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Review Article

Supply Chain Risk Management for Sustainable and Resilient Operations:A Comprehensive Review and Strategic Framework in the Era of Industry 4.0-5.0

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ABSTRACT

Global supply chains face increasingly complex, interdependent, and dynamic risks driven by sustainability pressures, climate change, geopolitical uncertainties, technological disruptions, and market volatility. Traditional risk management approaches—often reactive, fragmented, and siloed—are insufficient for multi-tier, digitally connected, and sustainability-driven networks, particularly as industries transition from the automation-focused Industry 4.0 paradigm to the human-centric, resilient, and sustainable Industry 5.0 era.This study develops a comprehensive Supply Chain Risk Management (SCRM) framework to enhance resilience, sustainability, and operational performance. A systematic review identifies critical gaps in current practices, including fragmented risk coverage, limited multi-tier visibility, and insufficient integration of sustainability, resilience, and advanced digital technologies for predictive and adaptive risk management.To address these gaps, the study proposes the Strategic Integrated Risk Assessment Framework (SIRAF), integrating sustainability, resilience, and digitalization via Industry 4.0 technologies and Industry 5.0 human-centric principles. SIRAF's six interconnected modules provide end-to-end risk integration, real-time visibility, ESG alignment, dynamic risk assessment, human–technology collaboration, and organizational readiness. Operationalized through Lean Six Sigma DMAIC, the framework combines process improvement, predictive analytics, and human-centered decision-making to transform fragmented SCRM practices into proactive, resilient, and sustainable supply chain management.

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1. Introduction

Supply Chain Performance (SCP) is increasingly recognized as a multidimensional construct, extending beyond operational efficiency to encompass responsiveness, resilience, and alignment with evolving customer expectations. SCP reflects an organization's capacity to meet end-customer demands through timely deliveries, optimized inventory management, and consistent product availability, thereby enhancing customer satisfaction and competitive advantage [1]. Rapid technological advancements, evolving socioeconomic conditions, and heightened consumer expectations are redefining performance benchmarks, compelling supply chains to adopt agile, flexible, and customer-centric strategies [2].

1.1 Risks in Modern Supply Chains

SCP is influenced by a complex interplay of operational, financial, strategic, and external risks. Operational risks—such as production delays, equipment failures, and logistics disruptions—typically arise internally, whereas financial and strategic risks often emerge from external factors, including market volatility, currency fluctuations, and regulatory changes. External shocks, including natural disasters, geopolitical tensions, and global pandemics, can propagate across multi-tier networks, amplifying vulnerabilities and affecting both operational and financial outcomes. This interconnectedness underscores the need for proactive, anticipatory, and comprehensive supply chain risk management (SCRM) [3].

Identifying and prioritizing supply chain risks is essential for maintaining product quality, reliability, and continuity. Conventional methods, such as Risk Priority Numbers (RPN) within an input–process–output framework, are limited by imprecise data and the inability to adequately capture uncertainty, potentially resulting in inaccurate risk assessments [4]. Systematic, data-driven methodologies for risk identification and prioritization are therefore critical for effective SCRM.

Effective SCRM requires resilience, adaptability, and anticipatory capabilities. Strategies such as dual sourcing, inventory optimization, flexible production planning, and inter-organizational collaboration enhance responsiveness and enable rapid recovery from disruptions [5]. The integration of advanced practices—including continuous monitoring, predictive analytics, digital twins, and other Industry 4.0 technologies—further strengthens operational continuity. Complementary sustainability-oriented practices, such as green logistics, circular economy initiatives, and ethical sourcing, align operations with environmental and social objectives while reinforcing SCP [6]. Collectively, these approaches enable supply chains to achieve operational efficiency, strategic agility, long-term resilience, and sustained value creation.

1.2. Sustainable Supply Chain Management

Sustainable Supply Chain Management (SSCM) has emerged as a critical discipline in response to global challenges, including resource scarcity, climate change, and societal expectations for ethical business conduct. SSCM integrates environmental, social, and economic considerations across the value chain—from raw material sourcing and production to distribution, consumption, and end-of-life management—enhancing long-term competitiveness while promoting sustainable development [7-10].

Modern supply chains contribute significantly to global greenhouse gas emissions, often exceeding the direct operational emissions of individual firms. Indirect emissions—from upstream suppliers, downstream distribution, product use, and end-of-life disposal—pose substantial measurement and control challenges, positioning supply chains at the core of organizational and national sustainability agendas, including carbon-

neutrality commitments [11]. Assessing sustainability-related risks is therefore essential for evaluating both the likelihood and potential impact of uncertain events.

1.3. Risk Identification and Prioritization Tools

Failure Mode and Effects Analysis (FMEA) is widely employed to systematically identify, prioritize, and mitigate potential failures in supply chains. FMEA calculates Risk Priority Numbers (RPN) based on severity, likelihood, and detectability, guiding risk mitigation strategies [12]. However, traditional FMEA approaches often rely on simplistic ranking and insufficient weighting of risk factors, which can compromise prioritization accuracy [13,14]. Multi-criteria decision-making (MCDM) techniques enhance traditional approaches by integrating multiple dimensions of risk and supporting more robust, evidence-based prioritization.

Supply chain risks may be internal—such as supplier reliability, quality defects, and operational inefficiencies—or external, including natural disasters, political instability, and regulatory changes [15]. Internal failures can cascade across supply chain networks, impacting production, logistics, and fulfillment. Mitigation strategies include multiple sourcing, strategic partnerships, and investments in robust infrastructure. Porter's value chain framework illustrates that risks affecting downstream activities can influence overall competitiveness [16]. Critical infrastructure—including energy, communication, and digital systems—supports proactive risk management [17].

As summarized in Table 1, supply chain risks can be categorized by type, element, and origin—internal, external, or hybrid. Key categories include demand, supply, financial, customer, technological, operational, strategic, compliance and legal, reputational, logistics and transportation, innovation and R&D, political and geopolitical, natural and climate, market and competitive, and environmental risks. Understanding risk origin and interdependencies enables targeted mitigation: internal risks are addressed through operational improvements, external risks require monitoring and collaboration, and hybrid risks necessitate integrated strategies. Recognizing cascading effects among interdependent risks is critical for prioritization, resource allocation, and effective mitigation [18,19].

The transition from Industry 4.0 to Industry 5.0 underscores the need for integrated, human-centric risk management frameworks. Industry 4.0 technologies—including IoT, AI, blockchain, and digital twins—enhance automation, connectivity, and real-time decision-making but often overlook human-centered and sustainability considerations. Industry 5.0 emphasizes human–machine collaboration, circularity, and sustainable value creation, requiring risk management frameworks aligned with these emerging paradigms.

1.4. Study Objectives and Structure

To address these challenges, this study proposes a comprehensive Supply Chain Risk Management (SCRM) framework that overcomes the limitations of traditional, fragmented approaches in complex, multi-tier, and digitally connected supply chains. By integrating sustainability, resilience, and digitalization through the Strategic Integrated Risk Assessment Framework (SIRAF) and implementing it via Lean Six Sigma DMAIC methodology, organizations can transition from reactive to proactive, resilient, and sustainable supply chain operations.

The remainder of the paper is organized as follows: Section 2 presents a literature review; Section 3 identifies key challenges and research gaps; Section 4 introduces the proposed SIRAF framework; and Section 5 concludes with key insights and directions for future research.

Table 1. Supply Chain Risk Elements Categorized by Type, Nature, and Scope

(Legend: 🟢 Internal | 🟡 Both Internal & External | 🟠 External)

(This table has been conceptually developed by the authors)

Risk Category	#	Adjusted Risk Element	Nature (I/E)	Scope
Demand Risk	1	Forecasting errors and estimation bias	I/E	🟡
	2	Demand volatility and unpredictability	E	🟠
	3	Market fluctuations and shifts	E	🟠
	4	Intensified competitive forces	E	🟠
	5	Distribution and channel variability	E	🟠
Supply Risk	6	Inventory imbalances and control issues	I	🟢
	7	Operational inefficiencies and delays	I	🟢
	8	Quality deviations and safety non-conformance	I	🟢
	9	Procurement delays and capacity constraints	I	🟢
	10	Raw material shortages	E	🟠
	11	Supplier unreliability and logistics variability	E	🟠
Financial Risk	12	Cost overruns and budget variability	I	🟢
	13	Price instability and market-driven cost fluctuations	E	🟠
Customer Risk	14	Delivery delays and fulfillment gaps	I	🟢
	15	Product quality and safety issues	I	🟢
	16	Declining customer satisfaction and loyalty	E	🟠
Technology Risk	17	System failures and digital disruptions	I/E	🟡
	18	Cybersecurity breaches and IT service interruptions	I/E	🟡
Operational Risk	19	Equipment failures, downtime, and bottlenecks	I	🟢
	20	Human errors and workforce capability limitations	I	🟢
Strategic Risk	21	Strategic misalignment and market repositioning	I/E	🟡
	22	Restructuring, mergers, and acquisitions	I/E	🟡
Compliance & Legal Risk	23	Regulatory non-compliance and contractual issues	I/E	🟡
Reputational Risk	24	Negative publicity and brand deterioration	E	🟠
	25	Loss of stakeholder and customer trust	E	🟠
Logistics & Transportation Risk	26	Transport disruptions and route failures	E	🟠
	27	Port congestion and customs delays	E	🟠
Innovation & R&D Risk	28	Product development delays and technology adoption barriers	I	🟢
Political & Geopolitical Risk	29	Trade restrictions, sanctions, and policy barriers	E	🟠
	30	Political instability and conflict	E	🟠
Natural & Climate Risk	31	Natural disasters and extreme weather	E	🟠
	32	Long-term climate change impacts	E	🟠

Risk Category	#	Adjusted Risk Element	Nature (I/E)	Scope
Market & Competitive Risk	33	Price volatility and competitive turbulence	E	●
	34	Shifts in consumer preferences and expectations	E	●
Environmental Risk	35	Resource scarcity and environmental constraints	E	●

2. Literature Review on Supply Chain Risk Management

This study conducts a systematic literature review of peer-reviewed articles published between 2015 and 2025, indexed in Scopus, Web of Science, and ScienceDirect. The review examines supply chain risk management (SCRM) in the context of sustainability, resilience, and digital transformation. Keywords included *supply chain risk management, sustainable supply chains, resilient supply chains, digital supply chains, Industry 4.0, Industry 5.0, IoT, artificial intelligence (AI),* and *blockchain*. Studies were selected based on relevance, methodological rigor, and theoretical or empirical contribution, resulting in a consolidated body of literature addressing environmental, social, economic, operational, technological, and geopolitical risks.

2.1. Conceptual Foundations of SCRM

Supply chains coordinate the flow of materials, information, and finances across multi-tier networks of suppliers, manufacturers, distributors, and customers. This interdependence renders them inherently vulnerable to disruptions. Traditional efficiency-focused approaches, such as lean and just-in-time systems, improve cost and speed performance but often reduce redundancy and adaptive capacity, increasing systemic risk under uncertainty [18,20]. Accordingly, SCRM has emerged as a strategic capability, emphasizing the identification, assessment, and mitigation of risks while ensuring continuity, operational stability, and long-term sustainability.

Modern supply chains face a wide spectrum of interconnected risks, including natural disasters, geopolitical instability, economic volatility, pandemics, cyber threats, and technological failures. These risks frequently cascade across networks, amplifying their impact beyond individual organizations. Proactive SCRM practices—such as supplier diversification, contingency planning, structured risk assessment, and real-time monitoring—are critical resilience enablers. Complementary mechanisms—including dual sourcing, flexible production planning, inventory buffers, redundancy, collaboration, and adaptive decision-making—strengthen the capacity to absorb shocks and maintain operational continuity [5,21,51].

The COVID-19 pandemic highlighted global supply chain vulnerabilities, reinforcing the strategic importance of SCRM [22-24]. However, research remains heavily focused on large multinational corporations, while SMEs—particularly in developing and emerging economies—are underrepresented [25-27]. SMEs typically operate in volatile, uncertain, complex, and ambiguous (VUCA) environments, where limited financial, technological, and managerial resources increase vulnerability. While innovation is crucial for SME adaptability, resource constraints often hinder effective SCRM implementation [28-31].

2.2 SCRM, Innovation, and SME Performance

Although SMEs play a critical role in global value chains, they remain underexplored in SCRM research, which predominantly focuses on large firms in manufacturing, automotive, construction, and food sectors [32-35]. The role of SCRM in supporting product and process innovation during disruptions is insufficiently studied, despite evidence linking innovation to resilience and competitive advantage [23,36]. Empirical

studies examining the direct relationship between SCRM practices and SME performance are limited, representing a key research gap [37].

Recent research has introduced advanced analytical approaches to enhance risk identification, assessment, and prioritization. Techniques such as enhanced Failure Mode and Effects Analysis (FMEA), probabilistic modeling, Bayesian networks, cloud-based platforms, and multi-criteria decision-making frameworks improve predictive accuracy and enable proactive intervention [38-41]. These approaches support data-driven, simulation-based, and predictive SCRM, enabling SMEs to manage uncertainty despite limited internal resources.

Regulatory pressures regarding environmental protection, social responsibility, and supply chain due diligence have intensified attention to supply chain sustainability risks (SCSR). While much research remains compliance-driven and firm-centric, emerging studies emphasize stakeholder engagement, supplier-level assessments, and regional impact considerations [42]. Stakeholder-driven risk identification, science-based assessment, equitable cost allocation, and responsible disengagement strategies increasingly position sustainability risks as strategic drivers of resilience, competitiveness, and long-term value creation.

2.3. Digitalization and Industry 4.0–5.0 Enabled SCRM

Digital transformation is reshaping SCRM by enabling real-time visibility, predictive analytics, and proactive decision-making. Blockchain, IoT, and AI enhance transparency, traceability, and responsiveness, particularly under geopolitical or sustainability-related disruptions [20,43]. Machine learning applications—including demand forecasting, inventory optimization, supplier risk assessment, and fraud detection—further strengthen resilience, although challenges related to data quality, system integration, cost, scalability, privacy, and ethics remain significant [44,45]. Integrating Industry 4.0 and 5.0 technologies facilitates a transition from reactive risk management toward predictive, adaptive, and human-centric SCRM.

Beyond operational risks, recent literature emphasizes strategic and geopolitical dimensions. Coordinated logistics for energy security, vulnerabilities of emerging-market firms embedded in global supply chains, and systemic impacts of extreme geopolitical events underscore the importance of strategic risk awareness [46-48]. Simultaneously, sustainability-oriented SCRM practices enhance competitiveness by improving ESG performance, strengthening stakeholder trust, and facilitating access to financing [49]. Evidence also suggests that effective SCRM supports innovation and sustainability outcomes in SMEs, particularly when reinforced by entrepreneurial networks and technological adoption [50].

2.4 Integrated Frameworks and Research Gaps

Despite notable progress, many existing SCRM frameworks remain fragmented, reactive, or sector-specific. Integrated frameworks—such as the Sustainability, Innovation, Resilience, and Adaptive Framework (SIRAF)—address these limitations by combining sustainability, resilience, and digital enablers into cohesive, proactive risk management systems. Such frameworks enable SMEs and large enterprises alike to anticipate disruptions, enhance agility, and sustain long-term competitiveness while generating economic, social, and environmental value [54-59].

The literature underscores the growing strategic importance of SCRM, particularly for SMEs operating under high uncertainty. Effective integration of risk management, sustainability, innovation, and digital transformation is essential for building resilient, adaptive, and competitive supply chains. Future research should prioritize SME-focused empirical studies, multi-level and cross-regional analyses, and integrated Industry 4.0–5.0 frameworks capable of managing complex global risks while supporting long-term strategic objectives [60-68].

3. Challenges and Research Gaps in SCRM

Despite substantial progress in SCRM, modern supply chains face persistent challenges in integrating sustainability, resilience, and digital transformation. These limitations hinder organizations' ability to anticipate, mitigate, and adapt to risks across complex global networks, underscoring the need for comprehensive frameworks such as the SIRAF.

Table 2 summarizes key challenges, research gaps, and implications for implementing SIRAF across six dimensions: fragmentation and limited integration, multi-tier visibility and data, sustainability and resilience, dynamic and uncertain risks, technology adoption and human–machine collaboration, and organizational and cultural barriers. By addressing these areas, SIRAF enables supply chains to operate efficiently, ethically, and resiliently under uncertainty [69-96].

Fragmentation and limited integration remain major challenges. Many SCRM approaches focus on isolated risk types—supply, process, or demand—without considering the end-to-end supply chain. This siloed approach reduces multi-tier visibility, weakens responsiveness to cascading disruptions, and constrains alignment with sustainability and resilience objectives. It often leads to duplicated efforts, inefficient resource allocation, and suboptimal mitigation strategies, highlighting the need for holistic, cross-functional frameworks.

Multi-tier visibility and data limitations further impede effective risk management. Traditional models often consider only immediate suppliers, neglecting upstream and downstream interdependencies. Technologies such as IoT, blockchain, AI, and digital twins can provide predictive insights and transparency, but adoption remains uneven and integration with legacy systems is challenging. Without comprehensive visibility, supply chains remain exposed to operational, environmental, and reputational risks.

Sustainability and resilience are frequently underrepresented. While ESG considerations are increasingly prioritized, circular economy initiatives, ethical sourcing, and green logistics are rarely embedded into predictive risk models. Resilience mechanisms—flexibility, redundancy, and adaptive decision-making—are often reactive rather than proactive, limiting the supply chain's ability to anticipate disruptions and achieve long-term triple-bottom-line performance. Proactively embedding these principles is essential for competitive, responsible supply chains.

Dynamic and uncertain risks present additional complexity. Global supply chains face interdependent and volatile threats, including geopolitical instability, climate events, technological disruptions, and fluctuating demand. Traditional methods such as FMEA and probabilistic models struggle to capture uncertainty, fuzziness, and cascading effects. Hybrid, adaptive approaches that integrate quantitative and qualitative insights and leverage real-time data are crucial for proactive decision-making.

Technology adoption and human–machine collaboration offer both opportunities and barriers. Industry 4.0 technologies enhance predictive risk management, yet integration, scalability, and workforce adaptation remain significant challenges, particularly for SMEs. The Industry 5.0 paradigm emphasizes human-centric collaboration, ethical decision-making, and circularity, requiring socio-technical frameworks that balance digital tools with human expertise for adaptive and resilient risk management.

Organizational and cultural barriers also constrain SCRM effectiveness. Resistance to change, low risk awareness, insufficient training, and unclear accountability can undermine monitoring, mitigation, and resilience initiatives. Leadership, culture, and structured change management are critical to successfully deploying SCRM strategies and technologies.

The literature highlights several research gaps, including the need for integrated multi-tier frameworks capturing upstream and downstream risks; dynamic, adaptive methodologies addressing uncertainty and interdependencies; sustainability-oriented models incorporating circular economy principles, ethical sourcing,

and ESG metrics; human–digital collaborative approaches combining AI, IoT, and digital twins with human expertise; and validation across industries and SMEs to ensure scalability and practical relevance.

Modern supply chains face complex, interconnected risks that can disrupt operations, reduce profitability, and undermine competitiveness. Table 3 organizes fifteen key risk domains, linking specific risk elements to potential consequences and proactive mitigation strategies. Demand and supply risks, including forecasting errors, market fluctuations, supplier unreliability, and raw material shortages, can cause inventory imbalances, production bottlenecks, delivery delays, and revenue loss. Mitigation strategies include AI-driven forecasting, predictive analytics, digital twin simulations, flexible production planning, multi-sourcing, IoT-enabled monitoring, smart inventory systems, and blockchain-based traceability, collectively enhancing operational efficiency and agility.

Financial, customer, technology, and operational risks impact profitability, service quality, and productivity. Cost overruns, delivery gaps, system failures, cybersecurity breaches, equipment breakdowns, and human errors can cause downtime, margin erosion, and reputational damage. Proactive measures—such as AI-based cost optimization, predictive maintenance, redundancy systems, AR/VR training, IoT tracking, and AI-assisted quality inspection—strengthen operational continuity and safeguard assets.

Strategic, compliance, reputational, political, natural, market, and environmental risks shape long-term resilience and sustainability. Strategic misalignment, regulatory non-compliance, negative publicity, political instability, climate change, and resource scarcity can disrupt operations, erode stakeholder trust, and threaten competitiveness. Mitigation strategies include scenario planning, agile decision support, compliance automation, digital prototyping, sustainable sourcing, circular economy practices, and resilient network design, promoting adaptive, human-centric, and environmentally responsible supply chains.

In summary, Table 3 provides a comprehensive SCRM framework, linking risk elements to consequences and actionable mitigation strategies. Implementing these measures enables organizations to enhance agility, resilience, and sustainability, delivering long-term economic, social, and environmental value. This approach aligns with Industry 4.0–5.0 paradigms, emphasizing digitalization, human–machine collaboration, and sustainable operations.

Table 2. Challenges, Research Gaps, and Mitigation Strategies for SCRM.

(This table has been conceptually developed by the authors)

#	SCRM Dimension	Key Challenges	Research Gaps	Implications for SIRAF	Representative Literature
1	Fragmentation & Limited Integration	Siloed risk management; focus on individual risk types; limited end-to-end visibility	Need for integrated, cross-functional SCRM covering supply, process, and demand risks	Provides a unified framework for holistic, end-to-end risk coverage	Shelar et al. (2023) [53] ; Hajmohammad et al. (2024) [15]
2	Multi-Tier Visibility & Data	Poor visibility beyond first-tier suppliers; uneven adoption of IoT, AI, blockchain, digital twins	Integration of real-time, multi-tier data; predictive insights for early risk detection	Enhances transparency and enables proactive, predictive risk management	Zhang & Song (2022) [43] ; Kwaramba et al. (2024) [6]
3	Sustainability & Resilience	ESG factors often neglected; resilience measures reactive	Embedding circular economy, ethical sourcing, green logistics, and proactive resilience	Proactively integrates sustainability and resilience to achieve long-term triple-bottom-line performance	Liu et al. (2023) [1]; Kwaramba et al. (2024) [6]
4	Dynamic & Uncertain Risks	Exposure to geopolitical, climate, technological, and market volatility;	Adaptive, hybrid risk assessment methods addressing uncertainty,	Supports predictive and adaptive risk assessment in complex, uncertain supply networks	Huang & Yang (2025) [39]; He et al. (2025) [41]

#	SCRM Dimension	Key Challenges	Research Gaps	Implications for SIRAF	Representative Literature
		traditional models insufficient	fuzziness, and cascading effects		
5	Technology Adoption & Human–Machine Collaboration	SMEs may lack resources and expertise; Industry 5.0 requires human–machine synergy	Human–digital collaborative approaches integrating AI, IoT, digital twins with expert judgment	Balances automation with human expertise, enabling ethical, adaptive, and resilient risk management	Swaminathan & Venkitasubramony (2024) [51] ; Kwaramba et al. (2024) [6]
6	Organizational & Cultural Barriers	Resistance to change; low risk awareness; insufficient training; unclear accountability	Integration of leadership, culture, and change management into SCRM	Strengthens governance, accountability, and organizational alignment	Shelar et al. (2023) [53] ; Swaminathan & Venkitasubramony (2024) [51]

Table 3. Supply Chain Risk Elements and Proactive Actions.

(This table has been conceptually developed by the authors)

Risk Category	#	Risk Element	Risk Consequence	Proactive Actions
1. Demand Risk	1	Forecasting errors and estimation bias	Inventory imbalances, production inefficiencies	AI-driven forecasting, predictive analytics, scenario-based demand planning
	2	Demand volatility and unpredictability	Production disruptions, stock shortages	Real-time demand monitoring, flexible production planning, digital twin simulations
	3	Market fluctuations and shifts	Revenue instability, misaligned strategy	Big data analytics, trend prediction, agile response strategies
	4	Intensified competitive forces	Loss of market share, reduced profitability	Competitor intelligence, benchmarking, adaptive strategic planning
	5	Distribution and channel variability	Delivery delays, customer dissatisfaction	IoT logistics tracking, route optimization, 3PL collaboration
2. Supply Risk	6	Inventory imbalances and control issues	Stockouts or excess inventory	Smart inventory systems, automated replenishment, predictive stock analytics
	7	Operational inefficiencies and delays	Reduced throughput, higher costs	IoT process monitoring, Lean 4.0 practices, continuous improvement
	8	Quality deviations and safety non-conformance	Recalls, reputational damage	Digital twin simulations, AI quality inspection, automated alerts
	9	Procurement delays and capacity constraints	Production bottlenecks, delayed delivery	Supplier dashboards, digital procurement platforms, HR analytics
	10	Raw material shortages	Production interruptions, revenue loss	Multi-sourcing, supplier integration, risk-based inventory planning
	11	Supplier unreliability and logistics variability	Supply disruptions, operational delays	Blockchain traceability, IoT monitoring, supplier KPI dashboards
3. Financial Risk	12	Cost overruns and budget variability	Reduced profitability	AI cost optimization, predictive budgeting, real-time financial monitoring
	13	Price instability and market-driven cost fluctuations	Margin erosion	Dynamic pricing models, market simulations, scenario planning

Risk Category	#	Risk Element	Risk Consequence	Proactive Actions
4. Customer Risk	14	Delivery delays and fulfillment gaps	Customer dissatisfaction, lost sales	IoT shipment tracking, automated scheduling, real-time alerts
	15	Product quality and safety issues	Returns, recalls, reputational damage	AI quality inspection, digital twin testing, compliance monitoring
	16	Declining customer satisfaction and loyalty	Reduced retention, lower revenue	Sentiment analysis, AI feedback, personalized service platforms
5. Technology Risk	17	System failures and digital disruptions	Downtime, data loss	Predictive maintenance, redundancy systems, cloud failover solutions
	18	Cybersecurity breaches and IT service interruptions	Data compromise, operational risk	AI threat detection, blockchain security, continuous monitoring
6. Operational Risk	19	Equipment failures, downtime, bottlenecks	Production delays, higher costs	Real-time monitoring, predictive maintenance, digital twin simulations
	20	Human errors and workforce capability limitations	Reduced productivity, operational errors	Human–machine collaboration, AR/VR training, AI-assisted operations
7. Strategic Risk	21	Strategic misalignment and market repositioning	Loss of competitiveness	Scenario planning, dashboards, agile decision support
	22	Restructuring, mergers, and acquisitions	Integration failures, operational disruption	Data-driven integration planning, AI due diligence, risk simulations
8. Compliance & Legal Risk	23	Regulatory non-compliance and contractual issues	Legal penalties, reputational damage	Compliance AI tools, blockchain contracts, automated reporting
9. Reputational Risk	24	Negative publicity and brand deterioration	Loss of trust, market share	Social media monitoring, sentiment analysis, rapid response systems
	25	Loss of stakeholder and customer trust	Reduced loyalty and partnerships	Blockchain transparency, proactive communication, CSR initiatives
10. Logistics & Transportation Risk	26	Transport disruptions and route failures	Delivery delays, cost escalation	IoT tracking, predictive analytics, alternative routing strategies
	27	Port congestion and customs delays	Slowed shipments, inventory issues	Real-time monitoring, simulation-based planning, collaborative scheduling
11. Innovation & R&D Risk	28	Product development delays, technology adoption barriers	Time-to-market delays, lost opportunities	Digital prototyping, AI-enabled innovation, technology scouting
12. Political & Geopolitical Risk	29	Trade restrictions, sanctions, policy barriers	Supply interruptions, market limitations	Scenario planning, diversified sourcing, blockchain compliance tracking
	30	Political instability and conflict	Operational disruptions, revenue loss	Risk mapping, adaptive networks, contingency planning
13. Natural & Climate Risk	31	Natural disasters, extreme weather	Production and logistics disruptions	Digital twin simulations, AI predictive models, resilient network design
	32	Long-term climate change impacts	Strategic supply chain vulnerability	Sustainable sourcing, carbon footprint monitoring, circular strategies
14. Market & Competitive Risk	33	Price volatility, competitive turbulence	Margin fluctuations, market share loss	Predictive pricing analytics, benchmarking, flexible contracts

Risk Category	#	Risk Element	Risk Consequence	Proactive Actions
	34	Shifts in consumer preferences and expectations	Misaligned products, lost opportunities	AI trend analysis, adaptive product design, personalized marketing
15. Environmental Risk	35	Resource scarcity, environmental constraints	Operational disruption, increased costs	Circular economy practices, sustainable sourcing, predictive resource planning

4. Strategic Integrated Risk Assessment Framework (SIRAF)

Modern supply chains are increasingly complex, multi-tiered, and exposed to dynamic risks driven by globalization, technological disruption, and sustainability pressures. Traditional risk management approaches are often fragmented, reactive, and insufficient to ensure operational resilience, ESG performance, and strategic alignment. To address these challenges, this study proposes the SIRAF—a comprehensive, proactive, and data-driven approach to SCRM. SIRAF integrates technological, human-centric, and governance dimensions, enabling organizations to anticipate, evaluate, and mitigate risks while enhancing resilience, ethical decision-making, and sustainability outcomes.

4.1. SIRAF Modules

SIRAF leverages Industry 4.0 digital technologies and Industry 5.0 human-centric principles to provide predictive, adaptive, and ethically guided risk management. By combining advanced digital tools with human expertise, it enables decision-making across environmental, social, economic, operational, and technological dimensions. Table 4 summarizes the six interconnected modules of SIRAF:

- Fragmentation & Integration: Consolidates siloed risk management across functions and supply chain tiers. Enterprise-wide risk mapping, centralized dashboards, and integrated registries enhance coordination, reduce redundancies, and ensure effective mitigation. *KPIs:* risk coverage completeness, cross-tier alignment, mitigation plan execution.
- Multi-Tier Visibility & Data: Facilitates real-time monitoring and predictive insights. IoT sensors, blockchain traceability, digital twins, and AI/ML analytics improve early risk detection and predictive modeling, while human validation ensures context-aware interpretation. *KPIs:* data integration rate, real -time visibility index, predictive accuracy.
- Sustainability & Resilience: Embeds ESG principles and strengthens operational flexibility and redundancy. Circular economy practices, green logistics, ethical sourcing, and resource diversification support proactive disruption management and sustainability alignment. *KPIs:* ESG compliance, resilience index, carbon footprint reduction.
- Dynamic Risk Assessment: Supports scenario-driven evaluation of interdependent and cascading risks. Hybrid qualitative–quantitative analysis, predictive modeling, Bayesian networks, and simulations allow organizations to explore multiple scenarios, quantify uncertainties, and enhance preparedness. *KPIs:* risk detection lead time, scenario coverage, predictive model accuracy.
- Technology–Human Collaboration: Aligns digital tools with human expertise according to Industry 5.0 principles. AI-assisted decision-making, AR/VR-enabled training, and collaborative platforms ensure ethical, adaptive, and informed decisions. *KPIs:* adoption rate of digital tools, human–machine collaboration scores, ethical compliance.
- Organizational & Cultural Alignment: Embeds risk management into governance, leadership, and organizational culture. Structured training, governance frameworks, performance monitoring, and

cultural initiatives foster accountability, knowledge sharing, and proactive risk awareness. *KPIs:* risk awareness index, training completion rate, governance effectiveness.

Collectively, SIRAF transforms SCRM from fragmented, reactive practices into a proactive, integrated, and sustainability-aligned discipline, equipping organizations to anticipate disruptions, enhance resilience, and sustain competitive advantage.

4.2. Lean Six Sigma DMAIC Framework for SCRM

Managing modern supply chain complexity requires structured, systematic approaches that integrate process improvement, data-driven insights, and human-centric decision-making. The Lean Six Sigma DMAIC framework provides such a methodology, enabling organizations to proactively identify, analyze, and mitigate risks while improving operational resilience, ESG performance, and ethical governance. Integrated with Industry 4.0 technologies and Industry 5.0 principles, DMAIC supports predictive, adaptive, and ethically guided SCRM. Table 5 summarizes the DMAIC framework applied to SCRM:

- Define: Establishes scope, objectives, and strategic priorities. Activities include identifying critical risks, mapping supply chain processes, analyzing stakeholders, and defining KPIs/KRIs. *Industry 4.0:* centralized dashboards, automated documentation. *Industry 5.0:* human-centric prioritization, ethical alignment, collaborative decision-making. *Tools:* SIPOC diagrams, risk prioritization matrices. *Metrics:* critical risks identified, ESG alignment score, stakeholder engagement index.
- Measure: Quantifies risk exposure and establishes baselines. Activities include data collection, process mapping, KPI/KRI calculation, and statistical analysis. *Industry 4.0:* IoT-enabled monitoring, ERP integration. *Industry 5.0:* human validation, context-aware interpretation. *Tools:* process mapping, statistical process control, dashboards. *Metrics:* baseline risk exposure, data completeness, on-time delivery, carbon footprint, supplier compliance rate.
- Analyze: Identifies root causes, interdependencies, and cascading risks using FMEA, Pareto analysis, Ishikawa diagrams, and scenario evaluation. *Industry 4.0:* predictive analytics, simulations, digital twin testing. *Industry 5.0:* ethical evaluation, collaborative problem-solving, risk-aware culture. *Metrics:* root-cause coverage, risk impact score, predictive model accuracy, scenario coverage, ESG risk exposure.
- Improve: Implements mitigation strategies to reduce risk and optimize performance. Activities include Lean process improvement, Six Sigma optimization, contingency planning, and standardization. *Industry 4.0:* predictive modeling, digital twins, blockchain traceability. *Industry 5.0:* adaptive human–AI collaboration, resilient process design. *Tools:* Lean (5S, Kaizen), Six Sigma optimization, digital twins, blockchain, predictive analytics. *Metrics:* risk reduction rate, process efficiency improvement, ESG performance, resilience index, supplier reliability improvement.
- Control: Ensures sustainability of improvements and continuous monitoring. Activities include standardization, dashboards, audits, and feedback loops. *Industry 4.0:* real-time dashboards, automated alerts, predictive triggers. *Industry 5.0:* human oversight, adaptive governance, accountability. *Tools:* SOPs, dashboards, control charts. *Metrics:* risk recurrence rate, KPI/KRI compliance, continuous improvement adoption, ESG compliance, operational resilience index.

By integrating DMAIC with Industry 4.0 and 5.0 principles, organizations gain a structured, systematic, and human-centric approach to SCRM, enhancing resilience, sustainability, and strategic performance.

4.3. Strategic Objectives and KPIs for SCRM

Modern supply chains operate in highly dynamic, globally interconnected environments, where operational, technological, and sustainability risks are closely interdependent. Effective SCRM requires proactive identification and mitigation of risks, alignment with strategic objectives, and human-centric decision-making. Table 6 presents strategic objectives for SCRM, their associated KPIs, and complementary roles of Industry 4.0 digital technologies and Industry 5.0 human-centric principles. The six strategic objectives are:

1. End-to-End Risk Integration: Establishes a unified risk framework across all supply chain tiers. *Industry 4.0:* centralized dashboards, automated risk documentation, digital process mapping. *Industry 5.0:* human-centric prioritization, collaborative decision-making, ethical alignment. *KPIs:* risk coverage completeness, cross-tier alignment score, mitigation plan execution rate.
2. Sustainability & ESG Alignment: Ensures risk practices align with ESG principles. *Industry 4.0:* ESG monitoring systems, carbon analytics, traceable reporting. *Industry 5.0:* human oversight, ethical interpretation, sustainability-focused decision-making. *KPIs:* ESG compliance rate, carbon footprint reduction, supplier ethical compliance rate.
3. Operational Resilience & Flexibility: Builds adaptive supply chains capable of responding to disruptions. *Industry 4.0:* predictive modeling, digital twins, disruption simulations. *Industry 5.0:* adaptive human–AI collaboration, flexible decision-making, risk-aware culture. *KPIs:* resilience index, supplier reliability, process flexibility score.
4. Predictive & Data-Driven Decision-Making: Supports proactive risk identification and mitigation. *Industry 4.0:* IoT, ERP, AI/ML analytics, real-time dashboards. *Industry 5.0:* contextual validation, collaborative scenario analysis. *KPIs:* predictive model accuracy, early risk detection lead time, data integration rate.
5. Human–Digital Collaboration: Leverages human expertise alongside digital tools for ethical, adaptive decision-making. *KPIs:* digital tool adoption rate, human–machine collaboration score, ethical compliance.
6. Organizational & Cultural Readiness: Embeds risk awareness within governance, leadership, and culture. *Industry 4.0:* digital knowledge management, automated reporting, performance dashboards. *Industry 5.0:* proactive leadership, knowledge sharing, accountability. *KPIs:* risk awareness index, training completion rate, governance effectiveness.

Aligning these strategic objectives with measurable KPIs and integrating Industry 4.0 digital tools with Industry 5.0 human-centric principles forms a forward-looking, proactive SCRM framework. This enables organizations to anticipate, evaluate, and mitigate risks while enhancing resilience, ethical governance, and sustainability across complex supply chains.

Table 4. SIRAF: Modules, Objectives, Focus Areas, Tools, and KPIs.
(This table has been conceptually developed by the authors)

Module	Objective	Focus Areas	Key Actions / Tools	KPIs
1. Fragmentation & Integration	Create an end-to-end, integrated risk management system	Consolidation of supply, demand, and process risks; cross-functional and multi-tier alignment	Risk mapping, centralized dashboards, integrated risk registry, coordinated multi-tier workflows	Risk coverage ratio, alignment score, mitigation execution rate
2. Multi-Tier Visibility & Data	Enable real-time visibility and predictive insights across the supply network	Integrated data flows across suppliers, logistics, production, and customers	IoT monitoring, blockchain traceability, digital twins, AI/ML analytics, ERP/data-platform integration	Data integration index, visibility level, prediction accuracy
3. Sustainability &	Embed ESG	Circularity, green	ESG monitoring tools,	ESG

Module	Objective	Focus Areas	Key Actions / Tools	KPIs
Resilience	priorities and enhance resilience capabilities	logistics, ethical sourcing, redundancy, flexibility	carbon analytics, resilience scenario modeling, diversified sourcing strategies	performance score; resilience index; carbon reduction rate
4. Dynamic Risk Assessment	Support adaptive, predictive, and scenario-driven risk evaluation	Interdependent, uncertain, and cascading risks	Hybrid qualitative–quantitative risk analysis, predictive modeling, Bayesian networks, simulation engines	Detection lead time, scenario coverage, model accuracy
5. Technology–Human Collaboration	Integrate digital intelligence with human expertise for responsible decision-making	Human–machine collaboration; human -centric Industry 5.0 principles	AI-driven decision support, AR/VR training, collaborative platforms, ethical governance protocols	Digital adoption index, collaboration score, and ethical compliance level
6. Organizational & Cultural Alignment	Strengthen governance, accountability, and enterprise-wide risk culture	Leadership engagement, capability development, change management	Governance frameworks, structured training pathways, performance monitoring tools, cultural transformation initiatives	Risk awareness index, training completion rate, and governance effectiveness

Table 5. Lean Six Sigma DMAIC Framework for SCRM.

(This table has been conceptually developed by the authors)

Phase	Objectives	Key Activities	Industry 4.0 Focus	Industry 5.0 Focus	Tools
Define	Set SCRM scope, objectives, and strategic priorities	Identify critical risks, map supply chain processes, analyze stakeholders, define KPIs/KRIs, develop project charters	Centralized dashboards, automated risk documentation, digital process mapping	Human-centric prioritization, ethical alignment, collaborative decision-making	SIPOC diagrams, risk prioritization matrix, stakeholder analysis
Measure	Quantify risk exposure, establish baselines, validate data	Collect and validate supply chain data, process mapping, KPI/KRI calculation, statistical analysis	IoT-enabled monitoring, ERP integration, sensor -based real-time data	Context-aware interpretation, human validation, integration of tacit knowledge	Process mapping, data analytics, statistical process control, risk dashboards
Analyze	Identify root causes, interdependencies, and cascading risks	FMEA, Pareto analysis, Ishikawa diagrams, cause-effect mapping, scenario evaluation	AI/ML predictive analytics, simulation models, digital twin scenario testing	Ethical evaluation of scenarios, human–AI collaboration, collective problem-solving, risk-aware culture	FMEA, Pareto charts, Ishikawa diagrams, Bayesian networks, simulation software
Improve	Implement mitigation strategies to reduce risk and optimize performance	Lean process improvement, Six Sigma optimization, contingency planning, standardization	Predictive modeling, digital twins, blockchain-enabled traceability	Human–AI collaboration for adaptive solutions, ethical decision-making, resilient and flexible process design	Lean tools (5S, Kaizen), Six Sigma optimization, digital twins, blockchain, predictive analytics
Control	Sustain improvements, monitor effectiveness, and	Standardize procedures, dashboards, audits, feedback loops,	Real-time dashboards, automated alerts, predictive risk	Human oversight of AI insights, adaptive governance,	SOPs, dashboards, audits, KPI tracking

Phase	Objectives	Key Activities	Industry 4.0 Focus	Industry 5.0 Focus	Tools
	enable continuous improvement	continuous improvement initiatives	triggers	accountability, risk -aware culture	software, control charts

Table 6. Strategic Objectives and KPIs for SCRM.

(This table has been conceptually developed by the authors)

#	Strategic Objective	Description	KPIs	Industry 4.0 Focus	Industry 5.0 Focus
1	End-to-End Risk Integration	Establish a unified, multi-tier risk management framework to reduce silos, improve coordination, and enhance visibility across the supply chain.	Risk coverage completeness (%), Cross-tier alignment score, Mitigation plan execution rate	Centralized dashboards, automated risk documentation, digital process mapping	Human-centric prioritization, collaborative decision-making, ethical alignment
2	Sustainability & ESG Alignment	Integrate ESG principles to ensure sustainable, ethical, and compliant operations throughout the supply chain.	ESG compliance rate (%), Carbon footprint reduction (%), Supplier ethical compliance rate	ESG monitoring systems, carbon analytics, traceable reporting	Human oversight of ESG metrics, ethical interpretation, sustainability-driven decision-making
3	Operational Resilience & Flexibility	Build resilient and adaptive supply chains capable of responding effectively to disruptions while maintaining continuity and performance.	Resilience index, Supplier reliability (%), Process flexibility score	Predictive modeling, digital twins, disruption scenario simulations	Adaptive human–AI collaboration, flexible decision-making, risk-aware culture
4	Predictive & Data-Driven Decision-Making	Enable proactive identification and mitigation of risks using real-time data, predictive analytics, and scenario modeling.	Predictive model accuracy (%), Early risk detection lead time, Data integration rate (%)	IoT sensors, ERP integration, AI/ML analytics, real-time dashboards	Context-aware interpretation, human validation, collaborative scenario analysis
5	Human–Digital Collaboration	Leverage human expertise alongside advanced digital tools to enable informed, ethical, and adaptive risk decisions.	Digital tool adoption rate (%), Human–machine collaboration score, Ethical compliance	AI-assisted decision support, AR/VR-enabled training, collaborative digital platforms	Ethical oversight, contextual decision-making, team-based problem solving
6	Organizational & Cultural Readiness	Foster a risk-aware culture through governance, training, knowledge sharing, and leadership engagement.	Risk awareness index, Training completion rate (%), Governance effectiveness score	Digital knowledge management, automated reporting, performance dashboards	Leadership-driven culture, knowledge sharing, accountability, proactive risk mindset

5. Conclusion and Future Work

This study investigates the evolving challenges of Supply Chain Risk Management (SCRM) in today's complex, multi-tiered, and digitally connected supply chains. Modern supply chains are increasingly exposed to dynamic risks arising from globalization, technological disruption, and sustainability pressures. Traditional

risk management approaches are often fragmented, reactive, and insufficient to maintain operational resilience, ethical governance, and ESG performance.

To address these challenges, the study proposes the Strategic Integrated Risk Assessment Framework (SIRAF), a comprehensive, proactive, and data-driven methodology. SIRAF integrates sustainability, resilience, and digitalization by leveraging Industry 4.0 technologies and Industry 5.0 human-centric principles, enabling predictive, adaptive, and ethically guided risk management across environmental, social, economic, operational, and technological dimensions. The framework consists of six interconnected modules —Fragmentation & Integration, Multi-Tier Visibility & Data, Sustainability & Resilience, Dynamic Risk Assessment, Technology–Human Collaboration, and Organizational & Cultural Alignment—each supported by targeted objectives, tools, and KPIs to ensure end-to-end, systemic risk management.

The study further operationalizes SIRAF using the Lean Six Sigma DMAIC framework, providing a structured approach to define, measure, analyze, improve, and control supply chain risks. The integration of Industry 4.0 digital tools—such as IoT, AI/ML analytics, digital twins, and blockchain—with Industry 5.0 human-centric practices, including collaborative decision-making, ethical oversight, and adaptive governance, ensures that risk management is both data-driven and human-centered. This approach enhances organizational resilience, operational efficiency, and sustainability performance.

Additionally, the study identifies six strategic objectives for SCRM—End-to-End Risk Integration, Sustainability & ESG Alignment, Operational Resilience & Flexibility, Predictive & Data-Driven Decision-Making, Human–Digital Collaboration, and Organizational & Cultural Readiness—together with measurable KPIs and the complementary contributions of Industry 4.0 and 5.0. These objectives provide a structured roadmap for organizations to proactively anticipate, assess, and mitigate risks while achieving sustainable and resilient supply chain operations.

In conclusion, this study presents a holistic, forward-looking framework for SCRM, integrating advanced technologies, human expertise, and sustainability principles. By combining SIRAF, Lean Six Sigma DMAIC, and strategic objectives, organizations can transform fragmented, reactive practices into proactive, resilient, sustainable, and ethically guided supply chain management, fully aligned with the paradigms of Industry 4.0 and 5.0.

Theoretical Implications: SIRAF advances SCRM theory by integrating sustainability, resilience, and digital transformation within a unified framework. It highlights the interconnection of risk domains and the role of human–machine collaboration in enabling proactive, predictive, and adaptive risk management across multi-tier supply chains.

Practical Implications: For practitioners, SIRAF provides a structured methodology to identify, assess, and mitigate risks across complex supply networks. By integrating advanced digital tools with sustainability principles, organizations can improve visibility, responsiveness, and operational efficiency while aligning risk management with ESG objectives.

Managerial Implications: Managers can leverage SIRAF to strengthen strategic decision-making, enhance supply chain resilience, and optimize resource allocation for risk mitigation. The framework supports scenario planning, data-driven insights, and transparent reporting, enabling organizations to balance operational performance with long-term sustainability and resilience goals.

Study Limitations: Despite its contributions, SIRAF remains conceptual and requires empirical validation across diverse industries and multi-tier supply chains. Implementation may demand significant technological investment, organizational transformation, and stakeholder engagement, potentially limiting adoption in resource-constrained contexts.

Future Research Directions: Future research should focus on advancing SCRM in the Industry 4.0–5.0 era by:

- Developing hybrid AI–human risk intelligence for adaptive, ethical, and context-aware decision-making.
- Establishing cross-industry digital ecosystems for collaborative risk management across complex supply networks.
- Enhancing socio-technical resilience by integrating technology, human expertise, and organizational culture.
- Exploring decentralized risk-sharing mechanisms and circular supply chain principles to optimize resource efficiency, sustainability, and distributed risk mitigation.
- Conducting empirical validation of AI-driven predictive analytics across multi-tier supply chains to ensure effectiveness and scalability.

These directions will refine SIRAF, strengthen SCRM theory and practice, and support the development of resilient, sustainable, and digitally empowered supply chains capable of navigating uncertainty while delivering long-term economic, social, and environmental value.

Conflicts of Interest

The authors declare no conflicts of interest.

Generative Artificial Intelligence Statement

The authors used the free version of ChatGPT to refine the writing quality of some paragraphs. No generative artificial intelligence (GenAI) was used in creating the manuscript content.

Data Availability Statement

All data supporting this study are contained within the article.

Abbreviations

Abbreviation	Full Term	Definition
AI	Artificial Intelligence	Systems performing tasks that normally require human intelligence.
AIoT	Artificial Intelligence of Things	AI embedded in IoT devices for automation and predictive analytics.
AR	Augmented Reality	Digital overlays on the physical world for visualization or training.
CPS	Cyber-Physical Systems	Integration of computation with physical processes for real-time control.
DT	Digital Twin	Virtual model of assets for monitoring and simulation.
DMAIC	Define, Measure, Analyze, Improve, Control	Lean Six Sigma method for process improvement.
ESG	Environmental, Social, and Governance	Criteria for sustainability, ethics, and responsible practices.
FMEA	Failure Mode and Effects Analysis	Method for identifying and evaluating potential failures.
IoT	Internet of Things	Network of devices collecting and sharing real-time data.
KPI	Key Performance Indicator	Metric to evaluate performance objectively.
LSS	Lean Six Sigma	Method combining Lean and Six Sigma for efficiency and quality.
MCDM	Multi-Criteria Decision-Making	Approach for making decisions with multiple criteria.
ML	Machine Learning	AI systems that learn from data to improve performance.

Abbreviation	Full Term	Definition
OEE	Overall Equipment Effectiveness	Metric assessing equipment productivity and efficiency.
RAMS	Reliability, Availability, Maintainability, Safety	Metrics evaluating system reliability and safety.
RPN	Risk Priority Number	Value used in FMEA to prioritize risks.
SCP	Supply Chain Performance	Measure of supply chain efficiency and effectiveness.
SIRAF	Strategic Integrated Risk Assessment Framework	Framework for evaluating and managing risks strategically.
SCRM	Supply Chain Risk Management	Process to identify, assess, and mitigate supply chain risks.
SLR	Systematic Literature Review	Structured summary and synthesis of research evidence.
SMEs	Small and Medium-sized Enterprises	Organizations of limited size that drive innovation.
SSCM	Sustainable Supply Chain Management	Incorporating sustainability into supply chain operations.
VR	Virtual Reality	An immersive digital environment for simulation or training.

References

[1] Liu, P., Atifeh, M., Khorshidnia, M. and Taheri, S.G., 2023. System dynamics: An approach to modeling supply chain performance measurement. Technological and Economic Development of Economy, 29(4), pp.1291-1317.
[2] Zaman, S.I. and Kusi-Sarpong, S., 2024. Identifying and exploring the relationship among the critical success factors of sustainability toward consumer behavior. Journal of modelling in management, 19(2), pp.492-522.
[3] Umar, M. and Wilson, M.M., 2024. Inherent and adaptive resilience of logistics operations in food supply chains. Journal of Business Logistics, 45(1), p.e12362.
[4] Mukherjee, S., De, A. and Roy, S., 2024. Supply chain risk prioritization: a multi-criteria based Intuitionistic Fuzzy TOPSIS approach. International Journal of Quality & Reliability Management, 41(6), pp.1693-1725.
[5] Guntuka, L., Corsi, T.M. and Cantor, D.E., 2024. Recovery from plant-level supply chain disruptions: supply chain complexity and business continuity management. International Journal of Operations & Production Management, 44(1), pp.1-31.
[6] Kwaramba, C.S., Goldstein, S.M., Lowry, P.B., Nottingham, Q.J. and Cooper, E.F., 2024. Supply chain resilience as endotherm resilience: Theorizing through metaphorical transfer. Production and Operations Management, 33(2), pp.456-474.
[7] Edalatpour, M.A., Al-e, S.M.J.M. and Ghasemi, S., 2025. Harmonizing Project Management and Supply Chain for Sustainable Construction: A Comprehensive Mathematical Model and Case Study. Sustainable Futures, p.100805.
[8] Narimissa, O., Kangarani-Farahani, A. and Molla-Alizadeh-Zavardehi, S., 2020. Evaluation of sustainable supply chain management performance: Dimensions and aspects. Sustainable Development, 28(1), pp.1-12.
[9] Pacheco, D.A.D.J. and Clausen, D.M., 2024. Sustainable purchasing supply management assessment in construction supply chains: a design science research approach. Supply Chain Management: An International Journal, 29(6), pp.943-962.
[10] Zhou, X., Jiang, J., Zhou, C., Li, X. and Yin, M., 2024. Circular supply chain management: Antecedent effect of social capital and big data analysis capability and their impact on sustainable performance. Sustainable Development, 32(5), pp.5311-5330.
[11] Huang, D.H., 2025. 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, 257, p.110821.
[12] Gomaa, A.H., 2025. 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, 14(2), pp.1-12.

[13] Saputro, T.E., Rosiani, T.Y., Mubin, A., Dewi, S.K. and Baroto, T., 2024. Green supplier selection under supply risks using novel integrated fuzzy multi-criteria decision making techniques. Journal of Cleaner Production, 449, p.141788.
[14] Tian, Y., Song, S., Zhou, D., Pang, S. and Wei, C., 2023. 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, 223, p.119826.
[15] Hajmohammad, S., Klassen, R.D. and Vachon, S., 2024. Managing supplier sustainability risk: an experimental study. Supply Chain Management: An International Journal, 29(1), pp.50-67.
[16] Bustinza, O.F., Vendrell-Herrero, F. and Jabbour, C.J.C., 2024. Integration of product-service innovation into green supply chain management: Emerging opportunities and paradoxes. Technovation, 130, p.102923.
[17] Ngo, V.M., Quang, H.T., Hoang, T.G. and Binh, A.D.T., 2024. Sustainability-related supply chain risks and supply chain performances: The moderating effects of dynamic supply chain management practices. Business Strategy and the environment, 33(2), pp.839-857.
[18] Shahbaz, M.S., Sohu, S., Khaskhelly, F.Z., Bano, A. and Soomro, M.A., 2019. A Novel Classification of Supply Chain Risks: A Review. Engineering, Technology & Applied Science Research, 9(3).
[19] Gomaa, A.H., 2024. Boosting supply chain effectiveness with Lean Six Sigma. American Journal of Management Science and Engineering, 9(6), pp.156-171.
[20] Hamida, H.B. and Aloui, C., 2025. The Influence of Global Risks on Supply Chain Tokens' Intra-Market Dynamics. Engineering, Technology & Applied Science Research, 15(6), pp.28427-28431.
[21] Balan, S. and Handfield, R., 2025. An integrated supply chain risk mitigation tool–model, analysis and insights. International Journal of Management Science and Engineering Management, 20(2), pp.225-240.
[22] El Baz, J. and Ruel, S., 2021. Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. International journal of production economics, 233, p.107972.
[23] Shahed, K.S., Azeem, A., Ali, S.M. and Moktadir, M.A., 2021. A supply chain disruption risk mitigation model to manage COVID-19 pandemic risk. Environmental Science and Pollution Research, pp.1-16.
[24] Hohenstein, N.O., 2022. Supply chain risk management in the COVID-19 pandemic: strategies and empirical lessons for improving global logistics service providers' performance. The International Journal of Logistics Management, 33(4), pp.1336-1365.
[25] Mishra, R. and Singh, R.K., 2023. A systematic literature review on supply chain resilience in SMEs: learnings from COVID-19 pandemic. International Journal of Quality & Reliability Management, 40(5), pp.1172-1202.
[26] Awain, A.M.S.B., Jantan, M.D. and Sukati, I., 2022. Assessing the effect of integration in logistics sector on economic growth: Evidence from Sultanate of Oman. International Business Research, 15(1), p.35.
[27] Abdelfattah, F., Malik, M., Al Alawi, A.M., Sallem, R. and Ganguly, A., 2023. Towards measuring SMEs performance amid the COVID-19 outbreak: exploring the impact of integrated supply chain drivers. Journal of Global Operations and Strategic Sourcing, 16(2), pp.520-540.
[28] Klein, V.B. and Todesco, J.L., 2021. COVID-19 crisis and SMEs responses: The role of digital transformation. Knowledge and process management, 28(2), pp.117-133.
[29] Zutshi, A., Mendy, J., Sharma, G.D., Thomas, A. and Sarker, T., 2021. From challenges to creativity: Enhancing SMEs' resilience in the context of COVID-19. Sustainability, 13(12), p.6542.
[30] Thukral, E., 2021. COVID-19: Small and medium enterprises challenges and responses with creativity, innovation, and entrepreneurship. Strategic Change, 30(2), pp.153-158.
[31] Foli, S., Durst, S. and Temel, S., 2024. The link between supply chain risk management and innovation performance in SMEs in turbulent times. Journal of Entrepreneurship in Emerging Economies, 16(3), pp.626-648.
[32] Grondys, K., Ślusarczyk, O., Hussain, H.I. and Androniceanu, A., 2021. Risk assessment of the SME sector operations during the COVID-19 pandemic. International journal of environmental research and public health, 18(8), p.4183.
[33] Ali, I., Sadiddin, A. and Cattaneo, A., 2023. Risk and resilience in agri-food supply chain SMEs in the pandemic era: a cross-country study. International Journal of Logistics Research and Applications, 26(11), pp.1602-1620.

[34] Mohezar, S., Mohamad, M.N. and Mohd Nor, M.N., 2023. Supply chain risk and SME business continuity strategies in the food industry during COVID-19 pandemic. Continuity & Resilience Review, 5(2), pp.116-134.
[35] Sun, K.X., Ooi, K.B., Tan, G.W.H. and Lee, V.H., 2023. Enhancing supply chain resilience in SMEs: a deep Learning-based approach to managing Covid-19 disruption risks. Journal of Enterprise Information Management, 36(6), pp.1508-1532.
[36] Sulaiman, M.A.B.A., Asad, M., Awain, A.M.S.B., Asif, M.U. and Shanfari, K.S.A., 2024. Entrepreneurial marketing and performance: contingent role of market turbulence. Discover Sustainability, 5(1), p.492.
[37] Abdallah, A.B., Alfar, N.A. and Alhyari, S., 2021. The effect of supply chain quality management on supply chain performance: the indirect roles of supply chain agility and innovation. International Journal of Physical Distribution & Logistics Management, 51(7), pp.785-812.
[38] Annamalah, S., Aravindan, K.L. and Ahmed, S., 2025. Resilience in the Face of Uncertainty: Navigating Supply Chain Challenges Through Proactive Risk Surveillance and Mitigation Strategies among SMEs in ASEAN countries. F1000Research, 13, p.1037.
[39] Huang, A. and Yang, Y., 2025. FMEA Risk Assessment Method: Integration of Multi-Perspective Weights and Interval Cloud Model with TOPSIS Approach. Expert Systems with Applications, p.128377.
[40] Das, S., Dutta, R. and De, S., 2025. Integrated assessment of supply risks, techno-economic and environmental factors for sustainable hybrid energy systems with emerging storage technologies: A MCDM approach. Applied Energy, 399, p.126519.
[41] He, S., Shi, S., Lin, Z., Lu, Y., Li, H. and You, B., 2025. Risk assessment of coal mine gas explosion based on cloud model and Bayesian network. Reliability Engineering & System Safety, p.111798.
[42] Both, C.M. and Wilhelm, M., 2025. Supply Chain Sustainability Risk Management in the Era of Mandatory Due Diligence: A Literature Review. Journal of Purchasing and Supply Management, p.101083.
[43] Zhang, F. and Song, W., 2022. Sustainability risk assessment of blockchain adoption in sustainable supply chain: An integrated method. Computers & Industrial Engineering, 171, p.108378.
[44] Jia, Y., Liu, Y. and Taghizadeh-Hesary, F., 2025. The nexus among geopolitical risk, metal prices, and global supply chain pressure: Evidence from the TVP-SV-VAR approach. Economic Analysis and Policy, 85, pp.1776-1789.
[45] Nezianya, M.C., Adebayo, A.O. and Ezeliora, P., 2024. A critical review of machine learning applications in supply chain risk management. World Journal of Advanced Research & Reviews, 23(3), pp.1554-1567.
[46] Khan, K., 2025. How do supply chain and geopolitical risks threaten energy security? A time and frequency analysis. Energy, 316, p.134501.
[47] Gao, J., Qin, Q. and Zhou, S., 2025. Spillover effects of US economic policy uncertainty on emerging markets: Evidence from transnational supply chains. Journal of International Financial Markets, Institutions and Money, 100, p.102136.
[48] Fang, Y., Tang, Q. and Wang, Y., 2024. Geopolitical risk and cryptocurrency market volatility. Emerging Markets Finance and Trade, 60(14), pp.3254-3270.
[49] Zhao, Q., Wang, W. and Tao, Y., 2025. Supply chain sustainability and its impact on firm market competitiveness: A perspective based on ESG practices. International Review of Economics & Finance, p.104236.
[50] Ba Awain, A.M.S., Asad, M., Sulaiman, M.A.B.A., Asif, M.U. and Shanfari, K.S.A., 2025. Impact of supply chain risk management on product innovation performance of Omani SMEs: Synergetic moderation of technological turbulence and entrepreneurial networking. Sustainability, 17(7), p.2903.
[51] Swaminathan, K. and Venkitasubramony, R., 2024. Demand forecasting for fashion products: A systematic review. International Journal of Forecasting, 40(1), pp.247-267.
[52] Yan, J., Gui, Q., Jiang, S., Yu, Z., Fernandes, K., Tian, K., Xia, S. and Gong, Y., 2025. How does blockchain application impact on supply chain alliance?. Technovation, 143, p.103199.
[53] Shelar, A., Nile, S.H., Singh, A.V., Rothenstein, D., Bill, J., Xiao, J., Chaskar, M., Kai, G. and Patil, R., 2023. Recent advances in nano-enabled seed treatment strategies for sustainable agriculture: challenges, risk assessment, and future perspectives. Nano-Micro Letters, 15(1), p.54.
[54] Aljohani, A., 2023. Predictive analytics and machine learning for real-time supply chain risk mitigation and agility. Sustainability, 15(20), p.15088.

[55] AlZayani, F., Mohammed, A. and Shoaib, H.M., 2024. The impact of smart technologies on SMEs' sustainability: the mediation effect of sustainability strategy. Competitiveness Review: An International Business Journal, 34(1), pp.28-50.
[56] Farazi, M.Z.R., 2025. Building Agile Supply Chains with Supply Chain 4.0: A Data-Driven Approach to Risk Management. The American Journal of Engineering and Technology, 7(03), pp.21-34.
[57] Ghanbari, H., Shabani, M., Mohammadi, E. and Seiti, H., 2025. A Comprehensive Bibliometric Review of Digitalization Impacts on Supply Chain Risk Management. Supply Chain Analytics, p.100165.
[58] Hasan, N., Ahmed, N. and Ali, S.M., 2024. Improving sporadic demand forecasting using a modified k-nearest neighbor framework. Engineering Applications of Artificial Intelligence, 129, p.107633.
[59] Jahin, M.A., Naife, S.A., Saha, A.K. and Mridha, M.F., 2023. Ai in supply chain risk assessment: A systematic literature review and bibliometric analysis. arXiv preprint arXiv:2401.10895.
[60] Berger, N., Schulze-Schwering, S., Long, E. and Spinler, S., 2023. Risk management of supply chain disruptions: An epidemic modeling approach. European Journal of Operational Research, 304(3), pp.1036-1051.
[61] Chepkwemoi, A.N., Oteki, E.B. and Otieno, R.J., 2025. Role of supply chain risk management on operational performance of manufacturing firms in Nairobi City County, Kenya.
[62] de Oliveira, U.R., Brasil, T.F., Aprigliano, V., Santos, C.R.D. and Lima, G.B.A., 2025. Evaluation of ISO 31010 Techniques for Supply Chain Risk Management in Automotive Suppliers. Applied Sciences, 15(8), p.4169.
[63] Egila, A.E., Kamal, M.M., Kumar Mangla, S., Rich, N. and Tjahjono, B., 2025. Highly reliable organisations and sustainability risk management: safety cultures in the Nigerian oil and gas supply chain sector. Business Strategy and the Environment, 34(2), pp.2680-2701.
[64] Elmsalmi, M., Hachicha, W. and Aljuaid, A.M., 2021. Prioritization of the best sustainable supply chain risk management practices using a structural analysis based-approach. Sustainability, 13(9), p.4608.
[65] Hosseini Shekarabi, S.A., Kiani Mavi, R. and Romero Macau, F., 2025. Supply chain resilience: A critical review of risk mitigation, robust optimisation, and technological solutions and future research directions. Global Journal of Flexible Systems Management, 26(3), pp.681-735.
[66] Ikasari, D.M., Suef, M. and Vanany, I., 2025. A Bibliometric Analysis of Risk Management and Sustainability in the Agri-Food Supply Chain: Future Directions. Engineering Proceedings, 84(1), p.13.
[67] Jidda Jidda, D., Zhen, L., Ashraf, S.F., Nasir, A. and Amoako, T., 2025. Value of Enterprise Risk Management Integration and Supply Chain Performance: Mediating Role of Firm's Resilience Capability. SAGE Open, 15(1), p.21582440241305618.
[68] Kalla, C., Scavarda, L.F. and Hellingrath, B., 2025. Integrating supply chain risk management activities into sales and operations planning. Review of Managerial Science, 19(2), pp.467-497.
[69] Khan, M.A., Saqib, S., Alyas, T., Rehman, A.U., Saeed, Y., Zeb, A., Zareei, M. and Mohamed, E.M., 2020. Effective demand forecasting model using business intelligence empowered with machine learning. IEEE access, 8, pp.116013-116023.
[70] Li, J., Zhang, Y., Fang, H. and Fang, S., 2023. Risk evaluation of photovoltaic power systems: An improved failure mode and effect analysis under uncertainty. Journal of Cleaner Production, 414, p.137620.
[71] Löffel, M., Schmidt, C.G. and Wagner, S.M., 2025. Supply chain risk management for humanitarian aid delivery: risk identification and contingency analysis. The International Journal of Logistics Management, 36(1), pp.225-258.
[72] Long, Y., Yang, Y., Feng, T., Cheng, Y. and Farooq, S., 2025. Green supply chain integration, lean management, and manufacturers' performance: role of supply chain risk management. Total Quality Management & Business Excellence, 36(5-6), pp.369-394.
[73] Machfudiyanto, R.A., Humang, W.P., Kamil, I., Latief, Y., Wahjuningsih, N. and Putra, Y.Y.A., 2025. Enhancing Small-Scale LNG supply Chains: Risk mitigation strategies and frameworks for archipelagic distribution. Cleaner Logistics and Supply Chain, 16, p.100249.
[74] Minguito, G. and Banluta, J., 2023. Risk management in humanitarian supply chain based on FMEA and grey relational analysis. Socio-economic planning sciences, 87, p.101551.

[75] Munir, M.A., Hussain, A., Farooq, M., Rehman, A.U. and Masood, T., 2024. Building resilient supply chains: Empirical evidence on the contributions of ambidexterity, risk management, and analytics capability. Technological Forecasting and Social Change, 200, p.123146.
[76] Ordibazar, A.H., Hussain, O.K., Chakrabortty, R.K., Irannezhad, E. and Saberi, M., 2025. Artificial intelligence applications for supply chain risk management considering interconnectivity, external events exposures and transparency: a systematic literature review. Modern Supply Chain Research and Applications, (ahead-of-print).
[77] Ouarrak, Y.E., Derrouiche, R. and Hmioui, A., 2025. Big Data Analytics and Supply Chain Risk Management: scientometric mapping based on the Scopus database. LogForum, 21(2).
[78] Piprani, A.Z., Jaafar, N.I., Ellahi, R.M., Watabe, M., Islam, M.A. and Najmi, A., 2025. Supply Chain Mapping for High Risk Environment: Industry 4.0 and the Quest for Resilient and Sustainable Supply Chains. Sustainable Development.
[79] Plakantara, S.P. and Karakitsiou, A., 2025, August. Transforming Agrifood Supply Chains with Digital Technologies: a Systematic Review of Safety and Quality Risk Management. In Operations Research Forum (Vol. 6, No. 3, p. 113). Cham: Springer International Publishing.
[80] Reshad, A.I., Biswas, T., Agarwal, R., Paul, S.K. and Azeem, A., 2023. Evaluating barriers and strategies to sustainable supply chain risk management in the context of an emerging economy. Business strategy and the environment, 32(7), pp.4315-4334.
[81] Rohaninejad, M., Janota, M. and Hanzálek, Z., 2023. Integrated lot-sizing and scheduling: Mitigation of uncertainty in demand and processing time by machine learning. Engineering Applications of Artificial Intelligence, 118, p.105676.
[82] Shekarian, M. and Mellat Parast, M., 2021. An Integrative approach to supply chain disruption risk and resilience management: a literature review. International Journal of Logistics Research and Applications, 24(5), pp.427-455.
[83] Smith, C. and Fatorachian, H., 2025. Strengthening supply chain risk management: Unveiling opportunities through the lens of behavioral economics and organizational culture. Procedia Computer Science, 253, pp.124-133.
[84] Stephen, G., 2025. Business Continuity and Risk Mitigation in the Pharmaceutical Industry: Strengthening Supply Chains for Pandemic Preparedness. International Journal of Scientific Research and Management (IJSRM), 13(02), pp.8398-8412.
[85] Sumrit, D., 2025. 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, 25, p.104499.
[86] Sutrisno, A. and Kumar, V., 2023. Supply chain sustainability risk assessment model using integration of the preference selection index (PSI) and the Shannon entropy. International journal of quality & reliability management, 40(3), pp.674-708.
[87] Thi Binh An, D., Nguyen, T.T.B. and Truong Quang, H., 2024. Service-oriented supply chain: what do we know about its risks?. International Journal of Logistics Research and Applications, 27(11), pp.2021-2048.
[88] Tsang, Y.P., Choy, K.L., Wu, C.H., Ho, G.T., Lam, C.H. and Koo, P.S., 2018. An Internet of Things (IoT)-based risk monitoring system for managing cold supply chain risks. Industrial Management & Data Systems, 118(7), pp.1432-1462.
[89] Ventura, L., Martín-Jimenez, I. and Gallego-Garcia, M., 2025. A Risk Management Framework to Enhance Environmental Sustainability in Industrial Symbiosis Ecosystems. Sustainability, 17(6), p.2604.
[90] Wang, Y., Zhou, B., Zhang, C., Or, S.W., Gao, X. and Da, Z., 2024. A Hybrid Data and Knowledge Driven Risk Prediction Method for Distributed Photovoltaic Systems Considering Spatio-Temporal Characteristics of Extreme Rainfalls. IEEE Transactions on Industry Applications.
[91] Yaghoubi, E., Yaghoubi, E., Maghami, M.R. and Jahromi, M.Z., 2025. Comprehensive technical risk indices and advanced methodologies for power system risk management. Electric Power Systems Research, 244, p.111534.
[92] Yang, C., Tian, K. and Gao, X., 2025. Supply chain resilience: Measure, risk assessment and strategies. Fundamental Research, 5(2), pp.433-436.
[93] Yun, N.Y. and Ülkü, M.A., 2023. Sustainable supply chain risk management in a climate-changed world: Review of extant literature, trend analysis, and guiding framework for future research. Sustainability, 15(17), p.13199.

[94] Zheng, L.J., Islam, N., Zhang, J.Z., Behl, A., Wang, X. and Papadopoulos, T., 2025. Aligning risk and value creation: a process model of supply chain risk management in geopolitical disruptions. International Journal of Operations & Production Management, 45(5), pp.1178-1210.
[95] Zhou, H., Wang, Q. and Yang, Q., 2025. How does digitalisation influence supply chain performance? Evidence from a supply chain risk management perspective. International Journal of Logistics Research and Applications, 28(3), pp.325-343.
[96] Zhu, X.X., Zhu, J., Regan, D. and Wen, Z.M., 2025. Exploring cascading failures in supply chain risk management: A systematic review, 2013-2024. Journal of Safety Science and Resilience, p.100234.