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ARTICLE

FMEA-Based Sustainable Supply Chain Risk Assessment: Systematic Review and Case Study of an Egyptian Manufacturing Firm

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Abstract

The increasing complexity of global supply chains, combined with mounting economic, environmental, and social sustainability challenges, has highlighted the importance of robust approaches for Sustainable Supply Chain Risk Assessment (SSCRA). Among established risk assessment techniques, Failure Mode and Effects Analysis (FMEA) has gained considerable attention due to its proactive and structured capability to identify, evaluate, and prioritize potential risks. However, existing FMEA-based research in sustainable supply chain contexts remains dispersed, with limited integration of the triple bottom line sustainability perspective and insufficient empirical evidence from emerging economies.

This study addresses these gaps through a two-stage research framework integrating a systematic literature review and an industrial case study. First, a systematic review of publications from 2010 to 2026 is conducted to examine the evolution of FMEA-based SSCRA research, identify prevailing research themes, methodological developments, and unresolved challenges. The findings reveal that existing studies predominantly emphasize economic and operational risk dimensions, whereas environmental and social sustainability risks remain comparatively underrepresented. Moreover, the application of FMEA-based approaches within developing-country supply chains requires further investigation.

To extend the existing body of knowledge, an empirical case study was conducted in a medium-sized Egyptian manufacturing firm operating in the electrical control panel industry. Data were collected through structured expert assessments involving eight senior managers from key supply chain functions, including procurement, production, logistics, and quality management. A total of 30 supply chain failure modes were identified and evaluated using the conventional FMEA dimensions of Severity, Occurrence, and Detection. Subsequently, Risk Priority Numbers (RPNs) were calculated to rank and prioritize critical supply chain risks.

The results demonstrate that supply chain vulnerability is highly concentrated among a limited number of failure modes. The most significant risks were identified as supplier delivery delays (RPN = 504), raw material shortages (RPN = 448), currency fluctuations affecting imported materials (RPN = 324), and demand forecasting errors (RPN = 294). These risks primarily reflect supply uncertainty, import dependency, and coordination deficiencies across supply chain functions.

This study contributes to the sustainable supply chain risk management literature by providing a comprehensive synthesis of FMEA-based SSCRA research and extending empirical evidence from an emerging manufacturing economy. The findings offer valuable insights for practitioners and policymakers seeking to enhance supply chain resilience and sustainability through systematic risk identification, prioritization, and mitigation.

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Keywords: Sustainable Supply Chain Risk Assessment (SSCRA); Failure Mode and Effects Analysis (FMEA); Sustainable Supply Chain Management; Supply Chain Risk Management; Emerging Economies; Egyptian Manufacturing Industry.

1. INTRODUCTION

Global supply chains have evolved into complex adaptive systems characterized by nonlinear interactions, tight coupling, and emergent behavior. Within such systems, localized disruptions can propagate across multiple tiers, generating cascading failures that amplify operational, financial, and sustainability impacts. This systemic fragility is increasingly intensified by demand volatility, geopolitical instability, and rising environmental and social governance requirements. These challenges are particularly pronounced in emerging economies, where infrastructural constraints, institutional uncertainty, and resource limitations further undermine system stability. Consequently, supply chain management has shifted from efficiency-driven optimization toward resilience- and sustainability-oriented system design under deep uncertainty [1-3].

A supply chain comprises all activities involved in transforming and delivering goods from raw material sourcing to final consumption, integrating suppliers, manufacturers, logistics providers, warehouses, retailers, and customers as an interconnected value system [4]. Within this system, Supply Chain Performance (SCP) is increasingly viewed as a multidimensional construct that extends beyond cost efficiency to include responsiveness, resilience, and customer alignment. SCP reflects the ability to meet demand through timely delivery, optimized inventory, and reliable product availability, thereby strengthening competitiveness and customer satisfaction [5]. Rapid technological advancement and evolving market expectations are further driving firms toward agile, adaptive, and customer-centric supply chain structures [6,7].

In an increasingly globalized and uncertain environment, organizations recognize the necessity of resilient supply chains capable of adapting to disruptions, mitigating risks, and supporting sustainability objectives [8]. As uncertainty intensifies due to economic volatility, environmental pressures, and social dynamics, firms must adopt integrated and collaborative approaches to supply chain risk management and sustainability [9,10]. This shift emphasizes not only continuity of operations but also long-term environmental, social, and economic value creation.

Building resilience requires acknowledging that supply chain risks are diverse and interconnected, ranging from natural disasters and geopolitical shocks to supplier failures and technological disruptions [11,12]. Effective risk mitigation depends on enhanced information sharing through transparent communication channels that enable real-time visibility and faster response [13]. In parallel, coordinated contingency planning---such as alternative suppliers, production relocation, and logistics diversification---strengthens preparedness and adaptive capacity under uncertainty [14-16].

Supply chain performance is shaped by the interaction of operational, financial, strategic, and external risks. Operational risks such as production delays, equipment failures, and logistics disruptions originate internally, while financial and strategic risks arise from external volatility, including exchange rate fluctuations and regulatory changes. High-impact disruptions such as geopolitical conflicts, natural disasters, and pandemics further intensify systemic exposure [17,18]. Due to tight coupling across supply chain tiers, these risks rarely remain isolated. Instead, they propagate through interconnected networks, generating cascading effects that amplify system-wide instability. This reinforces the need for resilience-oriented strategies such as dual sourcing, inventory buffering, production flexibility, and cross-functional coordination, which enhance absorption capacity and recovery speed [19-21].

1.1. Sustainable Supply Chain Risk Management Context

Supply chain management has progressively expanded beyond cost and efficiency objectives to include sustainability and ethical responsibility [22,23]. This transformation is driven by regulatory pressure, stakeholder expectations, and growing awareness of environmental and social impacts [24,25]. Sustainability in supply chains is typically structured around three interdependent dimensions: economic sustainability, focused on long-term profitability and resource efficiency [26]; social sustainability, addressing ethical sourcing and labor conditions; and environmental sustainability, emphasizing emission reduction and resource conservation [27,28].

Manufacturing firms are therefore required to simultaneously balance profitability, efficiency, compliance, and sustainability integration [29]. Although SSCM incorporates these dimensions into decision-making, it remains largely conceptual and normative, with limited operational tools for handling uncertainty [30,31].

SSCM has gained increasing relevance as organizations respond to global challenges such as resource scarcity, climate change, and stakeholder pressure by embedding sustainability across supply chain stages [32,33], thereby strengthening long-term competitiveness [34,35]. At the same time, modern supply chains contribute significantly to greenhouse gas emissions, particularly through upstream and downstream activities, making sustainability risk assessment essential [36]. As a result, performance measurement systems have evolved toward multidimensional sustainability frameworks [37].

Supply risks include internal inefficiencies and external disruptions such as geopolitical instability and regulatory uncertainty [38]. These risks propagate across networks, while mitigation strategies such as multi-sourcing and strategic alliances enhance resilience [39,40]. Within this context, Sustainable Supply Chain Risk Management (SSCRM) emerges as an integrative extension of SSCM, yet remains methodologically underdeveloped in translating sustainability constructs into operational risk assessment models.

1.2. Failure Mode and Effects Analysis in Supply Chain Risk Assessment

Failure Mode and Effects Analysis (FMEA) is a structured methodology for identifying, evaluating, and prioritizing potential failure modes across systems and processes. It enables proactive risk mitigation by anticipating failures and assessing their consequences. Traditionally, it relies on expert judgment and historical data and is applied in static environments, limiting its suitability for dynamic supply chains [41,42].

FMEA is widely adopted in supply chain risk prioritization due to its simplicity and interpretability [43]. It calculates a Risk Priority Number (RPN) based on severity, occurrence, and detection [44]. However, classical FMEA has notable limitations: the multiplicative RPN assumes independence among variables, equal weighting introduces bias, and ordinal scales reduce analytical precision. Furthermore, reliance on expert judgment may lead to inconsistency in ranking outcomes [26,45].

Despite these limitations, FMEA remains a foundational tool in risk-based maintenance and quality management and continues to evolve through integration with digital and analytical advancements.

1.3. Research Gaps, Objectives, and Contributions

Three main gaps are identified in the literature. First, FMEA applications remain largely operational, focusing on isolated failures rather than system-level resilience and sustainability outcomes. Second, empirical evidence from emerging economies remains limited despite their higher exposure to systemic uncertainty. Third, existing approaches inadequately capture interdependencies among failure modes, overlooking cascading and network-based risk effects.

To address these gaps, this study applies FMEA within an SSCRM framework in a medium-sized Egyptian manufacturing firm in the electrical control panel industry. The firm operates under import dependency, demand volatility, and resource constraints, with recurring disruptions across procurement, production, inventory, and logistics. The study identifies, evaluates, and prioritizes supply chain failure modes using expert judgment based on Severity, Occurrence, and Detection criteria.

Research Questions:

RQ1. How can FMEA be integrated within an SSCRM framework?
RQ2. What are the key supply chain failure modes in the case firm?

RQ3. How do S–O–D criteria support risk prioritization under uncertainty?
RQ4. How are supply chain risks interrelated across functions?
RQ5. How can FMEA-based prioritization enhance resilience and sustainability?

Research Objectives:

RO1. To integrate FMEA within an SSCRM framework.
RO2. To identify and classify supply chain failure modes.
RO3. To evaluate and prioritize risks using S–O–D and RPN.
RO4. To analyze interdependencies among supply chain risks.
RO5. To derive insights for resilience and sustainability improvement.

This study contributes by: (i) integrating sustainability-oriented risk perspectives into SSCRM, (ii) providing empirical evidence from an emerging economy under high uncertainty, and (iii) repositioning FMEA as a system-aware diagnostic framework capable of partially capturing cascading risk structures. Figure 1 presents the research framework, illustrating the application of FMEA within SSCRM. It links risk identification and evaluation to sustainability and resilience outcomes. Failure modes are assessed using S–O–D criteria, generating RPN values that support prioritization and targeted mitigation strategies, thereby enhancing operational resilience and sustainability performance.

The remainder of the paper is organized as follows: Section 2 reviews relevant literature; Section 3 discusses research gaps; Section 4 presents the methodology; Section 5 presents the case study; Section 6 presents results; and Section 7 concludes with limitations and future research directions.

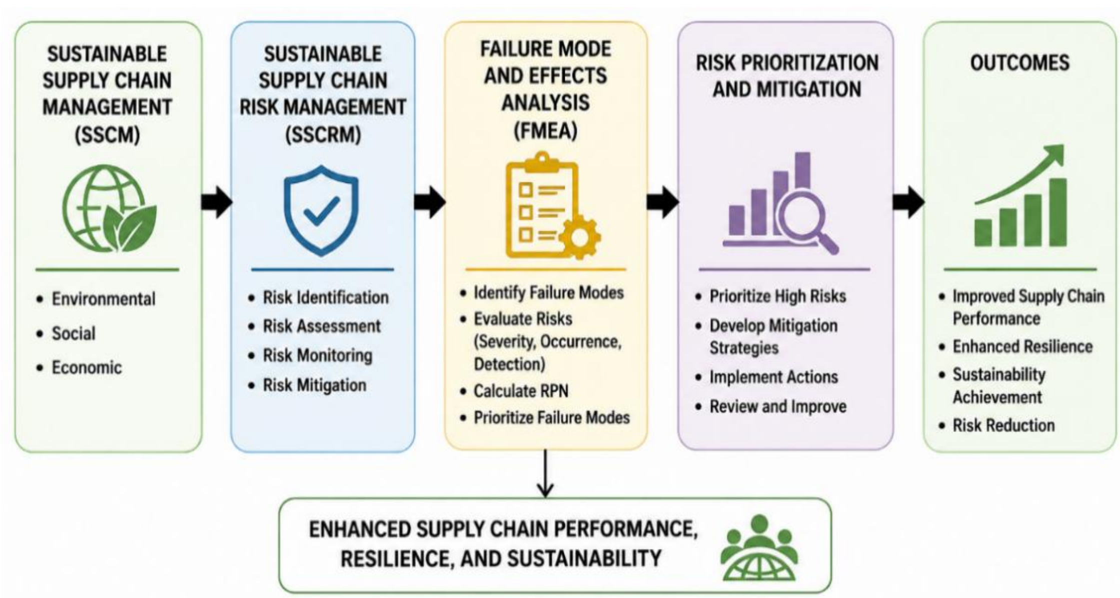

Figure 1. Sustainable Supply Chain Risk Management using FMEA

2. LITERATURE REVIEW

This study conducts a PRISMA 2020--compliant systematic literature review (SLR) to systematically identify, evaluate, and synthesize existing research on FMEA-based Sustainable Supply Chain Risk Assessment (SSCRA). The review follows the four major stages recommended by PRISMA 2020, namely identification, screening, eligibility assessment, and inclusion [46]. A structured review protocol was developed before the literature search to ensure consistency, transparency, and reproducibility. The protocol defined the research objectives, database selection, search strategy, eligibility criteria, screening procedures, quality assessment approach, and data extraction framework. Unlike conventional narrative reviews, this

SLR applies a structured coding approach to analyze methodological developments, application contexts, sustainability dimensions, and risk assessment techniques adopted in previous studies. The review covers peer-reviewed journal articles published between 2010 and 2026, focusing on sustainable supply chain risk assessment, supply chain risk management, resilience, and FMEA-based decision-support approaches. Particular attention is given to the evolution of FMEA methodologies, including traditional FMEA, fuzzy and hybrid extensions, and emerging system-oriented frameworks designed to address increasing complexity and uncertainty in supply networks.

Data Sources and Search Strategy:

The literature search was conducted using two internationally recognized bibliographic databases: Scopus and Web of Science. These databases were selected because they provide extensive coverage of high-quality peer-reviewed publications in supply chain management, operations management, sustainability, industrial engineering, and decision sciences. The search strategy was carefully designed based on the research objectives and the key concepts underlying sustainable supply chain risk assessment. Specifically, the search terms were organized into four conceptual categories: (1) supply chain context, including terms such as "supply chain," "supply network," and "logistics"; (2) risk management and resilience, including "risk assessment," "risk management," "risk identification," "risk prioritization," and "resilience"; (3) sustainability perspective, including "sustainable supply chain," "green supply chain," "environmental sustainability," and "social sustainability"; and (4) methodological approaches, including "Failure Mode and Effects Analysis," "FMEA," "multi-criteria decision-making," "MCDM," "fuzzy," "neutrosophic," and "hybrid approaches." Boolean operators (AND/OR) were applied to combine these keywords and retrieve studies addressing the intersection between supply chain risks, sustainability challenges, and FMEA-based assessment methodologies. The search strategy was designed to capture the historical development of FMEA applications, from traditional risk prioritization models toward advanced approaches incorporating uncertainty, multiple criteria, and interconnected supply chain risks.

Eligibility Criteria:

To ensure methodological consistency and reduce potential selection bias, the eligibility criteria were established before initiating the screening process. Studies were considered eligible if they satisfied four main conditions: (1) they were published as peer-reviewed journal articles; (2) they were written in English; (3) they were published between 2010 and 2026; and (4) they directly addressed supply chain risk assessment, supply chain resilience, sustainability-related risks, or FMEA-based decision-support models. Both conceptual and empirical studies were considered eligible because the objective of the review was to capture theoretical developments as well as practical applications of FMEA-based SSCRA approaches.

Conversely, studies were excluded when they did not satisfy the research objectives. Specifically, conference papers, book chapters, editorials, and non-peer-reviewed publications were excluded to maintain academic rigor. Studies focusing exclusively on product reliability, mechanical failure analysis, or manufacturing process FMEA without a supply chain perspective were also excluded because they did not contribute to sustainable supply chain risk assessment. Furthermore, studies lacking meaningful integration of sustainability considerations, risk assessment methodologies, or FMEA applications were removed.

Screening Process and PRISMA Workflow:

The study selection process followed the PRISMA 2020 framework to ensure a transparent and reproducible review procedure. The initial database search identified 525 records from Scopus and Web of Science. Following duplicate removal, 112 records were eliminated, resulting in 413 unique studies available for screening. During the title and abstract screening stage, each record was evaluated against the predefined eligibility criteria. A total of 287 studies were excluded at this stage because they did not address sustainable supply chain risk assessment, did not apply FMEA or relevant risk assessment approaches, focused on unrelated research domains, or lacked sufficient connection to supply chain management.

The remaining 126 studies were retrieved for full-text assessment. Each article was examined in detail based on its research objectives, methodological approach, supply chain relevance, and contribution to sustainability-oriented risk assessment. Thirteen additional studies were excluded during this stage because they demonstrated methodological inconsistency, insufficient conceptual relevance, or inadequate alignment with the research objectives. Following the complete screening procedure, 113 studies were retained as the final review sample covering the period from 2010 to 2026. The complete PRISMA flow process, including identification, screening, eligibility, and final inclusion stages, is presented in Figure 2. To improve reproducibility, the supplementary appendix provides detailed information regarding exclusion categories, screening decisions, and the coding framework applied during the review.

Quality Assessment and Coding Framework:

A structured coding framework was developed to extract and analyze information from the selected studies systematically. The coding process was designed to capture both bibliometric characteristics and methodological developments within FMEA-based sustainable supply chain risk assessment research. Each study was coded according to publication characteristics, including publication year, journal source, country context, and industrial sector. In addition, methodological characteristics were recorded, including the type of FMEA approach adopted, integration with other decision-making methods, uncertainty modeling techniques, validation approaches, and major research outcomes.

The quality assessment process evaluated each study according to four dimensions: methodological clarity, research design rigor, analytical transparency, and relevance to SSCRA. Each dimension was assessed using a structured evaluation scale to support consistent comparison among studies with different research designs and methodological approaches. Studies demonstrating strong methodological justification, clear analytical procedures, and direct relevance to sustainable supply chain risk assessment received higher quality scores. This process reduced potential evaluator bias and ensured that the synthesis was based on studies with sufficient methodological reliability.

Data Synthesis:

The synthesis of the 113 reviewed studies provides insights into the methodological evolution and current limitations of FMEA-based sustainable supply chain risk assessment. The findings indicate that multi-criteria decision-making (MCDM) approaches represent the dominant methodological category, accounting for approximately 62% of reviewed studies. These approaches are frequently combined with FMEA to overcome limitations related to subjective judgments and risk prioritization. FMEA-based extensions account for approximately 28% of studies and mainly incorporate fuzzy logic, neutrosophic theory, and hybrid decision-support approaches to address uncertainty in expert evaluations.

However, only approximately 10% of reviewed studies explicitly consider risk interdependencies, cascading effects, or dynamic system behavior. The majority of existing approaches remain static (≈78%), expert-driven (≈81%), and primarily focused on risk ranking and prioritization (≈74%). This indicates that current methodologies are mainly designed to identify critical risks rather than explain how interconnected risks evolve and propagate throughout complex supply networks.

The sustainability analysis also reveals an imbalance among the three dimensions of sustainability. Economic considerations dominate the literature, appearing in approximately 85% of studies, while environmental and social dimensions are considered in approximately 52% and 37% of studies, respectively. This finding demonstrates that many existing approaches have not yet achieved comprehensive integration of economic, environmental, and social sustainability requirements.

Methodological Positioning:

The systematic review reveals a persistent gap between methodological advancement and the ability of existing approaches to represent complex supply chain risk structures. Although FMEA remains widely adopted because of its simplicity, interpretability, and practical applicability, conventional FMEA approaches are limited by assumptions of independent failure modes and linear risk aggregation. These assumptions may not adequately represent modern supply chains characterized by interconnected suppliers, uncertainty propagation, resource dependencies, and disruption amplification.

Therefore, this study advances a system-oriented reconceptualization of FMEA within Sustainable Supply Chain Risk Assessment (SSCRA). Rather than replacing traditional risk prioritization functions, the proposed perspective extends FMEA toward a diagnostic framework capable of identifying critical vulnerability structures and improving understanding of interconnected supply chain risks. This positioning enables FMEA to better support sustainability-oriented decision-making in complex and uncertain supply chain environments.

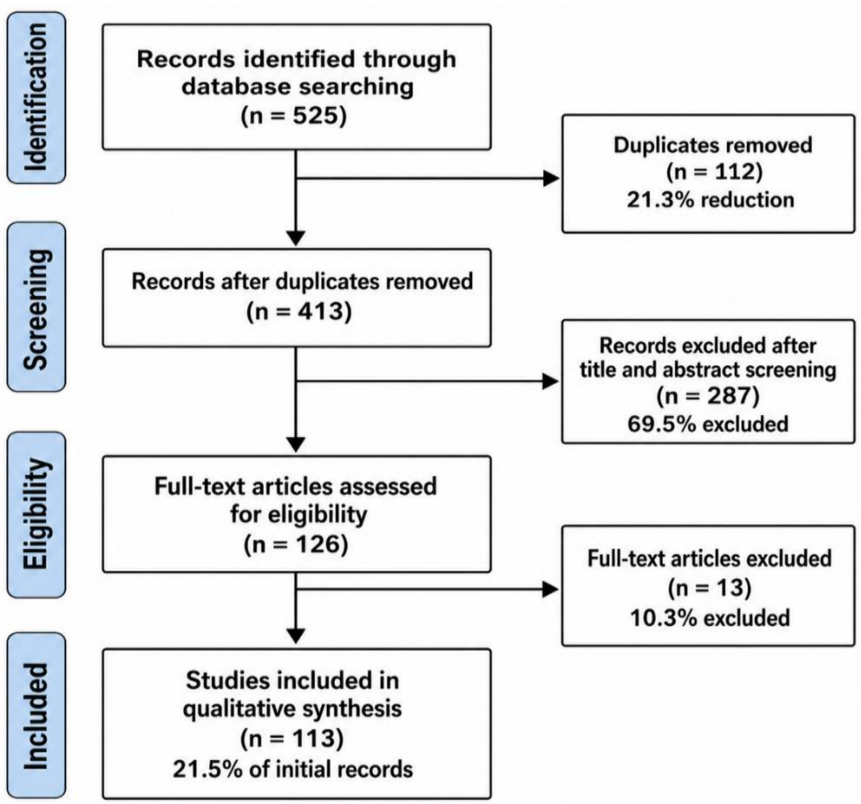

Figure 2. PRISMA flow diagram.

2.1. Literature Review on Supply Chain Risk Management

Supply chain risk management (SCRM) has emerged as a major research focus in operations and supply chain management due to increasing global uncertainty, expansion of outsourcing and offshoring activities, and rapid technological advancement [47-49]. These developments have transformed supply chains into highly interconnected, multi-tier systems in which disruptions can rapidly propagate across organizational and geographic boundaries. Although globalization has delivered substantial gains in efficiency, cost reduction, and scalability, it has also intensified systemic vulnerability by reducing buffers, increasing interdependence, and amplifying contagion effects during disruptions [50,51]. Consequently, SCRM has progressively shifted from reactive disruption management toward proactive, resilience-oriented, and adaptive governance frameworks [52,53].

Supply chain risk is broadly defined as any disruption that negatively affects the flow of materials, information, products, or financial resources across interconnected supply networks [54,55]. Extending this definition, risk is also understood as the adverse consequences arising from interactions among supply chain actors, emphasizing its systemic, relational, and network-based nature rather than a purely operational issue [56]. Within this context, SCRM is conceptualized as a structured managerial capability involving risk identification, assessment, monitoring, and mitigation under uncertainty [57]. This highlights SCRM as a continuous governance function embedded within supply chain design and execution.

From a classification perspective, supply chain risks are commonly divided into endogenous and exogenous categories. Endogenous risks originate within internal processes, managerial decisions, and operational inefficiencies, while exogenous risks arise from external environmental forces such as economic volatility, geopolitical instability, regulatory changes, and natural disasters. This distinction underscores that supply chain vulnerability is shaped by both internal weaknesses and external uncertainties, reinforcing the need for integrated risk management approaches.

A more detailed and widely adopted risk typology identifies six interdependent categories: supply, demand, operational, financial, ethical/social, and environmental risks. Supply risks arise from supplier capacity constraints, quality failures, or dependency issues [58], while demand risks stem from volatility, uncertainty, and forecasting errors [59]. Operational risks are linked to process inefficiencies and coordination failures across supply chain tiers [60], whereas financial risks result from macroeconomic instability such as exchange rate fluctuations, inflation, and credit constraints [61]. Ethical and social risks are associated with governance failures, labor violations, and stakeholder non-compliance [62], while environmental risks emerge from climate change impacts, regulatory pressures, and natural disasters [63,64]. Importantly, these risks are not isolated; instead, they are strongly interconnected and often generate cascading effects across the supply chain system.

The findings of studies indicated that improved risk mitigation requires collective efforts to strengthen supply chain resilience and enable coordinated contingency plans and diverse sourcing approaches [65]. In addition, working together allows various stakeholders to pool resources and expertise, leading to more robust risk mitigation strategies. The shared responsibility for sustainability through collaboration facilitates joint actions on issues like ethical sourcing, fair practices, and reducing environmental impact [66].

2.1.1. Sustainable Supply Chain Management (SSCM)

Sustainability has become a central strategic priority in supply chain management due to increasing stakeholder pressure, regulatory requirements, and heightened awareness of environmental degradation and social inequality [67]. Sustainable Supply Chain Management (SSCM) extends across the entire value chain with the aim of minimizing environmental and social impacts while ensuring long-term economic viability and competitiveness [68-70]. It integrates material, information, and relational flows across multi-tier networks in alignment with stakeholder expectations and the triple bottom line (TBL) framework [37].

SSCM requires continuous balancing of environmental, social, and economic objectives, often resulting in complex trade-offs between cost efficiency and sustainability performance [71,72]. Unlike traditional supply chains that focus primarily on financial outcomes, SSCM incorporates long-term ecological preservation and social responsibility into strategic and operational decision-making [73,74]. However, globalization, outsourcing, and offshoring have shifted many sustainability impacts outside organizational boundaries, increasing indirect exposure to environmental and social risks and reducing managerial control over key sustainability outcomes [75].

Within this expanded context, sustainability introduces additional and complex risk dimensions into supply chains, including environmental, social, operational, and financial risks [76-79]. Environmental risks can be categorized as "inside-out" risks originating from organizational activities or "outside-in" risks driven by external ecological and regulatory pressures. Financial risks include external shocks such as commodity price and exchange rate fluctuations, as well as internal consequences such as declining profitability, liquidity issues, and cash flow instability. These sustainability-related risks are highly interdependent, as environmental or social disruptions can quickly translate into financial losses and reputational damage.

Despite these complexities, sustainability is increasingly recognized as both a strategic opportunity and a source of competitive advantage. Empirical evidence shows that sustainability integration can improve long-term performance, efficiency, and competitiveness [80,81]. At the same time, it introduces additional layers of complexity, uncertainty, and risk exposure that must be actively managed.

From a managerial perspective, supply chain actors play a critical role in embedding sustainability through sustainable sourcing, supplier evaluation, relationship management, localization strategies, and asset recovery. These decisions directly influence exposure to sustainability-related risks while simultaneously strengthening resilience and operational efficiency. When effectively implemented, SSCM practices can reduce lifecycle costs and enhance long-term profitability and strategic flexibility [81].

2.1.2. SCRM Processes and Methodological Evolution

SCRM is generally structured as a cyclical process involving risk identification, risk assessment, risk monitoring, and risk mitigation [82]. While early approaches were largely reactive and focused on post-disruption responses, increasing uncertainty and complexity in global supply chains have shifted SCRM toward predictive, data-driven, and resilience-oriented decision frameworks.

Methodologically, Multi-Criteria Decision-Making (MCDM) techniques such as AHP, TOPSIS, and DEMATEL are widely used for supplier evaluation, risk prioritization, and complex decision support under multiple criteria [83,84,85]. These methods enable the integration of qualitative judgments and quantitative indicators, making them suitable for sustainability-intensive and uncertainty-driven environments.

Recent advancements extend these models through hybrid and uncertainty-aware approaches, including fuzzy logic, Conditional Value-at-Risk (CVaR), and possibilistic programming, which are designed to handle ambiguity and stochastic variability in supply chain systems [86,87,88]. Overall, this reflects a transition from deterministic optimization models toward adaptive, robust, and uncertainty-resilient decision-making frameworks.

Despite these methodological developments, sustainability-related risks remain insufficiently integrated into mainstream SCRM models [89,90]. To address this limitation, several structured modeling approaches have been proposed.

Hadiguna [91] introduced a sustainability risk framework based on interdependent environmental, social, and economic dimensions, integrating performance, structural, and attribute components. Ghadge et al. [92] developed dynamic risk modeling approaches capable of capturing evolving risk behaviors in supply chains. Mangla et al. [93] extended Interpretive Structural Modeling (ISM) into Total Interpretive Structural Modeling (TISM) to explicitly interpret relationships among sustainability risk factors, improving structural understanding.

Additional contributions include fuzzy AHP applications in green supply chain risk prioritization [94,95], ISM-based reverse supply chain risk modeling, and DEMATEL-based SSCM risk prioritization frameworks [85]. Empirical evidence further shows that sustainability integration can reduce supply chain risk exposure, particularly in emerging economies, although traditional mitigation approaches may not always be sufficient under uncertainty [96]. Supplier evaluation models incorporating sustainability criteria also demonstrate improved profitability and reduced risk exposure [97].

At a broader level, sustainability risk research has expanded to country-level analyses, resulting in sustainability country risk mapping tools for global supply chain decision-making [98]. However, the literature remains fragmented across sectors, methodologies, and geographic contexts.

Despite substantial advances in supply chain risk management (SCRM), the literature remains structurally fragmented across sustainability dimensions, methodological approaches, and risk classifications. Environmental [23], social [99], and economic risks [100,101] are still largely investigated as separate streams of inquiry, with limited theoretical and analytical integration. This fragmentation restricts the development of holistic frameworks capable of capturing the interdependent and cascading nature of sustainability risks, where disturbances in one dimension can propagate and amplify impacts across others. As a result, existing models often provide a partial representation of systemic risk exposure in global supply networks.

A further limitation concerns the weak operationalization of sustainability within SCRM models. Although sustainability is widely acknowledged as a core element of contemporary supply chain governance, there is still insufficient clarity on how sustainability concerns are translated into measurable, decision-relevant risk constructs suitable for quantitative modeling and managerial application [88,102,103]. In many studies, sustainability remains conceptual rather than fully embedded within formal risk assessment structures. This limits the ability of organizations to systematically evaluate trade-offs, prioritize interventions, and implement data-driven risk mitigation strategies under uncertainty.

In addition, environmental impacts associated with global logistics and transportation systems remain underexplored, particularly in relation to their cumulative, cross-border, and system-wide externalities. Existing research tends to focus on isolated environmental indicators such as emissions or energy use, rather than examining how logistics networks collectively shape environmental risk propagation across multi-tier supply chains. This gap constrains the development of integrated sustainability assessments that reflect the full environmental footprint of globally distributed supply chain operations.

Overall, SCRM has progressed from basic risk identification and classification toward more integrated, intelligent, and digitally enabled resilience-oriented frameworks. Advances in multi-criteria decision-making (MCDM), fuzzy systems, and hybrid optimization techniques have strengthened the handling of uncertainty, ambiguity, and multi-dimensional complexity in risk evaluation. At the same time, sustainability integration has broadened the conceptual scope of SCRM beyond traditional operational and financial concerns. However, persistent fragmentation across sustainability dimensions, methodological approaches, and empirical contexts continues to limit theoretical coherence and practical applicability. This underscores the need for unified, system-level frameworks capable of simultaneously modeling environmental, social, and economic risks within complex, interconnected global supply chains [104,105].

2.2 Literature Review on FMEA and its Applications in SSCM

Failure Mode and Effects Analysis (FMEA) is a proactive and systematic risk assessment methodology originally developed by NASA in the 1960s to enhance system reliability and safety. Since its introduction, it has been widely adopted across diverse industrial sectors, including aerospace, automotive, manufacturing, healthcare, energy, logistics, and service systems. In contrast to reactive approaches that address failures only after their occurrence, FMEA emphasizes early identification and structured evaluation of potential failure modes, enabling organizations to implement preventive actions that improve product quality, operational efficiency, safety performance, and cost-effectiveness [106-108].

The classical structure of FMEA is built upon three interrelated components: Failure Mode (FM), which describes the specific ways a system or process may fail; Failure Effect (FE), which captures the consequences of failure on system performance, stakeholders, the environment, or downstream operations; and Failure Cause (FC), which identifies underlying drivers such as design deficiencies, process variability, human error, or external disturbances [109]. These elements collectively form a structured representation of system vulnerability and provide the foundation for systematic risk identification in complex environments.

Based on this structure, several domain-specific variants of FMEA have been developed to address different lifecycle stages and application contexts. These include Design FMEA (DFMEA), Process FMEA (PFMEA), and Environmental FMEA, each tailored to distinct phases of system development and operational deployment [110,111]. These extensions demonstrate the evolution of FMEA from a purely engineering tool toward a broader decision-support framework capable of addressing environmental and sustainability-oriented concerns.

FMEA evaluates risk using three core parameters: severity (S), occurrence (O), and detection (D), which are aggregated into the Risk Priority Number ($RPN = S \times O \times D$). Although widely used due to its simplicity and intuitive structure, the classical RPN approach has been frequently criticized for its deterministic formulation, equal-weight assumption, and inability to properly capture uncertainty, ambiguity, and interdependencies among risk factors. These limitations become particularly evident in complex, dynamic, and interconnected systems.

In industrial practice, FMEA is embedded in quality management systems such as ISO 9001:2015, where it supports structured root cause analysis, systematic risk prioritization, and continuous improvement initiatives. These applications contribute to enhanced reliability, reduced operational disruptions, improved safety performance, minimized downtime, and sustained organizational competitiveness in highly competitive industrial environments.

2.2.1. Technological evolution and advanced extensions of FMEA

With the advancement of Industry 4.0, FMEA has evolved into a more intelligent and data-driven risk assessment methodology. Recent studies have integrated artificial intelligence, machine learning, Bayesian reasoning, and fuzzy logic into FMEA frameworks to enhance their capability to model uncertainty, complexity, and dynamic behavior in real-time systems. In particular, AI-enabled FMEA supports continuous risk monitoring, automated prioritization of failure modes, and integration with cyber-physical production systems, aligning the method with Quality 4.0 and smart manufacturing paradigms [112].

Beyond traditional industrial settings, FMEA has been extended into sustainability-oriented and socio-technical domains. Social Failure Mode and Effects Analysis (SFMEA) has emerged to incorporate social sustainability considerations, including ethical risks, labor conditions, and stakeholder impacts. AI-based conversational systems have further facilitated SFMEA by enabling interactive identification and structuring of social risks in organizational environments.

In parallel, hybrid fuzzy--analytic network approaches have been developed to capture interdependent and nonlinear relationships among risk factors, particularly in advanced manufacturing systems such as additive manufacturing, where process variables are strongly interconnected [109,113]. These developments reflect a paradigm shift from linear risk evaluation toward network-based and system-oriented modeling frameworks.

Moreover, the integration of FMEA with Industry 4.0 analytics platforms, digital twins, and large-scale failure databases has significantly strengthened predictive maintenance strategies. In healthcare systems, such integration improves equipment reliability, reduces unexpected failures, and enhances patient safety, particularly in critical and resource-constrained environments [114,115]. This demonstrates the transition of FMEA into a dynamic, intelligent decision-support system.

2.2.2. FMEA in sustainability and SSCM decision environments

Sustainability risk assessment is inherently a complex decision-making problem characterized by uncertainty, subjectivity, and strong interdependencies among risk factors. Within this context, FMEA has been widely applied as a structured methodology for identifying, analyzing, and prioritizing potential failure modes, thereby enabling proactive risk mitigation strategies [116-118].

Since failure modes and their associated drivers can be interpreted as alternatives and criteria, respectively, FMEA-based evaluation is naturally aligned with multi-criteria decision-making (MCDM) frameworks. However, when applied to Sustainable Supply Chain Management (SSCM), traditional FMEA faces significant challenges in capturing multidimensional sustainability risks. These challenges include limited representation of uncertainty, inadequate modeling of interdependencies, and oversimplification of complex causal structures, which may reduce the robustness and reliability of decision outcomes [119,120].

SSCM has emerged as a strategic paradigm that integrates economic performance, environmental protection, and social responsibility to achieve long-term competitiveness and sustainable development

[121,35]. In contemporary global supply chains, organizations face increasing sustainability pressures driven by climate change, resource scarcity, regulatory requirements, ethical sourcing expectations, and stakeholder accountability. Consequently, SSCM has evolved from a supporting operational function into a core strategic imperative for organizational resilience and long-term value creation.

The complexity of SSCM arises from the need to simultaneously balance multiple conflicting sustainability objectives under uncertainty and incomplete information. To address this challenge, multi-criteria decision-making (MCDM) methods have been widely adopted due to their ability to structure complex decision problems transparently and systematically. Compared to traditional approaches such as mathematical programming and brainstorming, MCDM techniques provide greater flexibility, interpretability, and applicability in real-world SSCM decision contexts [122,123].

Recent studies further emphasize the integration of MCDM with uncertainty modeling techniques to enhance decision robustness. For example, Sun et al. [124] and Sumrit [125] combined MCDM frameworks with fuzzy information theory to improve supply chain resilience under uncertain environments. Similarly, Saha et al. [126] integrated the MARCOS method with probabilistic hesitant fuzzy sets to address healthcare supplier selection problems, improving the handling of ambiguity and expert hesitation. In addition, Masoomi et al. [127] developed a hybrid decision model combining the Best--Worst Method (BWM) and DEMATEL to identify key sustainability enablers in Industry 5.0 contexts, highlighting the importance of capturing causal relationships in complex socio-technical systems.

To address uncertainty and subjectivity, extensive research has integrated fuzzy set theory into FMEA frameworks. Unlike conventional crisp rating scales used by Sutrisno et al. [128], Minguito and Banluta [129], and Ventura et al. [130], Ayyildiz et al. [131] and Ayyildiz et al. [132] employed Pythagorean fuzzy numbers to better represent expert hesitation and ambiguity. Tian et al. [133] further extended uncertainty modeling by introducing triangular interval type-2 fuzzy sets in electric vehicle applications, enabling more effective representation of high uncertainty and imprecision.

In addition, probabilistic and hybrid fuzzy extensions have been explored to improve realism in expert judgment modeling. Sun et al. [124] and Tang et al. [134] incorporated probabilistic information into FMEA frameworks to better reflect variability in expert evaluations, while Akdamar et al. [135] and Ceylan [136] developed fuzzy FMEA models applied in maritime risk environments. Despite these advancements, existing approaches still struggle to fully capture hierarchical dependencies, nonlinear interactions, and dynamic risk propagation mechanisms inherent in SSCM systems, highlighting the need for more expressive uncertainty modeling frameworks such as triangular interval type-2 fuzzy sets (TrIT2FSs).

In parallel, another important research stream focuses on improving the traditional Risk Priority Number (RPN) mechanism through integration with advanced MCDM techniques. Huang and Yang [137] proposed a hybrid framework combining FMEA with multi-perspective weighting, interval cloud models, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), improving ranking robustness under uncertainty.

Similarly, Sun et al. [124] and Wan et al. [138] developed fuzzy ORESTE-based approaches for failure mode prioritization, while Tang et al. [134] integrated FMEA with WASPAS and CRITIC methods to enhance critical failure mode identification in lithium-ion battery production systems. Collectively, these studies demonstrate that integrating FMEA with MCDM techniques significantly improves the reliability, consistency, and interpretability of risk prioritization outcomes.

Despite substantial methodological progress, existing literature still rarely considers the combined influence of expert interaction dynamics and interdependencies among risk factors. Moreover, the structural and causal relationships among failure modes in complex, highly uncertain, and interconnected supply chain environments remain insufficiently explored.

Septiani et al. [139] further emphasized the systemic nature of sustainability risks by proposing an Intelligent Decision Support System (IDSS) integrating HRBS and FMEA to map interrelated sustainability risks and their consequences. Collectively, these findings confirm that sustainability risks are inherently networked, dynamic, and system-driven, requiring more advanced integrated modeling approaches.

In conclusion, although significant progress has been achieved through fuzzy logic, MCDM integration, and intelligent extensions of FMEA, there remains a clear need for more comprehensive, interaction-aware, and uncertainty-resilient frameworks capable of supporting robust SSCM risk assessment and sustainable decision-making in complex real-world environments.

3. CHALLENGES AND RESEARCH GAPS ANALYSIS ON FMEA APPLICATIONS IN SSCM

Despite the extensive adoption and continuous methodological advancement of Failure Mode and Effects Analysis (FMEA), its application in Sustainable Supply Chain Management (SSCM) remains constrained by several interrelated challenges, as summarized in Table 1. These challenges arise from the inherent complexity of SSCM systems, where economic efficiency, environmental sustainability, and social responsibility must be simultaneously balanced under uncertainty, disruption risks, and multi-stakeholder decision environments [35,121]. In such contexts, conventional FMEA frameworks often struggle to adequately capture system-wide complexity, interdependencies, and temporal dynamics.

1) Uncertainty in expert judgment: Classical FMEA relies on crisp scoring systems that are insufficient for capturing linguistic ambiguity, hesitation, and inconsistency in expert evaluations. Although fuzzy extensions---such as interval type-2 fuzzy sets, probabilistic hesitant fuzzy models, and neutrosophic approaches---enhance uncertainty representation, they still do not fully address deep uncertainty and behavioral variability in SSCM contexts [131,132,133]. This limitation reduces the robustness and stability of risk prioritization results.
2) Risk interdependencies: Traditional FMEA assumes independence among failure modes, which is unrealistic in SSCM where disruptions propagate across multiple supply chain tiers. Although approaches such as DEMATEL, ISM, system dynamics, and graph-based models partially address this issue, many FMEA extensions still lack explicit and rigorous representation of complex interaction structures [137,138]. Consequently, cascading effects and systemic risk amplification remain insufficiently captured.
3) Structural limitation of FMEA: FMEA does not explicitly model causal relationships among failure modes, limiting interpretability and weakening understanding of how risks propagate and interact within complex supply chain systems.
4) Expert interaction dynamics: Most FMEA-based approaches aggregate expert opinions using static weighting or averaging techniques, without considering learning, feedback, or consensus evolution. This reduces realism in group decision-making, particularly in SSCM environments involving heterogeneous stakeholders with conflicting objectives [126,127].
5) RPN limitations: The classical Risk Priority Number ($S \times O \times D$) assumes equal importance and independence among risk factors, which may lead to biased or unstable rankings. Although hybrid MCDM methods such as TOPSIS, WASPAS, MARCOS, ORESTE, and VIKOR improve ranking performance, they do not fundamentally resolve the structural limitations of the RPN mechanism [122,123].
6) Sustainability integration: Many SSCM-FMEA models still treat economic, environmental, and social dimensions in a fragmented manner. This limits the ability to evaluate trade-offs and cross-dimensional interactions required for holistic sustainability assessment [120,119].
7) Data uncertainty and sparsity: Limited availability of reliable historical SSCM data increases reliance on expert judgment, thereby amplifying subjectivity and reducing robustness and generalizability of risk assessment outcomes.
8) Digital transformation gap: FMEA remains weakly integrated with Artificial Intelligence (AI) and Industry 4.0 technologies, resulting in predominantly static and reactive models rather than real-time, predictive, and adaptive decision-support systems.

9) Resilience and disruption modeling: Existing approaches insufficiently capture disruption propagation, system resilience, and recovery dynamics, limiting effectiveness under large-scale shocks such as pandemics or geopolitical crises.
10) Scalability and complexity: Advanced hybrid FMEA models often involve high computational burden and significant expert involvement, which restricts scalability and practical implementation in industrial environments.
11) Multi-tier supply chain visibility: Insufficient end-to-end visibility across supply chain tiers leads to hidden risks in upstream and downstream networks that remain unaddressed.
12) Human judgment bias: Cognitive and behavioral biases in expert evaluations can distort scoring outcomes and reduce consistency in risk prioritization.
13) Static risk representation: FMEA is typically implemented as a snapshot-based approach, limiting its ability to capture evolving and time-dependent risk dynamics in SSCM environments.

In summary, as reflected in Table 1, these challenges are deeply interconnected across uncertainty modeling, interdependencies, decision behavior, sustainability integration, and digital transformation. Addressing them requires the development of integrated, adaptive, and system-oriented FMEA frameworks capable of supporting robust, dynamic, and sustainable decision-making in complex SSCM environments.

Table 1. Challenges, Research Gaps, and Mitigation Strategies in FMEA Applications in SSCM

#	Challenge Area	Research Gap	Implications for SSCM	Mitigation Strategy
1	Uncertainty in expert judgment	Limited modeling of deep uncertainty, hesitation, and inconsistency	Unstable and unreliable risk prioritization	Advanced fuzzy and neutrosophic approaches
2	Risk interdependencies	Independence assumption among failure modes	Cascading supply chain risks not captured	DEMATEL, ISM, system dynamics models
3	Expert interaction dynamics	Static aggregation of expert opinions	Reduced realism in group decision-making	Dynamic consensus and adaptive weighting methods
4	RPN limitations	Equal-weight S × O × D structure	Biased and insensitive risk rankings	Hybrid MCDM methods
5	Structural limitation	Lack of causal representation among failures	Weak understanding of risk propagation	DEMATEL, ANP, causal loop modeling
6	Sustainability integration	Fragmented economic, environmental, social analysis	Incomplete SSCM risk evaluation	Integrated triple-bottom-line FMEA frameworks
7	Data uncertainty	Scarcity and low reliability of data	Reduced robustness of results	Big data analytics and expert data fusion
8	Digital transformation gap	Limited integration with Industry 4.0 technologies	Static and non-real-time decision-making	IoT, AI, and digital twins integration

9	Resilience modeling	Weak modeling of disruption and recovery	Limited shock response capability	System dynamics and stochastic modeling
10	Scalability	High computational and cognitive complexity	Limited industrial applicability	Modular and simplified decision frameworks
11	Supply chain visibility	Limited multi-tier transparency	Hidden upstream/ downstream risks	Blockchain-enabled traceability systems
12	Human bias	Cognitive and behavioral bias in expert judgment	Distorted risk assessments	Delphi method and bias correction techniques
13	Static representation	Lack of temporal/dynamic modeling	No adaptability to changing risks	Dynamic and time-updated FMEA models

4. CONCEPTUAL FRAMEWORK FOR FMEA-BASED SUPPLY CHAIN RISK MANAGEMENT

The increasing complexity, globalization, and interconnectedness of contemporary supply chains have substantially intensified organizational exposure to uncertainty and disruption. Modern supply chains are increasingly affected by supplier failures, demand volatility, operational disruptions, regulatory changes, geopolitical instability, technological vulnerabilities, and sustainability-related pressures. Consequently, firms are required to adopt proactive, structured, and systematic approaches to identify vulnerabilities, prioritize risks, and design mitigation strategies that enhance both resilience and sustainability performance.

Although supply chain risk management has received extensive scholarly attention, existing approaches remain largely fragmented and predominantly focused on isolated risks or single functional domains. Such perspectives insufficiently capture the systemic and interdependent nature of supply chains, where disruptions propagate across multiple tiers and generate amplified, network-wide effects. This limitation underscores the need for integrated analytical frameworks capable of representing multidimensional and network-based risk structures.

To address this gap, Figure 3 presents the conceptual framework for Failure Mode and Effects Analysis (FMEA)-based Supply Chain Risk Management (SCRM). The framework follows an iterative decision-support cycle comprising risk identification, assessment, prioritization, mitigation, and continuous improvement, to strengthen both resilience and sustainability performance. The process begins with systematic identification of failure modes across key supply chain functions, including procurement, demand planning, production operations, inventory management, logistics and distribution, regulatory environments, and digital information systems, which collectively represent the primary domains through which disruptions emerge and propagate.

Within this framework, FMEA serves as the core analytical mechanism for risk evaluation and prioritization. FMEA is widely established in operations and supply chain risk literature as a structured method for identifying and assessing failure modes under uncertainty while maintaining managerial interpretability. It is operationalized through three dimensions: Severity (S), representing the magnitude of impact on operational performance, cost efficiency, service level, and sustainability outcomes; Occurrence (O), reflecting the likelihood of failure based on expert judgment and experiential knowledge; and Detectability (D), indicating the ability of existing control systems to identify failures before escalation.

Expert judgments are elicited using structured linguistic scales and converted into quantitative values through consensus-based mapping procedures, thereby enhancing methodological rigor while preserving domain expertise under uncertainty. The Risk Priority Number (RPN) is computed as $RPN = S \times O \times D$, providing a composite measure of risk criticality. This formulation ensures systematic prioritization of failure modes characterized by high severity, high occurrence, and low detectability.

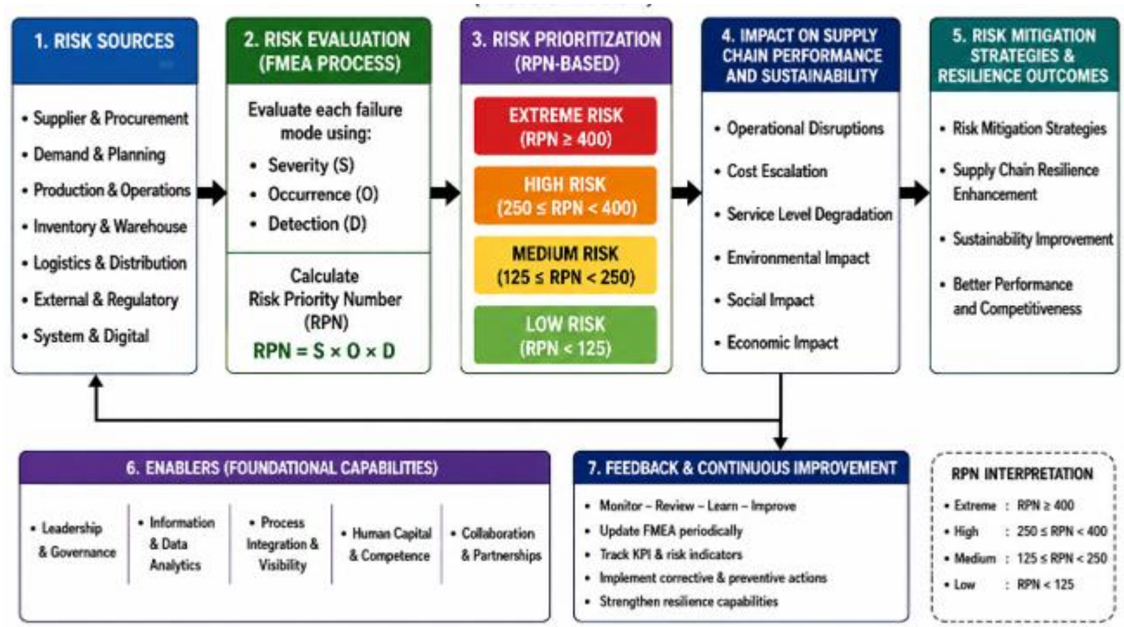

Figure 3. Conceptual Framework for FMEA-Based Supply Chain Risk Management.

The empirical results reveal a highly skewed distribution of risk, indicating that a limited number of failure modes account for a disproportionate share of overall system vulnerability. This pattern aligns with the Pareto principle and highlights the concentration of risk within specific supply chain segments.

In particular, supplier-related risks---especially delivery delays and raw material shortages---exhibit the highest RPN values due to their direct impact on production continuity, frequent occurrence, and limited detectability. Medium-priority risks, such as production scheduling instability and demand forecasting errors, are strongly linked to upstream variability, suggesting that internal inefficiencies often emerge as systemic responses to external uncertainty rather than isolated operational shortcomings. Lower-priority risks, including transportation delays and inventory mismanagement, contribute cumulatively to inefficiencies despite their lower individual criticality. Overall, the findings confirm that supply chain risk is structurally concentrated rather than evenly distributed, reinforcing the need for targeted mitigation strategies.

Within the proposed framework, FMEA performs a dual function. First, it enables structured ranking of risks based on relative criticality. Second, it functions as a diagnostic instrument for revealing structural vulnerabilities and concentration points within the supply chain network, thereby extending its role beyond traditional prioritization toward system-level risk interpretation. Based on RPN outcomes, risks are categorized into extreme, high, medium, and low priority levels to support efficient resource allocation and improve decision-making precision.

Mitigation strategies are subsequently aligned with prioritized risks, encompassing supplier diversification, strategic sourcing, collaborative supplier relationships, advanced forecasting systems, integrated production planning, preventive and predictive maintenance, inventory visibility systems, logistics optimization, regulatory compliance mechanisms, and cybersecurity controls. These interventions are designed to reduce both the probability and impact of disruptions while strengthening the absorptive, adaptive, and restorative capacities of the supply chain.

Supply chain resilience is conceptualized as the capability of a system to anticipate, absorb, respond to, adapt to, and recover from disruptions while maintaining acceptable performance levels. Within this context, effective risk mitigation enhances resilience by reducing vulnerability exposure and improving response capability under uncertainty.

Resilience further operates as a mediating mechanism linking risk management practices to sustainability outcomes. By minimizing disruption-induced losses and improving resource efficiency, it simultaneously enhances economic performance, operational stability, and environmental sustainability.

The framework is supported by key organizational enablers, including leadership commitment, governance mechanisms, digital transformation technologies, information-sharing infrastructure, advanced analytical capabilities, process integration, workforce competencies, and inter-organizational collaboration. These enablers are essential for ensuring effective implementation and for translating analytical insights into actionable managerial decisions.

Finally, the framework incorporates a continuous feedback and learning loop, whereby risk conditions are continuously monitored, reassessed, and updated in response to evolving internal and external environments. This dynamic capability ensures ongoing adaptation, organizational learning, and sustained improvement in resilience and sustainability performance within complex and uncertain supply chain systems.

5. CASE STUDY

Following the systematic literature review, an empirical case study was conducted to examine the application of FMEA-based Sustainable Supply Chain Risk Assessment (SSCRA) within an emerging-economy manufacturing context. The systematic review revealed that existing research has increasingly recognized the value of FMEA for supply chain risk identification and prioritization; however, empirical evidence remains limited regarding its application in manufacturing environments characterized by high import dependency, supplier uncertainty, and exposure to external disruptions. These characteristics are particularly relevant in emerging economies, where supply chain resilience is often constrained by structural dependencies, limited sourcing flexibility, and vulnerability to global market fluctuations.

Accordingly, this case study aims to provide contextualized insights into how supply chain risks are identified, evaluated, and prioritized within an import-dependent manufacturing system. The purpose is not to generate statistical generalization but to develop an in-depth understanding of the mechanisms through which supply chain vulnerabilities emerge and influence operational resilience. The case, therefore, represents an analytical investigation of FMEA-based SSCRA implementation within a complex industrial setting where internal operational capabilities interact with external supply chain pressures.

The selection of a case study methodology is appropriate because supply chain risks are context-dependent phenomena shaped by organizational characteristics, supply network structures, and external environmental conditions. A detailed examination of a real industrial setting enables the identification of risk patterns, causal relationships, and managerial challenges that may not be fully captured through large-scale quantitative approaches. Therefore, the case provides empirical evidence regarding the practical applicability of FMEA as a structured decision-support approach for sustainable supply chain risk management.

5.1. Case Context, Selection Rationale, and Research Boundaries

The empirical investigation was conducted in a medium-sized Egyptian manufacturing firm specializing in electrical control panel production. The organization was purposively selected based on its theoretical relevance to the research objectives and its representation of an import-dependent manufacturing supply chain. The firm relies significantly on imported raw materials, electrical components, and specialized production inputs that are essential for maintaining continuous operations. This sourcing configuration exposes the organization to multiple external uncertainties, including supplier delivery variability, international transportation disruptions, customs clearance delays, foreign exchange fluctuations, and changes in global supply conditions.

The selected firm represents an important supply chain configuration in which operational performance is strongly influenced by external dependencies. Unlike supply chains supported primarily by local sourcing networks, import-dependent systems are characterized by longer replenishment cycles, reduced substitution opportunities, and increased exposure to international market disruptions. In such environments, disturbances originating outside organizational boundaries can rapidly affect internal operations, creating challenges related to production continuity, inventory stability, and customer responsiveness. Therefore, the case provides a relevant empirical setting for investigating how FMEA can support the identification and prioritization of supply chain risks under conditions of uncertainty.

The suitability of the case is further supported by the characteristics of electrical control panel manufacturing. The production process requires coordination among multiple interconnected activities, including international supplier management, procurement, incoming material inspection, production planning, inventory control, logistics coordination, and quality assurance. Many electrical components require specific technical specifications and have limited short-term replacement alternatives. Consequently, disruptions affecting critical suppliers or imported materials may generate cascading operational consequences, including production delays, increased inventory pressure, schedule instability, and reduced delivery reliability.

Beyond the organizational level, the case reflects broader challenges experienced by manufacturing firms operating in emerging economies. Such firms frequently face structural constraints, including limited supplier diversification, dependence on imported technologies and materials, exchange-rate uncertainty, infrastructure limitations, and restricted resources for implementing advanced risk management systems. These conditions increase the importance of practical and transparent risk assessment approaches that enable organizations to identify critical vulnerabilities and prioritize mitigation efforts. Therefore, the investigated firm provides empirical evidence from an underrepresented context within the SSCRA literature.

Nevertheless, the contextual boundaries of the study should be explicitly recognized. The research adopts a single-case study design; therefore, the findings should not be interpreted as statistically representative of all manufacturing organizations or geographical contexts. Instead, the study follows an exploratory case study approach aimed at generating analytical insights into FMEA-based SSCRA implementation within a specific organizational and institutional environment. The identified failure modes, risk priorities, and managerial implications are influenced by the characteristics of the investigated firm, including its industrial sector, organizational scale, supply chain structure, import dependency, supplier relationships, and operational capabilities.

Accordingly, the contribution of the case study lies in analytical transferability rather than statistical generalization. Organizations operating under comparable conditions—such as dependence on imported materials, supplier uncertainty, exposure to international disruptions, and limited supply chain flexibility—may find the identified risk categories and assessment approach applicable. However, differences in technological maturity, regulatory environments, supplier networks, and sustainability capabilities should be considered when transferring these findings to other contexts. Future research employing multiple-case studies and cross-country comparisons is encouraged to further validate the broader applicability of FMEA-based SSCRA approaches.

5.2 Research Design, Expert Selection, and Data Collection

A qualitative triangulated research design was adopted to ensure a comprehensive assessment of supply chain risks. The study integrated semi-structured interviews, direct observations, and internal document analysis to capture different dimensions of supply chain vulnerability. This methodological approach was selected because supply chain risks are multidimensional and frequently emerge from interactions among multiple organizational functions rather than from isolated operational failures. Combining different evidence sources improves research credibility by enabling comparison between managerial perceptions, observed operational practices, and documented organizational information.

The expert assessment involved eight senior managers representing procurement, production, logistics, inventory management, and quality assurance functions. The experts were selected using purposive sampling based on their ability to provide informed and context-specific judgments regarding supply chain risks. Rather than determining the sample size based on numerical requirements, participant adequacy was evaluated according to expertise relevance, functional coverage, and information sufficiency.

Four selection criteria guided expert participation. First, participants were required to have direct responsibility or involvement in supply chain-related activities, including sourcing, production planning, inventory control, logistics coordination, or quality management. Second, participants were required to possess substantial professional experience within their respective functional areas to ensure familiarity with operational challenges and disruption patterns. Third, participants needed comprehensive knowledge of the firm's supply chain structure, including supplier relationships, material flows, operational dependencies, and historical disruptions. Fourth, participants were required to have experience in operational decision-making processes related to risk identification, evaluation, or mitigation.

The selected experts provided complementary perspectives across the supply chain. Procurement managers contributed knowledge regarding supplier performance, import dependency, sourcing constraints, and material availability risks. Production managers provided insights into manufacturing disruptions, process limitations, and operational reliability challenges. Logistics and inventory managers contributed expertise related to transportation uncertainty, stock availability, lead-time variability, and material flow disruptions. Quality managers supported the evaluation of failure consequences, process reliability, and detection capability. This cross-functional representation reduced the possibility of functional bias and enabled a more comprehensive assessment of supply chain vulnerabilities.

The adequacy of the eight experts was further supported through the assessment of information saturation. The expert elicitation process continued until additional discussions and evaluations did not generate substantially new failure modes, risk categories, or underlying causes. The repeated identification of similar risk patterns across different functional perspectives indicated convergence of expert knowledge and sufficient information coverage within the studied organizational context. Therefore, the number of experts was considered appropriate for the exploratory objectives of this single-case investigation.

Based on the expert evaluation process, 30 supply chain failure modes were identified across procurement, production, inventory, logistics, external environment, and supporting system domains. Each failure mode was assessed according to the traditional FMEA criteria of Severity (S), Occurrence (O), and Detection (D). The resulting Risk Priority Numbers (RPNs) were calculated to prioritize risks and identify the failure modes requiring greater managerial attention.

Although classical FMEA has been criticized for limitations associated with equal weighting assumptions, uncertainty representation, and potential ranking inconsistencies, it remains widely used in industrial practice because of its simplicity, transparency, and practical interpretability. In this study, the traditional FMEA approach was appropriate because the research objective was to develop an empirically grounded understanding of supply chain vulnerabilities and provide managers with a structured mechanism for risk prioritization and mitigation planning.

Table 2. Failure Modes and Root Causes.

Category	#	Failure Mode	Root Cause
1) Supplier & Procurement (F1)	F11	Supplier delivery delays	Ineffective supplier planning, coordination, and scheduling systems
	F12	Raw material shortages	Structural supply–demand imbalance and suboptimal sourcing strategy design
	F13	Supplier quality variability	Insufficient supplier quality assurance systems and limited monitoring capability

	F14	Exchange rate volatility affects imports	High dependency on foreign procurement and exposure to macroeconomic fluctuations
	F15	Supplier capacity constraints	Limited supplier scalability and constrained production expansion capability
	F16	Lack of supplier diversification	Overdependence on a narrow supplier base and restricted sourcing flexibility
	F17	Ineffective supplier communication	Weak information-sharing mechanisms and an underdeveloped coordination infrastructure
2) Demand & Planning (F2)	F21	Demand forecasting inaccuracies	Data quality limitations and inadequate forecasting methodologies
	F22	Production scheduling instability	Weak integration between demand planning and production control systems
	F23	Order cancellations and abrupt modifications	High demand, volatility, and weak order management governance mechanisms
3) Production & Operations (F3)	F31	Equipment failures	Asset aging and insufficient preventive maintenance strategy execution
	F32	Human errors in production processes	Lack of standardized operating procedures and insufficient workforce training systems
	F33	Labor skill gaps	Workforce competency deficiencies and limited capability development investment
	F34	Production defects requiring rework	Process variability and weak in-process quality assurance controls
	F35	Ineffective preventive maintenance systems	Reactive maintenance orientation and absence of predictive maintenance capabilities
4) Inventory & Warehouse (F4)	F41	Excess inventory of low-demand items	Forecasting inaccuracies and inefficient inventory optimization logic
	F42	Stockouts of critical materials	Ineffective replenishment policies and weak planning synchronization mechanisms
	F43	Lack of real-time inventory visibility	Limited digital integration and reliance on legacy inventory information systems
	F44	Inaccurate inventory records	Manual data entry processes and weak data validation and control systems
	F45	Warehouse space inefficiency	Suboptimal warehouse layout design and inadequate space utilization planning
	F46	Obsolete or slow-moving inventory accumulation	Weak inventory lifecycle governance and persistent demand–supply misalignment
5) Logistics & Distribution	F51	Transportation delays	Infrastructure constraints and inefficient transport planning systems

(F5)	F52	Unreliable third-party logistics (3PL) providers	Weak performance monitoring frameworks and limited contractual enforcement mechanisms
	F53	Packaging and shipment errors	Lack of standardized handling procedures and operational compliance weaknesses
	F54	Inefficient logistics coordination	Fragmented logistics systems and weak inter-organizational integration
6) External & Regulatory (F6)	F61	Customs clearance delays	Complex regulatory procedures and documentation inefficiencies
	F62	Energy supply disruptions	Infrastructure instability and exposure to external supply shocks
	F63	Regulatory and import policy instability	Frequent policy changes and weak regulatory predictability mechanisms
7) Systems & Digital (F7)	F71	ERP system downtime	IT infrastructure limitations and insufficient system resilience design
	F72	Cybersecurity threats in supply chain systems	System vulnerabilities and weak cybersecurity governance frameworks

6. RESULTS AND DISCUSSION

This section presents and interprets the results of the Failure Mode and Effects Analysis (FMEA) applied to assess and prioritize sustainable supply chain risks in the studied manufacturing firm. The analysis encompasses 30 identified failure modes spanning procurement, production, inventory, logistics, external environment, and digital systems. Each failure mode is evaluated using Severity (S), Occurrence (O), and Detection (D) scores, which are aggregated into Risk Priority Numbers (RPNs) to enable structured prioritization under uncertainty. While the RPN outputs provide a quantitative ranking mechanism, the analytical emphasis here extends beyond prioritization toward explaining the underlying system structure governing risk distribution, interdependencies, and cascade behavior in an import-dependent manufacturing environment.

Table 3 summarizes the FMEA-based evaluation and prioritization of 30 supply chain failure modes across seven functional domains. The results indicate that the most critical risks are concentrated in upstream procurement and planning activities, particularly supplier delivery delays, raw material shortages, supplier quality variability, and demand forecasting inaccuracies. External factors such as exchange rate volatility and customs clearance delays further increase system vulnerability. In contrast, production, inventory, logistics, and digital risks generally exhibit moderate to low RPN values. Overall, the findings suggest that supply chain performance is primarily constrained by supplier dependency, planning inefficiencies, and external uncertainty, emphasizing the importance of proactive risk mitigation to strengthen resilience and sustainability.

The results reveal a highly skewed and structurally concentrated risk landscape, where a limited number of upstream failure modes account for a disproportionate share of system-wide vulnerability. In particular, supplier delivery delays (RPN = 504) and raw material shortages (RPN = 448) emerge as dominant risk drivers, indicating that supply chain instability is primarily rooted in external supply-side dependence rather than internal operational inefficiencies. This pattern reflects a structurally embedded exposure typical of import-dependent systems, where external volatility is directly translated into internal disruption dynamics through tightly coupled procurement channels. Although downstream logistics, production, and digital risks exhibit lower individual RPN values, their systemic relevance remains significant due to their role in propagating, transforming, and amplifying upstream disturbances once they enter the system.

From a complex adaptive systems perspective, the observed risk structure exhibits a pronounced upstream-to-downstream cascade topology characterized by asymmetric vulnerability distribution and nonlinear propagation pathways.

1) Supplier and procurement risks function as the primary entry points of exogenous disturbances and therefore constitute the dominant cascade initiation layer. High-impact drivers such as supplier capacity constraints, exchange rate volatility, limited supplier diversification, and inconsistent supplier performance collectively indicate a structurally fragile sourcing architecture with low redundancy and high external coupling. This configuration increases the sensitivity of the entire system to marginal upstream fluctuations, which can escalate into disproportionate downstream instability through reinforcing interdependencies.
2) Demand and planning risks further intensify systemic fragility by weakening the integrity of feedback loops between environmental signals and operational decision-making processes. Forecasting inaccuracies and production scheduling disruptions indicate degraded information fidelity across planning layers, where delays, noise, and misalignment between data and execution generate persistent control lags. This produces a feedback distortion regime in which the system shifts from anticipatory optimization to reactive adjustment, resulting in oscillatory production and inventory dynamics. Such behavior is consistent with delayed negative feedback systems in which corrective actions are systematically misaligned with actual system states, thereby amplifying rather than dampening variability.
3) Production and operations risks, while moderate in RPN magnitude, represent a critical endogenous stability layer that determines the system's absorptive and adaptive capacity. Equipment failures, human errors, labor skill deficiencies, and weak preventive maintenance practices collectively indicate limited operational robustness and process maturity. Importantly, these risks exhibit strong interdependence, where localized failures propagate through tightly coupled operational routines, increasing conditional failure probabilities across adjacent subsystems. These produces reinforcing internal feedback loops that erode redundancy and reduce the system's ability to absorb external shocks without performance degradation.
4) Inventory and warehouse risks reveal structural breakdowns in demand–supply synchronization and informational coherence. The coexistence of stockouts, excess inventory, and obsolete materials reflects inconsistent demand interpretation and weak real-time visibility across the supply chain. Rather than functioning as a stabilizing buffer, the inventory system operates as a variability amplification mechanism, where information delays and forecasting errors generate oscillatory adjustment behavior. This pattern is indicative of bullwhip-like dynamics, in which local decision rules under delayed feedback conditions produce system-wide instability.
5) Logistics and distribution risks constitute downstream sensitivity nodes that translate internal system variability into external performance outcomes. Transportation delays, third-party logistics unreliability, and coordination inefficiencies do not merely represent execution failures but act as terminal transmission channels through which upstream and midstream disturbances are consolidated into customer-facing disruptions. Although their individual RPN values are relatively moderate, their systemic significance is amplified by their position at the output boundary of the supply chain, where they directly determine lead time reliability and service performance.
6) External and regulatory risks operate as exogenous volatility fields that define the boundary conditions of system behavior. Customs clearance delays, energy supply disruptions, and regulatory instability introduce externally generated uncertainty that cannot be mitigated internally but significantly shapes system dynamics. These factors function as multiplicative shock amplifiers, increasing both the propagation speed and systemic reach of endogenous disruptions by reducing environmental predictability and constraining operational flexibility. In import-dependent systems, this external layer becomes a persistent source of structural instability rather than episodic disturbance.
7) System and digital risks, including ERP downtime and cybersecurity threats, currently exhibit lower RPN values but represent latent high-impact structural dependencies. Their systemic importance lies in their cross-functional coupling capacity, as they simultaneously govern information processing, coordination efficiency, and decision execution across the entire supply chain. Consequently, disruptions in digital infrastructure generate synchronized failures across multiple subsystems, producing non-localized systemic breakdowns. With increasing digitalization, these risks are expected

to transition from peripheral vulnerabilities to central determinants of system stability, exposing inherent limitations of classical FMEA in capturing low-frequency, high-consequence systemic disruptions.

Overall, the findings demonstrate that the supply chain operates as a tightly coupled complex adaptive system characterized by nonlinear interdependencies, feedback delays, and cascade propagation dynamics. Risk is structurally concentrated in upstream procurement and planning functions, while downstream and supporting subsystems function as transmission, amplification, and consolidation layers within a multi-level system architecture. Six interacting mechanisms govern system behavior: upstream dependency concentration, feedback distortion in planning systems, endogenous operational fragility, inventory variability amplification, downstream sensitivity concentration, and exogenous volatility forcing. These mechanisms interact through reinforcing feedback loops that generate emergent instability, cross-functional propagation, and system-wide risk amplification. Accordingly, the results empirically substantiate the need to move beyond silo-based risk assessment toward a system-oriented SSCRM paradigm grounded in interdependency-aware modeling, cascade-sensitive governance, and resilience-oriented supply chain architecture design.

Figure 4 presents the FMEA-based prioritization and distribution of 30 identified supply chain failure modes within the studied manufacturing firm. The left panel ranks the ten most critical failure modes according to their Risk Priority Numbers (RPNs), revealing that supplier delivery delays (RPN = 504) and raw material shortages (RPN = 448) constitute the most severe risks, followed by forecasting inaccuracies, production scheduling disruptions, and supplier capacity constraints.

These results indicate that the highest-risk issues are concentrated in upstream procurement and planning activities rather than in downstream operational processes. The right panel illustrates the distribution of failure modes across supply chain functions, showing that procurement accounts for the largest share (30%), followed by planning and production (20% each), logistics (16.7%), and inventory and digital systems (6.7% each).

Collectively, the figure demonstrates that supply chain vulnerability is structurally concentrated in supplier-dependent and coordination-intensive functions, highlighting the dominant influence of external supply uncertainty and planning inefficiencies on overall system performance. The findings further suggest that effective risk mitigation efforts should prioritize strengthening supplier management, sourcing resilience, demand forecasting accuracy, and cross-functional coordination to enhance overall supply chain resilience and sustainability.

Table 3. FMEA-Based Evaluation and Prioritization of Supply Chain Failure Modes

Category	#	S	O	D	RPN	Rank	Risk Level
1) Supplier & Procurement	F11	9	8	7	504	1	Extreme
	F12	8	8	7	448	2	Extreme
	F13	8	7	6	336	3	High
	F14	9	6	6	324	4	High
	F15	8	6	6	288	5	High
	F16	8	5	6	240	9	High
	F17	6	5	5	150	13	Medium
2) Demand & Planning	F21	7	7	6	294	6	High
	F22	8	6	6	288	7	High
	F23	7	5	5	175	11	Medium
3) Production & Operations	F31	7	5	5	175	11	Medium
	F32	6	5	5	150	13	Medium
	F33	6	5	5	150	13	Medium

	F34	7	4	5	140	14	Low–Medium
	F35	7	5	4	140	14	Low–Medium
4) Inventory & Warehouse	F41	5	6	6	180	10	Medium
	F42	7	5	5	175	11	Medium
	F43	7	5	5	175	11	Medium
	F44	6	5	5	150	13	Medium
	F45	5	6	5	150	13	Medium
	F46	6	5	5	150	13	Medium
5) Logistics & Distribution	F51	6	6	5	180	10	Medium
	F52	7	4	5	140	14	Low–Medium
	F53	5	4	4	80	25	Low
	F54	6	4	5	120	20	Low
6) External & Regulatory	F61	7	6	6	252	8	High
	F62	8	4	4	128	21	Low–Medium
	F63	8	4	5	160	18	Medium
7) System & Digital	F71	7	4	4	112	22	Low
	F72	8	3	4	96	24	Low

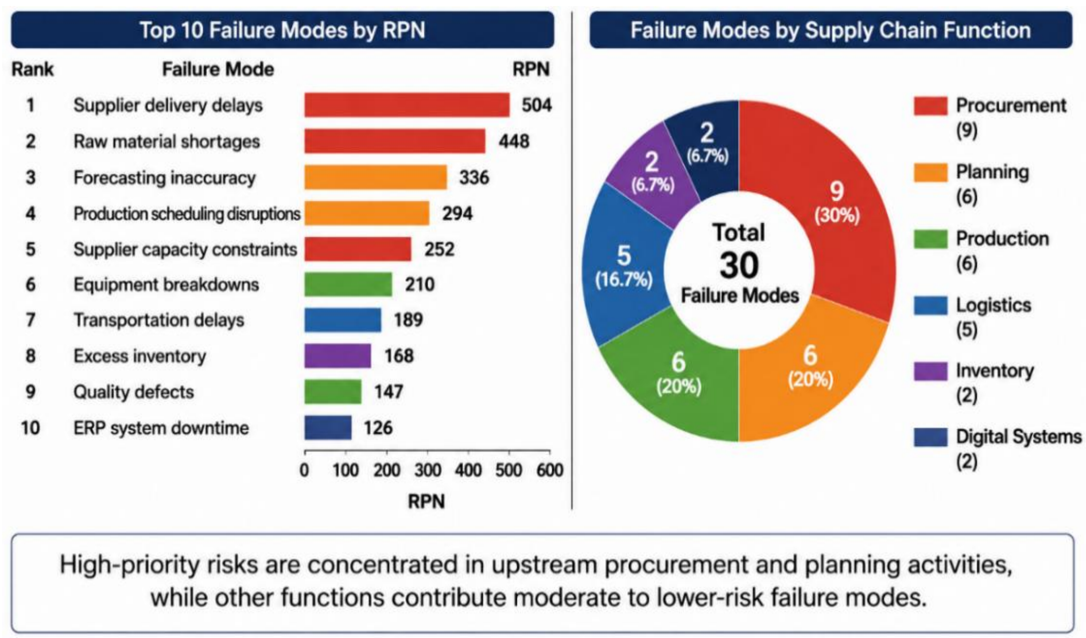

Figure 4. FMEA-Based Prioritization and Distribution of Supply Chain Failure Modes

7. CONCLUSION AND FUTURE WORK

This study addressed the increasing need for robust Sustainable Supply Chain Risk Assessment (SSCRA) under conditions of uncertainty, complexity, and sustainability-driven constraints. By integrating a systematic literature review (2010–2026) with an empirical case study, the research identified key limitations in existing SSCRA approaches and repositioned Failure Mode and Effects Analysis (FMEA) as a structured, system-oriented multi-criteria framework for sustainable supply chain risk analysis.

The literature review confirms that current SSCRA methods remain limited in their ability to represent risk interdependencies, cascading disruptions, and dynamic system behavior. These limitations are particularly critical in sustainable supply chains, where risks are inherently interconnected and propagate across multiple tiers and sustainability dimensions. In this regard, the study demonstrates that FMEA, when reconceptualized beyond a conventional ranking tool, can better capture structured failure relationships and support more systematic sustainability-oriented risk prioritization.

The empirical case study of a medium-sized Egyptian manufacturing firm further supports these findings. The results indicate that supply chain risk exposure is primarily concentrated in upstream activities, particularly supplier reliability issues, raw material shortages, currency fluctuations, and demand forecasting errors. These risks are strongly interdependent and collectively contribute to cascading disruptions, operational instability, and reduced system resilience. The findings emphasize that supply chain vulnerability in emerging economies is driven not only by individual risk factors but also by structural interdependencies and external environmental uncertainty.

Despite these contributions, several limitations should be acknowledged. First, the single-case study design limits the generalizability of the findings across different industries and supply chain configurations. Second, although FMEA offers interpretability and practical usability, it still relies on simplifying assumptions, particularly the partial independence among risk factors. Third, the proposed framework does not incorporate real-time, data-driven, or Industry 4.0-enabled monitoring capabilities.

Overall, this study contributes to both theory and practice by bridging sustainability-oriented risk perspectives with structured analytical modeling, offering a more integrated and system-oriented foundation for managing risks in sustainable supply chains.

Theoretical Implications: The study advances SSCRM theory by repositioning FMEA as a structural diagnostic framework for capturing interdependent and cascading risk architectures, strengthening the link between risk prioritization and system-level vulnerability analysis in uncertain and resource-constrained environments.

Practical Implications: The proposed framework provides a transparent and replicable decision-support tool that enhances risk visibility and supports prioritization of mitigation efforts, particularly in upstream and planning-related vulnerabilities.

Managerial Implications: Managers should prioritize strengthening upstream supply resilience through supplier diversification, strategic sourcing, and procurement coordination. In addition, improving demand forecasting, planning integration, and cross-functional information sharing is essential to reduce risk propagation and enhance resilience.

Study Limitations: This study has several limitations that should be considered when interpreting its findings. First, the single-case study design limits the extent to which the results can be generalized across different industries, organizational settings, and supply chain configurations. Second, although FMEA is valued for its interpretability and practical applicability, it is based on simplifying assumptions—particularly the partial independence among risk factors—which may not fully reflect the complex interdependencies observed in real-world supply chains. Third, the proposed framework does not integrate real-time data analytics or Industry 4.0-enabled technologies, which makes the analysis largely static and less capable of capturing dynamic changes in risk conditions over time.

Future Research Directions: Future research should adopt multi-case and cross-country designs to validate the robustness of observed risk concentration patterns. Methodologically, extensions such as fuzzy-FMEA, grey-FMEA, and Bayesian FMEA, as well as integration with MCDM techniques (e.g., DEMATEL, AHP, TOPSIS), are recommended to better capture uncertainty and interdependencies. In addition, future studies should move toward dynamic modeling approaches by integrating system dynamics, complex network theory, or agent-based modeling to explicitly capture feedback loops and cascading failures. The incorporation of Industry 4.0 technologies—such as digital twins, AI-driven analytics, real-time sensing, and blockchain—also represents a promising direction for improving predictive and adaptive risk management capabilities. Finally, future research should establish longitudinal and causal relationships between FMEA-based risk prioritization and sustainability performance outcomes, enabling a shift from descriptive assessment toward prescriptive and impact-oriented SSCRA frameworks.

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Data Availability Statement: All data supporting this study are contained within the article.

ABBREVIATIONS

Abbreviation	Full Term	Definition
AHP	Analytic Hierarchy Process	Pairwise comparison method for weighting and ranking.
AI	Artificial Intelligence	Systems performing tasks requiring human intelligence.
ANP	Analytic Network Process	MCDM method capturing interdependencies among criteria.
BWM	Best–Worst Method	Efficient pairwise comparison method for deriving weights.
DFMEA	Design Failure Mode and Effects Analysis	FMEA focused on design-stage failures.
FMEA	Failure Mode and Effects Analysis	Method for identifying and prioritizing failure modes.
IFS	Intuitionistic Fuzzy Sets	Fuzzy sets with membership, non-membership, and hesitation.
IoT	Internet of Things	Connected devices enabling real-time data exchange.
ISM	Interpretive Structural Modeling	Method for hierarchical structuring of system elements.
IT2FS	Interval Type-2 Fuzzy Sets	Advanced fuzzy sets for high uncertainty modeling.
MADM	Multi-Attribute Decision-Making	Decision methods for evaluating discrete alternatives.
MCDM	Multi-Criteria Decision-Making	Methods for decisions with multiple conflicting criteria.
PFMEA	Process Failure Mode and Effects Analysis	FMEA focused on process failures.
PFS	Pythagorean Fuzzy Sets	Extended fuzzy sets for uncertainty modeling.
RPN	Risk Priority Number	Score used to prioritize risks in FMEA.
SCM	Supply Chain Management	Management of supply chain activities.

SFMEA	Social Failure Mode and Effects Analysis	FMEA for social sustainability risks.
SSCRA	Sustainable Supply Chain Risk Assessment	Risk assessment considering sustainability factors.
SSCM	Sustainable Supply Chain Management	Integration of sustainability into supply chains.
SCRM	Supply Chain Risk Management	Process of managing supply chain risks.

REFERENCES

[1] Anugerah AR, Ahmad SA, Samin R, Samdin Z, Kamaruddin N. Modified failure mode and effect analysis to mitigate sustainable related risk in the palm oil supply chain. *Advances in Materials and Processing Technologies*. 2022;8(2):2229-2243.
[2] Silva USKD, Paul A, Hasan KW, Paul SK, Ali SM, Chakrabortty RK. Examining risks and strategies for the spice processing supply chain in the context of an emerging economy. *International Journal of Emerging Markets*. 2023;18(5):1124-1146.
[3] Gomaa AH. Supply Chain Risk Management for Sustainable and Resilient Operations: A Comprehensive Review and Strategic Framework in the Era of Industry 4.0-5.0. *Transnational Supply Chain Research*. 2026;2(1):1-23.
[4] Bastas A, Liyanage K. Sustainable supply chain quality management: A systematic review. *Journal of cleaner production*. 2018;181:726-744.
[5] Liu P, Atifeh M, Khorshidnia M, Taheri SG. System dynamics: An approach to modeling supply chain performance measurement. *Technological and Economic Development of Economy*. 2023;29(4):1291-1317.
[6] Zaman SI, Kusi-Sarpong S. Identifying and exploring the relationship among the critical success factors of sustainability toward consumer behavior. *Journal of modelling in management*. 2024;19(2):492-522.
[7] Stephen G. Business Continuity and Risk Mitigation in the Pharmaceutical Industry: Strengthening Supply Chains for Pandemic Preparedness. *International Journal of Scientific Research and Management (IJSRM)*. 2025;13(02):8398-8412.
[8] Zhang A, Wang JX, Farooque M, Wang Y, Choi TM. Multi-dimensional circular supply chain management: A comparative review of the state-of-the-art practices and research. *Transportation Research Part E: Logistics and Transportation Review*. 2021;155:102509.
[9] Vishnu CR, Sridharan R, Kumar PR. Supply chain risk management: models and methods. *International Journal of Management and Decision Making*. 2019;18(1):31-75.
[10] Akhavan P, Philsoophian M. Improving of supply chain collaboration and performance by using block chain technology as a mediating role and resilience as a moderating variable. *Journal of the Knowledge Economy*. 2023;14(4):4561-4582.
[11] Valinejad F, Rahmani D. Sustainability risk management in the supply chain of telecommunication companies: A case study. *Journal of Cleaner Production*. 2018;203:53-67.
[12] Chowdhury MMH, Chowdhury M, Khan EA, Sajib S. Supply chain relational capital for sustainability through governance: the moderating effect of network complexity. *Supply Chain Management: An International Journal*. 2023;28(2):347-362.
[13] Baah C, Acquah ISK, Ofori D. Exploring the influence of supply chain collaboration on supply chain visibility, stakeholder trust, environmental and financial performances: a partial least square approach. *Benchmarking: An International Journal*. 2022;29(1):172-193.

[14] Tran TH, Dobrovnik M, Kummer S. Supply chain risk assessment: a content analysis-based literature review. *International Journal of Logistics Systems and Management*. 2018;31(4):562-591.
[15] Babu H, Bhardwaj P, Agrawal AK. Modelling the supply chain risk variables using ISM: a case study on Indian manufacturing SMEs. *Journal of Modelling in Management*. 2021;16(1):215-239.
[16] Nayal K, Raut RD, Narkhede BE, Priyadarshinee P, Panchal GB, Gedam VV. Antecedents for blockchain technology-enabled sustainable agriculture supply chain. *Annals of operations research*. 2023;327(1):293-337.
[17] Keyghobadi AR, Ebadi A, Yeganegi MR, Motadel MR. The analysis of sustainable supply chain risks based on the FMEA method in the oil and gas industry and factors affecting risk management. *Petroleum Business Review*. 2020;4(1):95-116.
[18] Umar M, Wilson MM. Inherent and adaptive resilience of logistics operations in food supply chains. *Journal of Business Logistics*. 2024;45(1):e12362.
[19] Guntuka L, Corsi TM, Cantor DE. Recovery from plant-level supply chain disruptions: supply chain complexity and business continuity management. *International Journal of Operations & Production Management*. 2024;44(1):1-31.
[20] Balan S, Handfield R. An integrated supply chain risk mitigation tool--model, analysis and insights. *International Journal of Management Science and Engineering Management*. 2025;20(2):225-240.
[21] Bubicz ME, Moreira C, Ferasso M, Sellitto MA, Carvalho A, Barbosa-Póvoa APFD. Risk Management assessment of social sustainability in supply chains: a Bayesian Network model proposal. In: *Supply Chain Forum: An International Journal*. Taylor & Francis; 2026. p. 1-26.
[22] Chen Y, Chen IJ. Mixed sustainability motives, mixed results: the role of compliance and commitment in sustainable supply chain practices. *Supply Chain Management: An International Journal*. 2019;24(5):622-636.
[23] Miemczyk J, Luzzini D. Achieving triple bottom line sustainability in supply chains: The role of environmental, social and risk assessment practices. *International Journal of Operations & Production Management*. 2019;39(2):238-259.
[24] Bag S. Deconstructing Tensions in the Adoption of Digital Innovation in Sustainable Supply Chain Management: A Qualitative Study. *Sustainable Development*. 2025;33(6):8008-8024.
[25] Ikasari DM, Suef M, Vanany I. A Bibliometric Analysis of Risk Management and Sustainability in the Agri-Food Supply Chain: Future Directions. *Engineering Proceedings*. 2025;84(1):13.
[26] Giannakis M, Papadopoulos T. Supply chain sustainability: A risk management approach. *International journal of Production Economics*. 2016;171:455-470.
[27] Marshall D, McCarthy L, Heavey C, McGrath P. Environmental and social supply chain management sustainability practices: construct development and measurement. *Production Planning & Control*. 2015;26(8):673-690.
[28] Both CM, Wilhelm M. Supply Chain Sustainability Risk Management in the Era of Mandatory Due Diligence: A Literature Review. *Journal of Purchasing and Supply Management*. 2025;32:101083.
[29] Jain S, Sigurðardóttir S, Lindskog E, Andersson J, Skoogh A, Johansson B. Multi-resolution modeling for supply chain sustainability analysis. In: *2013 winter simulations conference (WSC)*. IEEE; 2013. p. 1996-2007.
[30] Razak SEA, Mustapha M, Kasim NAA, Shah SM. Sustainability risk management using failure mode effect analysis: evidence from Malaysia. *European Journal of Molecular & Clinical Medicine*. 2020;7(3):220-239.
[31] Wang L, Rani P. Sustainable supply chains under risk in the manufacturing firms: an extended double normalization-based multiple aggregation approach under an intuitionistic fuzzy environment. *Journal of Enterprise Information Management*. 2022;35(4-5):1067-1099.
[32] Edalatpour MA, Al-e SMJM, Ghasemi S. Harmonizing Project Management and Supply Chain for Sustainable Construction: A Comprehensive Mathematical Model and Case Study. *Sustainable Futures*. 2025:100805.

[33] Narimissa O, Kangarani-Farahani A, Molla-Alizadeh-Zavardehi S. Evaluation of sustainable supply chain management performance: Dimensions and aspects. *Sustainable Development*. 2020;28(1):1-12.
[34] Pacheco DADJ, Clausen DM. Sustainable purchasing supply management assessment in construction supply chains: a design science research approach. *Supply Chain Management: An International Journal*. 2024;29(6):943-962.
[35] Zhou X, Jiang J, Zhou C, Li X, Yin M. Circular supply chain management: Antecedent effect of social capital and big data analysis capability and their impact on sustainable performance. *Sustainable Development*. 2024;32(5):5311-5330.
[36] Huang DH. Evaluation and management of sustainable supply chain systems with carbon emissions and transport damage based on multi-state system reliability assessment. *Reliability Engineering & System Safety*. 2025;257:110821.
[37] Roy V, Schoenherr T, Charan P. The thematic landscape of literature in sustainable supply chain management (SSCM) A review of the principal facets in SSCM development. *International Journal of Operations & Production Management*. 2018;38(4):1091-1124.
[38] Hajmohammad S, Klassen RD, Vachon S. Managing supplier sustainability risk: an experimental study. *Supply Chain Management: An International Journal*. 2024;29(1):50-67.
[39] Bustinza OF, Vendrell-Herrero F, Jabbour CJC. Integration of product-service innovation into green supply chain management: Emerging opportunities and paradoxes. *Technovation*. 2024;130:102923.
[40] Ngo VM, Quang HT, Hoang TG, Binh ADT. Sustainability-related supply chain risks and supply chain performances: The moderating effects of dynamic supply chain management practices. *Business Strategy and the environment*. 2024;33(2):839-857.
[41] Wang Z, Ran Y, Yu H, Jin C, Zhang G. Failure mode and effects analysis using function--motion--action decomposition method and integrated risk priority number for mechatronic products: FMEA using FMA decomposition method and IRPN for MPs. *Quality and Reliability Engineering International*. 2021;37(6):2875-2899.
[42] Gomaa AH. Maintenance process improvement framework using lean six sigma: A case study. *International Journal of Business & Administrative Studies*. 2023;9(1):1-25.
[43] Li J, Zhang Y, Fang H, Fang S. Risk evaluation of photovoltaic power systems: An improved failure mode and effect analysis under uncertainty. *Journal of Cleaner Production*. 2023;414:137620.
[44] Gomaa AH. Enhancing Failure Mode and Effects Analysis with Industry 4.0 (FMEA 4.0): A Comprehensive Review and Strategic Framework. *International Journal of Darshan Institute of Engineering Research and Emerging Technologies*. 2025;14(2):1-12.
[45] Schneider D, Woerle M, Kagermeier J, Zaeh MF, Reinhart G. Sustainability risk assessment in manufacturing: A life cycle assessment-based failure mode and effects analysis approach. *Sustainable Production and Consumption*. 2024;47:617-631.
[46] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. *Journal of Clinical Epidemiology*. 2021;134:103-112.
[47] Hamdan B, Diabat A. Robust design of blood supply chains under risk of disruptions using Lagrangian relaxation. *Transportation research part E: logistics and transportation review*. 2020;134:101764.
[48] Colicchia C, Creazza A, Menachof DA. Managing cyber and information risks in supply chains: insights from an exploratory analysis. *Supply Chain Management: An International Journal*. 2019;24(2):215-240.
[49] Ghadge A, Wurtmann H, Seuring S. Managing climate change risks in global supply chains: a review and research agenda. *International Journal of Production Research*. 2020;58(1):44-64.
[50] Trkman P, McCormack K. Supply chain risk in turbulent environments---A conceptual model for managing supply chain network risk. *International journal of production economics*. 2009;119(2):247-258.

[51] Hamida HB, Aloui C. The Influence of Global Risks on Supply Chain Tokens' Intra-Market Dynamics. *Engineering, Technology & Applied Science Research*. 2025;15(6):28427-28431.
[52] Chepkwemoi AN, Oteki EB, Otieno RJ. Role of supply chain risk management on operational performance of manufacturing firms in Nairobi City County, Kenya. 2025.
[53] Al-Kharabsheh A, Mkheimer I, Assaf N, Alkhrabsheh A, Mohammad AM. The role of supply chain collaborative in enhancing sustainability through supply chain risk management. *Production*. 2026;36:e20250076.
[54] Kumar V, Bak O, Guo R, Shaw SL, Colicchia C, Garza-Reyes JA, et al. An empirical analysis of supply chain risk assessment in the automotive industry. *International Journal of Logistics Research and Applications*. 2018;21(4):396-418.
[55] Paul SK, Sarker R, Essam D. Managing risk and disruption in production-inventory and supply chain systems: A review. *Journal of Industrial and Management Optimization*. 2016;12(3):1009-1029.
[56] Junaid M, Xue Y, Syed MW, Li JZ, Ziaullah M. A neutrosophic ahp and topsis framework for supply chain risk assessment in automotive industry of Pakistan. *Sustainability*. 2019;12(1):154.
[57] Prashar A, Aggarwal S. Modeling enablers of supply chain quality risk management: a grey-DEMATEL approach. *The TQM Journal*. 2020;32(5):1059-1076.
[58] Dupont L, Bernard C, Hamdi F, Masmoudi F. Supplier selection under risk of delivery failure: a decision-support model considering managers' risk sensitivity. *International Journal of Production Research*. 2018;56(3):1054-1069.
[59] Chowdhury NA, Ali SM, Mahtab Z, Rahman T, Kabir G, Paul SK. A structural model for investigating the driving and dependence power of supply chain risks in the readymade garment industry. *Journal of Retailing and Consumer Services*. 2019;51:102-113.
[60] Lockamy III A, McCormack K. Examining operational risks in supply chains. In: *Supply Chain Forum: An International Journal*. Taylor & Francis; 2009. p. 2-14.
[61] Choudhury TT, Paul SK, Rahman HF, Jia Z, Shukla N. A systematic literature review on the service supply chain: research agenda and future research directions. *Production Planning & Control*. 2020;31(16):1363-1384.
[62] Bubicz ME, Barbosa-Póvoa APFD, Carvalho A. Incorporating social aspects in sustainable supply chains: Trends and future directions. *Journal of cleaner production*. 2019;237:117500.
[63] Mukhtar A, Romli A, Abdullateef M, Al-bashiri H. Environmental risks in supply chain: recommendations and directions for future research. In: *IOP Conference Series: Materials Science and Engineering*. IOP Publishing; 2019. p. 012034.
[64] Thapa SP, Shrestha S, Anal AK. Addressing the antibiotic resistance and improving the food safety in food supply chain (farm-to-fork) in Southeast Asia. *Food Control*. 2020;108:106809.
[65] Ahmed W, Ashraf MS, Khan SA, Kusi-Sarpong S, Arhin FK, Kusi-Sarpong H, et al. Analyzing the impact of environmental collaboration among supply chain stakeholders on firm's sustainable performance. *Operations Management Research*. 2020;13:198-215.
[66] Chen IJ, Paulraj A, Lado AA. Strategic purchasing, supply management, and firm performance. *Journal of Operations Management*. 2013;22(5):505-523.
[67] Carter CR, Liane Easton P. Sustainable supply chain management: evolution and future directions. *International journal of physical distribution & logistics management*. 2011;41(1):46-62.
[68] Dadhich P, Genovese A, Kumar N, Acquaye A. Developing sustainable supply chains in the UK construction industry: A case study. *International Journal of Production Economics*. 2015;164:271-284.
[69] Beske-Janssen P, Johnson MP, Schaltegger S. 20 years of performance measurement in sustainable supply chain management--what has been achieved?. *Supply chain management: An international Journal*. 2015;20(6):664-680.
[70] Beske P, Seuring S. Putting sustainability into supply chain management. *Supply Chain Management: an international journal*. 2014;19(3):322-331.

[71] Yun G, Yalcin MG, Hales DN, Kwon HY. Interactions in sustainable supply chain management: a framework review. *The International Journal of Logistics Management*. 2019;30(1):140-173.
[72] Kähkönen AK, Lintukangas K, Hallikas J. Sustainable supply management practices: making a difference in a firm's sustainability performance. *Supply Chain Management: An International Journal*. 2018;23(6):518-530.
[73] Gören HG. A decision framework for sustainable supplier selection and order allocation with lost sales. *Journal of Cleaner Production*. 2018;183:1156-1169.
[74] Meksavang P, Shi H, Lin SM, Liu HC. An extended picture fuzzy VIKOR approach for sustainable supplier management and its application in the beef industry. *Symmetry*. 2019;11(4):468.
[75] Esfahbodi A, Zhang Y, Watson G. Sustainable supply chain management in emerging economies: Trade-offs between environmental and cost performance. *International journal of production economics*. 2016;181:350-366.
[76] Xu M, Cui Y, Hu M, Xu X, Zhang Z, Liang S, et al. Supply chain sustainability risk and assessment. *Journal of cleaner production*. 2019;225:857-867.
[77] Freise M, Seuring S. Social and environmental risk management in supply chains: a survey in the clothing industry. *Logistics Research*. 2015;8(1):2.
[78] Majumdar A, Sinha SK, Govindan K. Determinants of sustainable supply chain management practices in Indian manufacturing firms. *Journal of Cleaner Production*. 2020;246:118999.
[79] Vafaeenezhad T, Tavakkoli-Moghaddam R, Cheikhrouhou N. Multi-objective mathematical modeling for sustainable supply chain management in the paper industry. *Computers & Industrial Engineering*. 2019;135:1092-1102.
[80] Kacar AS, Guldmann E, Tozanli O. The role of sustainability in supply chain management: A review. *International Journal of Production Research*. 2018;56(12):4014-4039.
[81] Wang K, Yan F, Zhang Y, Xiao Y, Gu L. Supply chain financial risk evaluation of small-and medium-sized enterprises under smart city. *Journal of advanced transportation*. 2020;2020(1):8849356.
[82] Hofmann H, Busse C, Bode C, Henke M. Sustainability-related supply chain risks: Conceptualization and management. *Business strategy and the environment*. 2014;23(3):160-172.
[83] Wang CN, Nguyen VT, Chyou JT, Lin TF, Nguyen TN. Fuzzy multicriteria decision-making model (MCDM) for raw materials supplier selection in plastics industry. *Mathematics*. 2019;7(10):981.
[84] Chowdhury MMH, Umme NJ, Nuruzzaman M. Strategies for mitigating supply-side barriers in the apparel supply chain: a study on the apparel industry of Bangladesh. *Global Journal of Flexible Systems Management*. 2018;19(Suppl 1):41-52.
[85] Song W, Ming X, Liu HC. Identifying critical risk factors of sustainable supply chain management: A rough strength-relation analysis method. *Journal of Cleaner Production*. 2017;143:100-115.
[86] Yan B, Wu J, Wang F. CVaR-based risk assessment and control of the agricultural supply chain. *Management Decision*. 2019;57(7):1496-1510.
[87] Abdel-Basset M, Mohamed R. A novel plithogenic TOPSIS-CRITIC model for sustainable supply chain risk management. *Journal of Cleaner production*. 2020;247:119586.
[88] Babazadeh R, Razmi J, Pishvaee MS, Rabbani M. A sustainable second-generation biodiesel supply chain network design problem under risk. *Omega*. 2017;66:258-277.
[89] Foerstl K, Reuter C, Hartmann E, Blome C. Managing supplier sustainability risks in a dynamically changing environment---Sustainable supplier management in the chemical industry. *Journal of Purchasing and Supply Management*. 2010;16(2):118-130.
[90] Phatak S, Sople V. Drivers and barriers of sustainable supply chain: A literature review on Indian perspective. *International Journal of Business Insights and Transformation*. 2018;12(1):17-25.
[91] Hadiguna RA. Decision support framework for risk assessment of sustainable supply chain. *International Journal of Logistics Economics and Globalisation*. 2012;4(1-2):35-54.
[92] Ghadge A, Dani S, Kalawsky R. Supply chain risk management: present and future scope. *The international journal of logistics management*. 2012;23(3):313-339.

[93] Mangla SK, Kumar P, Barua MK. Flexible decision approach for analysing performance of sustainable supply chains under risks/uncertainty. *Global Journal of Flexible Systems Management*. 2014;15(2):113-130.
[94] Mangla SK, Kumar P, Barua MK. Prioritizing the responses to manage risks in green supply chain: An Indian plastic manufacturer perspective. *Sustainable Production and Consumption*. 2015;1:67-86.
[95] Mangla SK, Kumar P, Barua MK. Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resources, Conservation and recycling*. 2015;104:375-390.
[96] Gouda SK, Saranga H. Sustainable supply chains for supply chain sustainability: impact of sustainability efforts on supply chain risk. *International Journal of Production Research*. 2018;56(17):5820-5835.
[97] Arabsheybani A, Paydar MM, Safaei AS. An integrated fuzzy MOORA method and FMEA technique for sustainable supplier selection considering quantity discounts and supplier's risk. *Journal of cleaner production*. 2018;190:577-591.
[98] Reinerth D, Busse C, Wagner SM. Using country sustainability risk to inform sustainable supply chain management: A design science study. *Journal of Business Logistics*. 2019;40(3):241-264.
[99] D'Eusanio M, Zamagni A, Petti L. Social sustainability and supply chain management: Methods and tools. *Journal of cleaner production*. 2019;235:178-189.
[100]Khan SAR, Zhang Y, Anees M, Golpîra H, Lahmar A, Qianli D. Green supply chain management, economic growth and environment: A GMM based evidence. *Journal of Cleaner Production*. 2018;185:588-599.
[101]Zhu Q, Feng Y, Choi SB. Customer relational governance and green supply chain performance. *Journal of Cleaner Production*. 2017;155:46-53.
[102]Kim S, Wagner SM, Colicchia C. The impact of supplier sustainability risk on shareholder value. *Journal of Supply Chain Management*. 2019;55(1):71-87.
[103]Xu M, Cui Y, Hu M, Xu X, Zhang Z, Liang S, et al. Supply chain sustainability risk and assessment. *Journal of cleaner production*. 2019;225:857-867.
[104]Wang L, Rani P. Sustainable supply chains under risk in the manufacturing firms: an extended double normalization-based multiple aggregation approach under an intuitionistic fuzzy environment. *Journal of Enterprise Information Management*. 2022;35(4-5):1067-1099.
[105]Chowdhury MMH, Umme NJ, Nuruzzaman M. Strategies for mitigating supply-side barriers in the apparel supply chain: a study on the apparel industry of Bangladesh. *Global Journal of Flexible Systems Management*. 2018;19(Suppl 1):41-52.
[106]Huang J, Li ZS, Liu HC. New approach for failure mode and effect analysis using linguistic distribution assessments and TODIM method. *Reliability Engineering & System Safety*. 2017;167:302-309.
[107]Sunday O, Adebayo AA, Aremu OA. A review of Failure Mode and Effects Analysis (FMEA) implementation in manufacturing firms. *Journal of Engineering and Applied Sciences*. 2018;13(7):1598-1606.
[108]Qin J, Xi Y, Pedrycz W. Failure mode and effects analysis (FMEA) for risk assessment based on interval type-2 fuzzy evidential reasoning method. *Applied Soft Computing*. 2020;89:106134.
[109]Spreafico C, Sutrisno A. Artificial intelligence assisted social failure mode and effect analysis (FMEA) for sustainable product design. *Sustainability*. 2023;15(11):8678.
[110]Sharma KD, Srivastava S. Failure mode and effect analysis (FMEA) implementation: a literature review. *Journal of Advance Research in Aeronautics and Space Science*. 2018;5(1):1-17.
[111]Spreafico C. A systematic robust design method to reduce products' environmental impact variations. *Knowledge*. 2022;2(2):266-285.
[112]Spreafico C, Russo D, Rizzi C. A state-of-the-art review of FMEA/FMECA including patents. *computer science review*. 2017;25:19-28.
[113]Kar A, Rai RN. A modified fuzzy PFMEA model for risk-centric Six Sigma assessment under the paradigm of Quality 4.0. *International Journal of Lean Six Sigma*. 2025;16(1):197-230.

[114]Gandhare S, Kumar P, Madankar T, Singh D, Bhamu J. Development and validation of a FMEA-based medical equipment maintenance framework using Industry 4.0. *International Journal of Quality & Reliability Management*. 2025;42(8):2250-2290.

[115]Gomaa AH. Enhancing Failure Mode and Effects Analysis with Industry 4.0 (FMEA 4.0): A Comprehensive Review and Strategic Framework. *International Journal of Darshan Institute of Engineering Research and Emerging Technologies*. 2025;14(2):1-12.

[116]Ceylan BO. Shipboard compressor system risk analysis by using rule-based fuzzy FMEA for preventing major marine accidents. *Ocean Engineering*. 2023;272:113888.

[117]Ceylan BO, Uslu S, Savaş A. Integrated data-driven and fuzzy logic-based failure mode and effects analysis (FMEA) for biodiesel risk quantification in maritime systems. *Process Safety and Environmental Protection*. 2025;205:108157.

[118]Li J, Zhang Y, Fang H, Fang S. Risk evaluation of photovoltaic power systems: An improved failure mode and effect analysis under uncertainty. *Journal of Cleaner Production*. 2023;414:137620.

[119]Ma Z, Ma W, Gong K, Tu Y. Grassroots perceptions-oriented failure mode and effects analysis-II approach with non-cooperative behaviors consideration for new energy security risk assessment. *Reliability Engineering & System Safety*. 2026:112820.

[120]Saputro TE, Rosiani TY, Mubin A, Dewi SK, Baroto T. Green supplier selection under supply risks using novel integrated fuzzy multi-criteria decision making techniques. *Journal of Cleaner Production*. 2024;449:141788.

[121]Chourasiya R, Pandey S, Malviya RK. Sustainable manufacturing adoption in textile industries: a systematic state-of-art literature review and future research outline. *Sustainable Development*. 2023;31(2):612-638.

[122]Gu Z, Irfan M, Singh AK, Ramaraju HK, Mohandes SR, Guan Y. Analyzing sustainability risks associated with blockchain technology implementation in the sustainable supply chain of construction industry: a fuzzy-based MCDM approach. *Annals of Operations Research*. 2025:1-26.

[123]Li C, Chen X, Yu Y. Multi-group decision-making approach for evaluating brand collaboration requirements of large-scale manufacturing industrial value chain. *Journal of the Operational Research Society*. 2024;75(9):1738-1760.

[124]Sun J, Wang H, Cui Z. Alleviating the bauxite maritime supply chain risks through resilient strategies: QFD-MCDM with intuitionistic fuzzy decision approach. *Sustainability*. 2023;15(10):8244.

[125]Sumrit D. Unveiling the effects of big data analytic capability on improving healthcare supply chain resilience: An integrated MCDM with spherical fuzzy information approach. *Results in Engineering*. 2025;25:104499.

[126]Saha A, Debnath BK, Chatterjee P, Panaiyappan AK, Das S, Anusha G. Generalized Dombi-based probabilistic hesitant fuzzy consensus reaching model for supplier selection under healthcare supply chain framework. *Engineering Applications of Artificial Intelligence*. 2024;133:107966.

[127]Masoomi B, Sahebi IG, Kumar A, Ghobakhloo M, Iranmanesh M. Industry 5.0 and opportunities for promoting supply chain sustainability: the study of the renewable energy industry. *Technology in Society*. 2025:103023.

[128]Sutrisno A, Kumar V. Supply chain sustainability risk assessment model using integration of the preference selection index (PSI) and the Shannon entropy. *International journal of quality & reliability management*. 2023;40(3):674-708.

[129]Minguito G, Banluta J. Risk management in humanitarian supply chain based on FMEA and grey relational analysis. *Socio-economic planning sciences*. 2023;87:101551.

[130]Ventura L, Martín-Jimenez I, Gallego-Garcia M. A Risk Management Framework to Enhance Environmental Sustainability in Industrial Symbiosis Ecosystems. *Sustainability*. 2025;17(6):2604.

[131]Ayyildiz E, Seyhan M, Kara B, Seyis GI. Investigation of risk factors in university Laboratories: An improved fuzzy based FMEA approach. *Safety Science*. 2025;191:106933.

[132]Ayyildiz E, Tanürün HE, Seyhan M, Kara B. Holistic risk assessment of oscillating water column devices using a hybrid hexagon and Pythagorean fuzzy multi-criteria approach. *Journal of Marine Engineering & Technology*. 2026:1-15.
[133]Tian Y, Song S, Zhou D, Pang S, Wei C. Canonical triangular interval type-2 fuzzy set linguistic distribution assessment TODIM approach: A case study of FMEA for electric vehicles DC charging piles. *Expert Systems with Applications*. 2023;223:119826.
[134]Tang Y, Zhou D, Zhu S, Ouyang L. A probabilistic uncertain linguistic approach for FMEA-based risk assessment. *Quality and Reliability Engineering International*. 2025;41(1):51-70.
[135]Akdamar E, Elidolu G, Gögebakan M, Ceylan BO. Entropy-Based Borda Extended Weighted Expert FMEA Approach: Comparison with Classical and Fuzzy FMEA on a Ship System. *Applied Soft Computing*. 2025;188:114424.
[136]Ceylan BO. Ship Bunkering Operations Risk Assessment using Rule-Based Fuzzy Failure Mode Effect Analysis (FFMEA). *journal of eta maritime science*. 2025;13(1):10-24.
[137]Huang A, Yang Y. FMEA Risk Assessment Method: Integration of Multi-Perspective Weights and Interval Cloud Model with TOPSIS Approach. *Expert Systems with Applications*. 2025:128377.
[138]Wan X, Cen L, Yue W, Xie Y, Chen X, Gui W. Failure mode and effect analysis with ORESTE method under large group probabilistic free double hierarchy hesitant linguistic environment. *Advanced Engineering Informatics*. 2024;59:102353.
[139]Septiani W, Marimin M, Herdiyeni Y, Haditjaroko L. Method and approach mapping for agri-food supply chain risk management: a literature review. *International Journal of Supply Chain Management*. 2014;3(4).