrating supply chain components can improve support systems, and exploring green energy, technology adoption, and consumer behavior can advance sustainability goals. Future research should also better integrate sustainability aspects and explore a broader range of literature for deeper insights.

Corresponding Author:

Zuraida Abal Abas
Department of Intelligent Computing and Analytics
Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
Email: zuraidaa@utem.edu.my

1. INTRODUCTION

The industry is experiencing an evolutionary transition known as supply chain 5.0, which aims to shift industry goals from technology-centric expansion to sustainable growth driven by value [1]. Rather than presenting a new perspective, supply chain 5.0 represents a fusion philosophy that adapts existing technologies to foster sustainable production and consumption, aligning with one of the sustainable development goals (SDGs). Supply chain 5.0 integrates supply chain 4.0 technologies for modeling and simulating production systems and supply chains, emphasizing the critical role of sustainable supply chains in achieving the SDGs. Sustainable development aims to meet the needs of both present and future generations through policies, practices, and goals [2]. This approach involves directing decisions and actions toward the entire system, ensuring coherence among its sub-systems, and recognizing the cumulative effects of these actions [3]. The triple bottom line (TBL) framework, which includes economic (profit), environmental (planet), and social (people) dimensions, is used to evaluate business performance in terms of sustainability [4], [5]. Industries must develop, strategize, and manage their supply chains according to TBL standards, safeguarding stakeholder interests and avoiding resource depletion to meet SDG targets. This integration advances sustainable supply chain management (SSCM) as a strategic approach that aligns stakeholder concerns with profitability, cost reduction, and environmental and social responsibility [6]. Understanding sustainability involves evaluating economic, ecological, and social conditions while considering the relationship between entities and supply chain management.

Maintaining efficiency and resilience is crucial for securing a competitive advantage in dynamic markets. Flexibility the capacity to adapt to changes [7], disruptions, or unforeseen events is vital for the sustainability of a supply chain [8]. It requires adaptability, agility, responsiveness [9], and effective risk management [10], [11]. Companies facing global risks are increasingly integrating sustainable development into their operations, driving a shift towards more complex supply chain management. As a result, there is growing interest in SSCM among researchers, academics, and practitioners exploring various strategies, approaches, methods, and techniques to enhance supply chain performance and foster sustainability from economic, social, and environmental perspectives [12], [13].

Modeling refers to the process of constructing a model that represents either a real or hypothetical system. Simulation uses the model to analyze the enforcement or behavior of a theoretical or actual system in reaction to various system inputs [14]. In the manufacturing supply chain, [15] identified three types of modeling: mathematical, simulation, and hybrid (a combination of mathematical and simulation models). They also observed a growing use of simulation and hybrid models, reflecting a shift from earlier years when mathematical models most widely used for modeling sustainable manufacturing supply chains. The rising prevalence of simulation and hybrid models can be attributed to their enhanced capability in managing uncertain and stochastic data, surpassing the performance of mathematical models, which are more adept at handling deterministic data.

Furthermore, [16] observed that simulation modeling is a valuable method for assessing supply chains by exploring various scenarios and conditions. Simulation modeling has a significant impact on the design of optimal systems. With simulation models, a modeler can replicate key actions and procedures [17] and assess the supply chain using multiple decision criteria [18].

The classification of simulation models includes system dynamics as well as agent-based, discrete event [19], and Monte Carlo simulation models [15]. Reductionism and holism, regarded as philosophical frameworks, are considered fundamental principles in system dynamics modeling. Reductionism involves breaking down complex systems, concepts, or events into their components for simplification. Additionally, system dynamics is generally characterized as holistic, prioritizing a thorough approach to understanding the dynamic behavior of systems in contrast to conventional problem descriptions and solution strategies [20].

In principle, a supply chain consists of many participants who manage the movement of materials and products by exchanging information. Consequently, supply chain represents complex systems with inherent dynamics as changes occur over time. Given its characteristics, the system dynamics simulation model dedicated to observing the behavior of supply chains over a certain period, such as how the supply chain responds to demand variability, coordination within the supply chain, and how supply chain activities relate to risk management. This modeling approach can capture uncertainty in supply chain dynamics [16], assess the composition of supply chain components and how they interact, combine the evaluation of cause-effect connections, response deferments, and feedback loops [21], and understand system behavior [22]. The utilization of system dynamics modeling to replicate the interactions among participants in production-distribution systems was first introduced by [23]. The interconnection of variables with nonlinear relationships and feedback loops that illustrate complexity characterize the system dynamics model. The escalation in problem complexity [24] underscores the importance of cultivating a systems-thinking outlook.

Based on the period, models are defined as strategic, tactical, and operational [25]. The strategic model refers to the long-term horizon of several years to decades. Tactical modeling addresses mid-term periods ranging from several months to a couple of years, and operational modeling focuses on short-term periods from a few days to a few weeks or sometimes up to a few months. The system dynamics paradigm exhibits a systemic inclination, generating broad effects both temporally and spatially. The implications observed in most studies conducted inside the scope of system dynamics typically relate to the level of strategy [26]. Nonetheless, system dynamics can also be used tactically and operationally, such as in studies of information sharing on supply chain, handling the bullwhip effect, inventory management, dependability, and risk management [27]–[31].

System dynamics modeling was a computer-aided approach to solving complex problems [16]. Creating a causal loop diagram was the first invention, as it allowed for the visual representation of the equations within the simulation model and demonstrated the system structure. Causal loop diagrams provide a high-level way to conceptualize models in terms of their feedback loop structures [32]. After that, generate stock-flow diagrams from this diagram for simulation modeling. With its characteristics, the system dynamics model can perform and offer predictive, what-if (scenario building), and trade-off analysis.

System dynamics can be employed for forward and reverse supply chain modeling. The significant emphasis on feedback loops within system dynamics models explains why reversed and closed-loop supply chain (CLSC) scenarios dominate the majority of system dynamics models utilized in manufacturing and other scenarios about supply chain. Circular economy (CE) models, which are essentially shaped by these feedback loops, are effectively addressed by system dynamics due to their ability to handle such requirements adeptly [33]. Within the scope of supply chains in general, the application of system dynamics exists in various areas. Some of these studies include the formulation of a resilience simulation paradigm, especially in the supply chain of prefabricated building projects [34], development of a system dynamics model that utilizes cause and effect graphs to improve supply chain achievements with a particular focus on the significance of agility and flexibility [35], and the development of system dynamics models for managing the entire agri-food supply chain (AFSC) to reduce costs, reduce delivery times, and increase customer satisfaction [36]. Apart from that, there are also developments in system dynamics models to replicate the relationship between information sharing (IS) and supply chain performance [37], examining electricity coal supply scenarios in China until 2060 [38], selecting suppliers by considering corporate social responsibility (CSR), profitability, productivity, transparency in social practices, and customer satisfaction [39], and assessing supply chain flexibility in the healthcare industry in Iran [40].

In recent years, there have been several studies exploring sustainable supply chain modeling in a general context. Schreiber [41] explored modularization and optimization of design tasks. Meanwhile, [42] integrated blockchain technology in SSCM for small and medium-sized enterprises (SMEs). Additionally, [43] conducted practical, simulation-focused research. In other research, [44] improved supplier selection processes, [45] discussed quantitative models and sustainability indicators in forward supply chain, and [46] focused on mathematical programming models. Moreover, [47] analyzed sustainability factors and their role in building resilience. On the other hand, [15] reviewed modeling approaches in sustainable manufacturing supply chains, and [48] validated a theoretical model of industry 5.0. Finally, [49] measured the impacts of SSCM on performance and competitive advantage. Unlike previous studies, this research is theoretical and review-based. It aims to pinpoint existing issues related to modeling sustainable supply chains using the system dynamics approach and providing insightful information for advancing understanding and supply chain modeling to be sustainable, flexible, and resilient. The emphasis of the modeling review on the application of the system dynamics approach in this investigation is grounded on its comparison with other simulation models, where system dynamics is not as complex as other models for modeling actual system operations [50] and deemed best appropriate for the range of study required by sustainability modeling [26]. Research findings conducted by [33] found that most system dynamics models related to sustainable supply chain models generally concentrate on the macroscopic level of analysis. This assertion is strengthened by [50], [51] who confirmed that system dynamics is valuable to apply to macroscopic simulation studies that investigate policy impacts for a large-scale system since the system dynamics approach allows understanding of the interconnection between variables through integrative and holistic concepts regarding long-term outcomes and feedback mechanisms that are interrelated with various choices and tactics [52], [53].

This study aims to address the research questions:

RQ1: What are the dynamics and behavior of supply chains in the context of sustainability?

RQ2: What challenges does supply chain management face regarding sustainability, and what strategies are implemented to overcome these challenges?

RQ3: What decision-making perspectives and context are the system dynamics approach addressed in sustainable supply chain modeling?

RQ4: What are the future directions for sustainable supply chain modeling?

This research includes exploring, mapping, and synthesizing current issues of sustainable supply chain modeling and providing valuable insights regarding further sustainable supply chain modeling using the system dynamics approach from selected literature between 2020 and 2023.

2. METHOD

The study used thematic analysis procedures within the context of a literature review. Clarke and Braun [54] characterized thematic analysis as a technique for recognizing patterns and building topics through a comprehensive examination of the subject during thorough reading. The initial step is to identify existing literature regarding sustainable supply chain modeling from the context of the system dynamics applications. Literature selection was carried out based on several criteria: i) have the keywords “system dynamics” plus “sustainable supply chain”, ii) publications from 2020 to 2023, and iii) only articles in English and open access. Criterion (i) is inclusion criteria, while criteria (ii) and (iii) are exclusion criteria. Review papers were not included in this study because they conflicted with the aims of this activity. Sources for literature encompass two research databases, i.e., Web of Science by Clarivate Analytics and Scopus by Elsevier. The filters applied for the literature search are in Table 1. The initial search resulted in 8 articles from Scopus and nine from Web of Science (WoS). However, seven articles were eliminated due to duplication, resulting in a final selection of 10 articles. Complete information about the selection process is available in Figure 1.

Table 1. Search string

Databases	String	Results
Scopus	TITLE-ABS-KEY (“system dynamics” AND “sustainable supply chain”) AND PUBYEAR > 2019 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (OA, “all”))	8 articles
Web of Science	TS=(“system dynamics” AND “sustainable supply chain”) and 2020 or 2021 or 2022 or 2023 (Publication Years) and Article (Document Types) and English (Languages) and All Open Access (Open Access)	9 articles

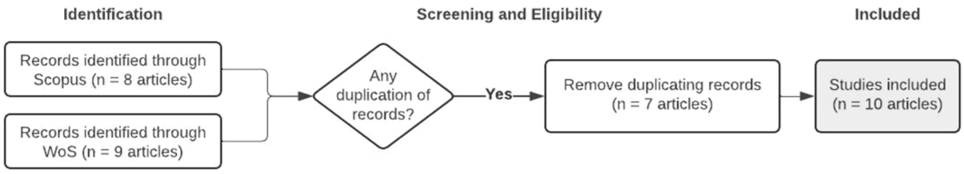

Figure 1. The literature selection phases

3. RESULTS AND DISCUSSION

This section outlines the thematic analysis conducted to address the research questions. Initially, studies identified themes, followed by developing narratives for each theme. In these sustainable supply chain modeling studies, “themes” refer to important patterns, concepts, or elements identified and extracted from the information in the model. They represent essential categories that organize and explain various aspects of sustainable supply chain modeling, including issues, trends, challenges, and opportunities. Identifying and analyzing themes is critical to gaining insights and making informed decisions to enhance the capabilities of sustainable supply chain models and operations.

The original coding yielded 19 attributes. However, the original coding was then adjusted and grouped, so the final coding identified only five distinct themes based on the focus and content of the article. The coding framework is presented in Table 2 in Appendix. The final themes are dynamic modeling, supply chain behaviors, management issues, sustainability strategies and implementation, and decision-making horizons. The dynamic modeling and supply chain behavior themes will address research question 1 (RQ1), while the themes on supply chain management issues and sustainability strategies and implementation will respond to research question 2 (RQ2). Lastly, the decision-making horizons theme will resolve research question 3 (RQ3). The narrative of each theme is outlined in the next subsection.

3.1. Dynamic modeling

This theme investigates dynamic modeling that uses the system dynamics approach from reviewed studies to understand how supply chain systems evolve through feedback loops and other dynamic components. Models analyzed by [27]–[29], [55]–[59] incorporated both positive (reinforcing) and negative (balancing) feedback loops. Positive feedback loops in these models often relate to optimization, efficiency, and sustainability improvements. Handaya *et al.* [27] found continuous process optimization can lead to better resource use and reduced waste. Additionally, Pasqualino *et al.* [28] identified positive feedback loops related to sustainability and market demand, innovation, and economic growth, and [29] found positive feedback loops related to consumer preferences and organic farming. Negative feedback loops typically involve balancing supply and demand, mitigating risks, or addressing environmental impacts. Handaya *et al.* [27] found that balancing feedback loops helps supply chains adjust to fluctuations in demand and supply. In addition, Pasqualino *et al.* [28] identified negative feedback loops related to regulation and innovation, and digital asset supply and inequality, and [29] found negative feedback loops related to consumer preferences and organic farming, and economic feasibility and environmental impact.

Ülkü *et al.* [55], reinforcing feedback loops related to effective risk response strategies, while balancing feedback loops involved the relationship between cost-increasing risk management and improvements in quality and yields. Additionally, Kaur and Kander [56] found a positive feedback loop between resource use and production efficiency, but also a negative feedback loop between resource use and environmental impacts. Moreover, Ding *et al.* [57] found a balancing feedback loop related to inventory management and efficiency, while the reinforcing feedback loop involved optimization and emission reduction. Furthermore, Shamsuddoha *et al.* [58] found positive feedback loops related to production and waste utilization, and negative feedback loops related to environmental impact and resource depletion. Finally, Allen *et al.* [59] found that the balancing feedback loop involved regulatory pressure and costs, while the reinforcing feedback loop related to stakeholder engagement.

Meanwhile, the models analyzed by Katsoras and Georgiadis [60] and Beltagui *et al.* [61] only include one feedback loop. Katsoras and Georgiadis [60] only found a negative feedback loop related to disaster impact, showing how CLSC can adapt to mitigate the effects of disasters. Conversely, Beltagui *et al.* [61] identified a positive feedback loops associated with the effective use of three-dimensional (3D) printing by small companies. These themes reveal the key dynamics in technology adoption, sustainability practices, risk management, and resource use. The strengthening loop drives growth in various areas including technology adoption and sustainability, while the balancing loop helps stabilize the system by addressing fluctuations, ensuring resilience, and optimizing supply chains. Models that integrate both types of feedback provide a more holistic view of supply chain dynamics.

3.2. Supply chain behaviors

This theme explores activity patterns, interaction, and performance in supply chains to gain insight into supply chain behavior and its impact on sustainability. Research by [27] highlights that the supply chain system adapts processes e.g., collection, storage, and transportation to stabilize supply and maintain production levels as palm kernel shells (PKS) production and consumption fluctuates. Meanwhile, Pasqualino *et al.* [28] reveals several supply chain behaviors. The supply chain responds to sustainability demands by adopting innovative practices and green technologies to align with market preferences and regulatory standards. It also integrates advanced systems to boost efficiency and foster economic growth while addressing digital asset availability and economic inequality by ensuring equitable access to technology and managing its effects on various market segments. Furthermore, Taghikhah *et al.* [29] unveils that the supply chain responds to consumer preferences for organic farming by adjusting operational and behavioral factors, e.g., price and social norms, to support sustainable practices.

On the other hand, Ülkü *et al.* [55] highlights that supply chains are willing to bear higher costs for effective risk management, such as flood prevention, to improve product quality and stabilize yields. Kaur and Kander [56] highlights that supply chains adapt to resource use and production efficiency, as well as their focus on minimizing waste and estimating resources accurately. Katsoras and Georgiadis [60] reveals that the CLSC responds to disaster impacts by adjusting demand patterns and applying mitigation policies to stabilize the system. Ding *et al.* [57] highlights that supply chains respond to inventory fluctuations and streamline logistics by implementing internet of things (IoT) technology to save costs and reduce emissions significantly. Moreover, Shamsuddoha *et al.* [58] unveils that supply chains respond to production demands by prioritizing waste utilization, minimizing environmental impact, and conserving resources to increase productivity and mitigate ecological damage. Meanwhile, Beltagui *et al.* [61] reveals that supply chains of small companies were adapting by leveraging 3D printing to drive market growth, pressuring large companies to adopt more socially sustainable practices. Finally, in response to regulatory pressure, [59] indicates that supply chains engage stakeholders, improving efficiency and embracing innovation. From this theme, it is reasonable to conclude that supply chains adapt to demand fluctuations and sustainable practices embracement. They leverage technology to enhance efficiency, manage risks, and address regulatory requirements, even at higher costs, to improve quality and performance.

3.3. Supply chain management issues

This theme explores the various challenges and problems encountered in the planning, coordinating, and implementing activities involved in the supply chain. The supply chain management issue highlighted by [27] comprises the complexity and dynamics of PKS supply chains, which require effective coordination of multiple processes and interactions. The research also emphasizes the challenge of optimizing efficiency and sustainability due to the variability in PKS availability and demand. Meanwhile, Pasqualino *et al.* [28] addresses the integration of sustainability and digitalization through traditional risk management, examining stakeholder demands, economic impacts, disparities, and labor market issues arising from digitalization. Taghikhah *et al.* [29] explores the interplay of environmental, economic, behavioral, and operational factors in transitioning to organic farming, underscoring the need for integrated modeling, stakeholder collaboration, and supportive policies to advance sustainable agricultural practices. Furthermore, Ülkü *et al.* [55] focuses on mitigating environmental risks like climate change and operational risks such as equipment damage and pesticide use, addressing cost management issues related to fluctuations in seed prices and equipment costs, and ensuring quality control. On the other hand, [56] tackles operational complexity by managing the flow of goods and services, addressing uncertainty and inefficiency, and dealing with environmental impact issues by minimizing waste and energy consumption.

Katsoras and Georgiadis [60] discusses disaster mitigation strategies at the manufacturing level for various demand patterns, using total CLSC profits and demand backlog as key performance indicators. Meanwhile, Ding *et al.* [57] examines the challenges of integrating IoT-supported supply chains from technical and operational perspectives, balancing efficiency and emissions, and adapting market dynamics for effective competition. Moreover, Shamsuddoha *et al.* [58] addresses several supply chain management issues in the dairy industry, including improving resource efficiency (feed, water, and energy), converting milk waste into biogas, and balancing productivity with sustainability while supporting employment opportunities and the social welfare of local communities. Furthermore, Beltagui *et al.* [61] discusses the lack of stakeholder pressure on major companies and the difficulties smaller socially responsible businesses face in changing supply chain practices and accessing broader markets. Finally, Allen *et al.* [59] highlights the theoretical gap in integrating SSCM and CE, which hinders decision-making and effective sustainability integration. According to this theme, supply chains encounter challenges related to sustainability. It includes theoretical gaps in integrating SSCM and CE principles, the complexity of coordinating multiple processes and interactions, technology integration, disruption mitigation, risk and cost management, and barriers posed by stakeholders.

3.4. Sustainability strategies and implementation

This theme explores the direction of decisions and actions of a sustainable process applied to the entire system, coherence between subsystems, and the cumulative impact of actions taken. The system dynamics approach to facilitate environmental sustainability is applied by [27] to develop a sustainable supply chain model for PKS, reducing waste, and increasing renewable energy use through biomass fuel. For economic sustainability, Katsoras and Georgiadis [60] used the system dynamics approach to improve the efficiency and resilience of CLSC during disasters. It assesses disaster impacts and mitigation strategies for resource optimization and operational continuity. Another research addresses social sustainability using 3D printing to improve fair supply chain practices, overcome resource constraints, and drive market growth and demand, influencing major players toward socially responsible practices [61].

Apart from that, some studies accommodate multi-dimensional sustainability, which ideally is the goal of sustainable development, which refers to TBL. Pasqualino *et al.* [28] explores economic sustainability by examining the financial impacts of industrial innovation, inequality, and inflation, while also addressing social sustainability through employment dynamics and inequality in the digital age. Meanwhile, Ülkü *et al.* [55] manages environmental risks from climate change and reduces harmful practices to promote sustainability, while balancing production costs for economic sustainability. Similarly, Kaur and Kander [56] examines economic and ecological sustainability through optimized resource use and reduced energy consumption, while [57] focuses on the role of IoT in enhancing operational efficiency and reducing carbon emissions.

Taghikhah *et al.* [29] addresses all three dimensions of sustainability. It promotes social sustainability through stakeholder engagement in adopting organic farming, environmental sustainability by reducing pollution, and economic sustainability by providing market support for farmers and incentives for consumers. Shamsuddoha *et al.* [58] addresses all dimensions through improved resource management, waste reduction, and providing rural employment and nutritious products for the local community. Lastly, Allen *et al.* [59] also integrates the three pillars by engaging stakeholders, reducing environmental impacts through SSCM and CE practices, and improving financial performance.

This theme suggests that organizations achieve economic sustainability by optimizing resources, maintaining operational effectiveness during disruptions, addressing industrial innovation and inequality, balancing production costs, leveraging technology, and supporting organic farming with market incentives. They achieve environmental sustainability by promoting green energy, managing climate risks, reducing energy use, waste, and emissions, and adopting sustainable farming and CE practices. Social sustainability is reached through fair supply chain practices, addressing inequality in digitalization, providing rural employment and nutritious products, and engaging stakeholders. It also reveals that only one-third of studies cover all three sustainability aspects. The remaining articles focus on just one or two dimensions.

3.5. Decision-making horizons

This theme explores decision-making in studies reviewed based on three horizon perspectives, i.e., short-term, mid-term, and long-term. The system dynamics approach for short-term decision-making was employed by [56] to optimize the use of materials, labor, and equipment in apparel manufacturing. This study seeks to enhance sustainability by increasing operational efficiency, minimizing waste, and reducing resource usage to lower the environmental impact in the short term.

In addition, several studies focused on mid-term decision-making. Katsoras and Georgiadis [60] analyzed the impact of disaster events and mitigation strategies on the CLSC over the mid-term, evaluating how different demand patterns and policies influence supply chain management during and after disasters. Similarly, Ding *et al.* [57] used system dynamics and agent-based modeling to assess IoT's impact on supply chains, emphasizing cost reduction and emission control under varying demand scenarios. Beltagui *et al.* [61] adopted a mid-term perspective, focusing on how 3D printing can gradually overcome resource constraints and facilitate market growth for socially oriented businesses.

Furthermore, for a long-term decision-making perspective, [27] employed the system dynamics approach to develop a sustainable supply chain model for PKS as a renewable energy source, focusing on the long-term impacts and interactions between various supply chain variables. Likewise, [28] explored long-term economic, technological, and labor market transformation, highlighting the effects of industrial innovation, inequality, and inflation. Taghikhah *et al.* [29] also took a long-term view, focusing on the systemic, behavioral, and policy changes required for sustainable agricultural practices. Additionally, Allen *et al.* [59] developed a dynamics sustainable supply chain circular economy management (D-SSCEM) framework to guide organizations in aligning their supply chain strategies with sustainability principles in the long term.

The system dynamics approach is ultimately employed to support multi-perspective decision-making. Ülkü *et al.* [55] used the system dynamics approach to support short-term decision-making around operational risks, such as equipment failures and pest management in cotton production logistics while addressing long-term environmental sustainability risks. Another study conducted by Shamsuddoha *et al.* [58] included a medium to long-term perspective. Mid-term strategies focus on optimizing operations and resource use, and long-term approaches emphasize sustainable practices and broader economic, social, and environmental benefits.

This theme underscores that short-term decision-making focuses on optimization and efficiency. Mid-term decision-making centers on mitigating disruptions and adopting technology. Long-term decision-making prioritizes green energy, digitalization, organic farming, environmental risk management, and circular economic integration. It also reveals that most studies using the system dynamics approach for sustainable supply chain modeling emphasize long-term decisions, with fewer addressing mid and short-term decisions. Therefore, this theme concludes that the system dynamics approach supports strategic, tactical, and operational decision-making, addressing environmental and social sustainability, economic efficiency, and supply chain resilience.

3.6. The future directions for sustainable supply chain modeling

This review outlines the issues identified in current research and offers insights for future research opportunities on modeling sustainable supply chains using the system dynamics approach. Studies reviewed are summarized, detailing each study's country, focus, the industrial sector, and existing research gaps. Table 3 in Appendix presents more detailed information. Based on the five themes discussed previously and the research gaps identified in Table 3 in Appendix, this subsection will explore potential future research directions focusing on modeling, supply chains, and sustainability. Additionally, it will answer research question 4 (RQ4).

In aggregate, future research should address gaps in SSCM-CE theory by translating theoretical insights into practical guidance for managers and policymakers, supported by case studies. Empirical studies are needed to validate models, assess their relevance, and understand stakeholder responses to SSCM and CE strategies. It is necessary to investigate how supply chain models adjust to demand variations and policy changes to encourage wider use of green energy for sustainable industrial uses. Moreover, research should include stakeholder engagement, policy support assessments, and cost-benefit studies for economic viability. Similarly, to support sustainable agriculture, particularly organic farming, future research should examine how market support mechanisms impact economic viability and understand the role of stakeholders and broader social impacts in the transition to organic farming. Furthermore, a comprehensive model is also needed to integrate various risk dimensions, including environmental and operational risks, and assess their cumulative impact on supply chain performance. Research requires applying the model across different industries to evaluate findings' generalizability and adapt the model to uncertainties.

Additionally, integrating the model with comprehensive life cycle assessment (LCA) and life cycle costing (LCC) is needed to evaluate the environmental impact and costs of infrastructure of the technology adopted and its implications for the CE. Research should also address the challenges of scaling technology solutions, integrating them with existing systems, and assessing their social implications, such as market dynamics and stakeholder behavior, including impacts on employment and skills. On the other hand, expanding the model to include global economic interactions is crucial for assessing their digitalization and sustainability impact. It should also be applied across industries and socio-economic groups to evaluate sector-specific dynamics and regional effects, with practical guidelines for real-world implementation. Finally, future research should prioritize examining the impact of different types, intensities, and frequencies of disruptions on supply chains. It includes developing integrated resilience strategies and enhancing supply chain responsiveness with adaptive and real-time mechanisms.

4. CONCLUSION

This paper presents an overview of the current sustainable supply chain modeling from an applying system dynamics approach and also explores future directions for sustainable supply chain modeling. The study was conducted on ten linked papers using a thematic analysis methodology. Reviewing these publications revealed that only one-third of publications addressed all three aspects of sustainability simultaneously. Future research could focus on better integrating these three aspects of sustainability. Meanwhile, most of these publications focused on strategic modeling for long-term decision-making, though some also applied tactical and operational modeling. The findings indicate that a comprehensive framework can improve management practices, support policy-making, and encourage more sustainable supply chains. In addition, an integrated risk management approach that considers systemic interactions between risks and incorporates comprehensive strategies is critical to building resilient and adaptable supply chains to strengthen their resilience and sustainability. Ensuring financial viability and scalability is also crucial for the widespread adoption of sustainability practices, and understanding the role of various actors and comprehensive integration of supply chain components can also improve support systems. Furthermore, understanding the application of technology solutions and green energy across different industries and socio-economic contexts and how consumer behavior and market dynamics relate to such applications can help achieve broader sustainability goals in supply chain practices. Due to the limited availability of literature reviewed in this study, future investigations need to explore more literature with an extensive range of periods to obtain more comprehensive studies.

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APPENDIX

Table 2. The initial coding of sub-themes and final themes

Sub-themes	Final themes
1a. Reinforcing feedback loop	1. Dynamic modeling
1b. Balancing feedback loop	
2a. Inventory management behavior	2. Supply chain behaviors
2b. Demand and supply behavior	
2c. Transportation and logistics behavior	
2d. Risk management behavior	
2e. Innovation and technology adoption behavior	
2f. Flexibility and responsiveness behavior	
3a. Operational issue	3. Supply chain management issues
3b. Technological issue	
3c. Risk and resilience issue	
3d. Regulatory issue	
3e. Strategic issue	
3f. Sustainability issue	
4.a Sustainability dimension	4. Sustainability strategies and implementation
4.b Sustainability practice	
5.a Long-term perspective	5. Decision-making horizons
5.b Mid-term perspective	
5.c Short-term perspective	

Table 3. Summary of studies

The country of study	Focus of the study	Industry sector	Research gap
Handaya *et al.* [27] Indonesia	The development of a PKS supply chain model to promote the greater use of green energy for continuous industrial purposes.	Biomass	a) The study does not address the role of stakeholder engagement and policy support in the sustainable PKS supply chain model implementation. Understanding the perspectives and backing of various stakeholders, such as government agencies, industry participants, and local communities, is crucial for successful execution. b) The study assumes certain conditions for PKS generation and consumption rate. However, it does not consider the impact of dynamic market conditions, such as fluctuating demand for biomass fuel or changes in policy regulations.
Pasqualino *et al.* [28] NA	The development of the IN4.0-SD model to depict changes in the relationship between industrial innovation, inequality, and inflation.	NA	a) The model is a closed economy and may not capture the complexities of open economies, where global trade, investments, and policies affect digitalization and sustainability. Further exploration of global economic impacts on the model's findings is needed. b) The model may overlook the varied impacts of digitalization and sustainability across different industries, socio-economic groups, and regions. Examining how these factors affect various sectors and demographics can offer deeper insights. c) Practical guidance is needed for businesses, governments, and financial institutions to apply theoretical insights and model-based scenarios effectively. d) Studying the impact of digitalization on employment, wealth distribution, and technological equality would be improved by delving deeper into these socio-economic factors.
Taghikhah *et al.* [29] Australia	Modeling the adaptive responses of cultivators, food processors, retailers, and consumers and simulating the dynamic interactions between consumer preferences and behavioral factors influence the viability and expansion of organic farming.	Food (wine)	a) This study suggests that organic agriculture may struggle financially without additional support and incentives. However, it may not thoroughly analyze how different types of help, financial aid, or market rewards affect its ability to make money. b) This study may not fully address how the proposed model's findings apply to various agricultural supply chain contexts, including generalizing results, changes in consumer behavior, and policy impacts on organic farming sustainability. c) These studies acknowledge the need for intermediary actors between consumers and farmers. However, it may not fully explore how these actors (e.g., governments and NGOs) can effectively facilitate the transition to organic farming and their specific roles.
Ülkü *et al.* [55] Turkey	The development of a comprehensive framework to mitigate cotton production logistics (CPL) risks to ensure quality, yield, and cost efficiency.	Textile	a) This study examines individual risks and their direct impact on costs and quality. However, it is essential to integrate the interactions between various risk factors and develop a comprehensive risk management strategy addressing multiple dimensions simultaneously. b) It is also crucial to understand the interaction between environmental and operational risks and how they collectively impact the performance and resilience of the CPL. For instance, changes in environmental conditions can affect operational risk factors like equipment failure, and vice versa.
Kaur and Kander [56] NA	The development of a system dynamics model (SDM) for a sustainable apparel manufacturing supply chain to enhance material, labor, and equipment utilization efficiency.	Textile (Shirt)	a) The study focuses solely on apparel manufacturing. However, it does not assess the scalability or practicality of larger or more complex systems. It is crucial to apply SDM to various manufacturing processes to determine if the findings apply to other sectors and to explore model adaptation on different scales and complexities. b) The study primarily focuses on manufacturing and does not extensively address the integration of SDM with other supply chain elements, such as procurement, logistics, or distribution. c) Real-world supply chains experience uncertainty and disruption. It is essential to explore how SDM can manage these dynamic conditions and consider factors such as supply chain disruptions, market fluctuations, and external shocks.
Katsoras and Georgiadis [60] NA	The development of a system dynamics model for a manufacturer operating in multiple echelons of a CLSC to address the impacts of disaster events.	NA	a) The study considers disaster events based on duration. However, it does not explore other dimensions like intensity, frequency, or specific types (e.g., natural disasters, technological failures, economic crises). Understanding the full spectrum of disaster impacts on CLSC is crucial for comprehensive mitigation strategies. b) The study focuses on the manufacturer's response to disasters, but CLSC involve multiple actors. Further research is needed to examine how disasters impact suppliers, distributors, retailers, and consumers and their interactions within the supply chain.

Table 3. Summary of studies *(Continue…)*

The country of study	Focus of the study	Industry sector	Research gap
Ding *et al.* [57] NA	Development of IoT-supported intelligent supply chain model and simulation for real-time market demand estimation and the development of production and transportation strategies.	Logistics	a) The study did not quantify the environmental and cost implications of creating the IoT infrastructure. b) There is a need to explore the challenges of scaling IoT solutions across different sizes and the complexities of supply chains. c) The study does not discuss how IoT-supported supply chains integrated with existing supply chain infrastructures. d) The study does not address the social implications of transitioning to IoT-supported supply chains, such as the impact on employment and skills requirements.
Shamsuddoha *et al.* [58] Bangladesh	Development and simulation of a model to analyze and enhance the dairy supply chain network, focusing on waste management and value addition to optimize resource use and achieve sustainable outcomes.	Dairy industry	a) The study emphasizes waste management and resource utilization. However, it might not comprehensively assess additional sustainability measurements, like the financial feasibility of small-scale dairy farming businesses or their influence on rural communities, in addition to their immediate environmental advantages. b) Consider exploring the application of the model and results to different types of dairy farming operations or regions with varying environmental and socio-economic conditions. c) It is also crucial to understand the perspectives and involvement of various stakeholders (e.g., local communities, government bodies, and market players) to enhance the effectiveness of sustainability initiatives.
Beltagui *et al.* [61] Netherlands	Analysis of the implications of technology (i.e., 3D printing) for overcoming resource limitations in supporting the diffusion of socially sustainable supply chain innovations.	Mobile phone	a) The study concentrates on a mobile phone producer and its accessories. To fully comprehend the potential and limitations of 3D printing, it is essential to investigate its impact on social sustainability across various industries and products. b) The study does not consider how 3D printing solutions can scale to accommodate larger markets or higher volumes (scalability challenges). c) Although the study focuses on social sustainability, it is necessary to conduct a detailed analysis of the cost implications of 3D printing compared to traditional manufacturing, including the initial, maintenance, and operational costs, as these may be consideration in its implementation (economic viability). d) While the study touches on consumer attitudes, it does not thoroughly investigate the factors affecting the adoption of 3D-printed products (consumer adoption).
Allen *et al.* [59] NA	The development of dynamic, sustainable supply chain-circular economy management framework to support decision-making and strategy development.	NA	a) The study proposed a dynamic framework. However, it did not fully explore practical interactions or their theoretical implications. b) There is insufficient detail on applying emerging theories to real-world supply chain and circular economy practices. c) The study does not consider how contextual factors (e.g., geographic, industry-specific, regulatory environments) could impact the proposed theoretical frameworks.

*NA: related information is not available.

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BIOGRAPHIES OF AUTHORS

Julia Kurniasih is a lecturer at the Department of Informatics, Faculty of Engineering, Universitas Sarjanawiyata Tamansiswa in Yogyakarta, Indonesia. Concurrently, she is pursuing her postgraduate studies for a Doctor of Philosophy in Big Data Analytics and Operational Research at the Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka (UTeM). Her areas of interest in academia encompass big data analytics, process mining, and operational research. She can be contacted at email: julia.kurniasih@ustjogja.ac.id.

Zuraida Abal Abas currently holds the position of associate professor at Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Information and Communication Technology, Department of Intelligent Computing and Analytics. She graduated from Universiti Teknologi Malaysia (UTM) with a B.Sc. in Industrial Mathematics, an M.Sc. in Operational Research from the London School of Economics (LSE), and a Ph.D. in Mathematics. Motivated by her fondness for analytics, operational research, and mathematics, she hopes to expand the scope of her research into diverse fields and promote cooperative research projects with other academic institutions and business partners. She can be contacted at email: zuraidaa@utem.edu.my.

Siti Azirah Asmai is a Senior Lecturer at the Department of Intelligent Computing and Analytics, Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka (UTeM). She completed her undergraduate studies in B.Sc. Computer Science from Universiti Teknologi Malaysia (UTM), pursued an M.Sc. in Information and Communication Technology for Engineers at Coventry University, UK, and obtained her Ph.D. in Computer Science from Universiti Teknikal Malaysia Melaka (UTeM). Her research focuses on text mining, information extraction, and artificial intelligence (AI) applications. She has contributed to numerous journal articles covering data analytics, time series forecasting, and deep learning. She can be contacted at email: azirah@utem.edu.my.

Agung Budhi Wibowo serves as an IT Manager at the Vocational School of Universitas Gadjah Mada in Yogyakarta, Indonesia. Additionally, he works as an IT consultant and part-time lecturer at various public and private universities. He holds an M.Eng. in Electrical Engineering from Universitas Gadjah Mada. His professional interests focus on databases, information systems, and the internet of things. He can be contacted at email: agung@ugm.ac.id.