



Review article

Sustainable supply chain management in Industry 4.0: A review, research gaps, and conceptual framework

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Abstract: Global supply chains are undergoing systemic transformation driven by escalating environmental pressures, rising stakeholder expectations, stricter regulatory requirements, and rapid technological advancement, positioning sustainable supply chain management (SSCM) as a key paradigm for integrating environmental, social, and economic performance with resilience and long-term competitiveness. In parallel, Industry 4.0 technologies—including the Internet of Things (IoT), artificial intelligence (AI), blockchain, robotics, and digital twins—are reshaping supply chain operations by enabling real-time visibility, predictive analytics, and enhanced decision-support capabilities, thereby improving transparency, traceability, and sustainability across multi-tier networks. However, despite substantial technological progress, a persistent gap remains between Industry 4.0 adoption and sustainability and circular economy objectives, reflecting fragmented theoretical development and limited practical integration. To address this gap, this study conducts a literature review of SSCM in the Industry 4.0 context, synthesizing existing research, identifying emerging themes, and examining key technological, organizational, and governance-related barriers. Building on this synthesis, a novel integrative SSCM framework is developed by combining Industry 4.0 technologies, Lean Six Sigma (LSS), and sustainability principles to enable adaptive, data-driven, and continuously improving supply chain systems. The framework is structured around five interrelated dimensions—digital integration and connectivity, intelligent decision-making, transparency and traceability, sustainability and circularity, and resilience and agility—supported by strategic alignment, end-to-end process integration, digital infrastructure, and human-centric capabilities. Furthermore, the DMAIC methodology is embedded as a structured continuous improvement mechanism for process optimization, waste reduction, and sustainability performance enhancement.

Keywords: Sustainable supply chain management; Industry 4.0; digital transformation; circular economy; lean six sigma; supply chain resilience; sustainability performance

1. Introduction

In today's globalized and highly competitive business environment, supply chains are critical drivers of organizational performance, resilience, and sustainability. Modern supply chains are no longer evaluated solely on operational efficiency and cost reduction; they must also address environmental protection, social responsibility, and ethical practices, driven by growing stakeholder expectations, stricter regulations, and heightened societal awareness. Recent disruptions—ranging from pandemics and geopolitical conflicts to climate-related events—have exposed vulnerabilities in conventional supply networks, highlighting the need for adaptive, transparent, and future-ready supply chains. At the same time, Industry 4.0 technologies—including the Internet of Things (IoT), artificial intelligence (AI), blockchain, robotics, and digital twins—provide unprecedented opportunities to integrate sustainability objectives with operational performance, enhance real-time decision-making, optimize resources, and improve overall supply chain resilience [1-3]. These converging pressures and opportunities underscore the importance of investigating how sustainable supply chain management (SSCM) can be effectively combined with Industry 4.0 technologies to create intelligent, adaptive, and socially and environmentally responsible supply chains.

1.1. Motivation and relevance

Despite the potential synergy between SSCM and Industry 4.0, their integration remains fragmented in practice. Organizations face challenges in aligning digitalization with sustainability objectives, measuring performance across multi-tier networks, and translating theoretical SSCM frameworks into actionable operational strategies. Existing research provides limited frameworks linking SSCM principles with Industry 4.0 capabilities to achieve efficiency, resilience, and long-term competitiveness simultaneously. The primary motivation of this study is to address these gaps by developing an integrative framework that guides organizations in building adaptive, resilient, and sustainable supply chains while leveraging Industry 4.0 technologies [1–3].

1.2. From traditional SCM to sustainable SCM

Traditional supply chain management (SCM) emphasizes cost reduction, operational efficiency, and productivity, ensuring a seamless flow of goods, services, and information from suppliers to customers. While effective for short-term competitiveness, conventional SCM often overlooks long-term environmental and social impacts, including resource depletion, ecological degradation, and labor inequities, which can generate operational, regulatory, and reputational risks [4–6]. Figure 1 illustrates the progression from traditional SCM to green supply chain management (GSCM) and SSCM,

highlighting the shift from efficiency-focused operations to comprehensive sustainability integration. Over the past decade, sustainability has evolved from a functional requirement to a strategic priority, with organizations increasingly expected to contribute to environmental protection, social equity, and stakeholder well-being. Sustainable supply chain performance (SSCP) has thus become a key measure of organizational success [7]. SSCM enables organizations to reduce emissions and waste, implement ethical practices, improve operational efficiency, comply with regulations, satisfy stakeholders, and maintain competitiveness. However, achieving these objectives remains challenging due to global market volatility, rapid technological change, complex multi-tier networks, and diverse regulatory frameworks [8–10].

1.3. Core dimensions and principles of SSCM

SSCM functions both as a strategic philosophy and an operational framework, transforming linear supply chains into circular, regenerative systems. By optimizing resource use, minimizing waste, and creating shared value, SSCM contributes to sustainable development across the value chain. It is structured around three interrelated dimensions [3,10].

Environmental sustainability focuses on minimizing ecological impact through green procurement, eco-design, energy efficiency, pollution reduction, and waste minimization. Social sustainability emphasizes fair labor practices, ethical operations, community engagement, workforce well-being, and corporate social responsibility (CSR). Economic sustainability ensures financial viability while supporting long-term growth, cost efficiency, risk management, and competitiveness. In practice, SSCM balances economic performance with environmental and social responsibility, fostering resilience, regulatory compliance, stakeholder trust, and competitive differentiation [11]. Figure 2 depicts the SSCM structure, positioning it at the center, supported by the three pillars. Table 1 summarizes SSCM's key elements, linking each element to objectives, associated practices, and expected impacts across ten dimensions, including collaboration, performance measurement, innovation, risk management, circular economy adoption, stakeholder engagement, and ethical compliance [12,13].

1.4. Industry 4.0 as an enabler of SSCM

Industry 4.0 technologies have significantly expanded SSCM's potential by enabling intelligent, adaptive, and transparent supply chains. Technologies such as IoT, AI, blockchain, robotics, and digital twins support real-time monitoring, predictive analytics, scenario modeling, and advanced traceability. Blockchain ensures secure and transparent data exchange; IoT optimizes energy and resource allocation; AI facilitates predictive risk management; and digital twins enable virtual simulation and operational optimization [2,14]. Industry 4.0 improves visibility, coordination, and decision-making across production, logistics, and distribution while enabling new business models and value creation [15,16]. Empirical evidence demonstrates that Industry 4.0 adoption positively influences SSCM performance. IoT-enabled logistics reduces emissions and energy consumption, automation enhances workplace safety, and predictive analytics improves operational efficiency and cost reduction [17,18]. Table 2 categorizes 12 key Industry 4.0 technologies—including IoT, AI & ML,

blockchain, robotics, digital twins, and 5G—detailing applications, SSCM relevance, and impact areas. Figure 3 illustrates the evolution from traditional SCM to SSCM under Industry 4.0, showing four layers: SCM (efficiency, cost, inventory management), GSCM (environmental practices), SSCM (social and economic sustainability), and Industry 4.0 (digital technologies), reflecting the transition toward technology-enabled, sustainable supply chains.

1.5. Research gaps, objectives, and contribution

Despite significant advancements enabled by Industry 4.0, critical challenges persist in aligning digital transformation with sustainability objectives, operationalizing sustainability across multi-tier supply chains, and developing robust mechanisms for integrated environmental, social, and economic performance measurement. The sustainable supply chain management (SSCM) literature remains fragmented, with limited integrative frameworks and insufficient empirical validation in Industry 4.0-enabled contexts. This fragmentation highlights the need for holistic, system-oriented approaches that explicitly integrate digital technologies, sustainability principles, and continuous improvement methodologies into a unified operational logic.

To address these gaps, this study conducts a systematic synthesis of SSCM research in the Industry 4.0 era, identifying dominant and emerging research streams while critically examining technological, organizational, and governance barriers to implementation. Building on this synthesis, an integrated conceptual framework is developed that combines Industry 4.0 capabilities, Lean Six Sigma (LSS), and the DMAIC methodology to enable structured, data-driven, and continuously improving supply chain systems. The framework establishes a direct linkage between digital enablement, process optimization, and sustainability outcomes, thereby enhancing operational efficiency, resilience, and long-term value creation.

By bridging fragmented theoretical perspectives with practical implementation requirements, this study provides a scalable and actionable roadmap for designing intelligent, adaptive, and sustainable supply chains capable of operating effectively in complex and uncertain environments. It advances SSCM scholarship by explicitly positioning continuous improvement mechanisms as a core enabler of digital-sustainability integration.

The following research questions guide the study:

RQ1: How do Industry 4.0 technologies enable sustainability in supply chains?

RQ2: What barriers hinder SSCM–Industry 4.0 integration?

RQ3: Which capabilities enable SSCM–Industry 4.0 convergence?

RQ4: How does DMAIC-based LSS enable continuous supply chain improvement?

The paper is structured as follows: Section 2 reviews SSCM literature; Section 3 identifies research gaps; Section 4 presents the proposed framework; and Section 5 concludes with key insights and future research directions.

Table 1. Key elements, objectives, and practices of SSCM.

#	Element	Description	Objectives	Key practices	Impact areas
1	Environmental sustainability	Eco-friendly supply chain practices	Reduce environmental impact and ensure compliance	Green procurement, waste reduction, energy efficiency, eco-design	Carbon footprint reduction, resource optimization, compliance
2	Social sustainability	Fair labor and societal responsibility	Ensure worker welfare and community engagement	Workplace safety, CSR initiatives, supplier code of conduct	Employee satisfaction, social compliance, brand reputation
3	Economic sustainability	Long-term financial viability	Achieve cost efficiency and risk mitigation	Lean management, sustainable sourcing, cost-effective logistics	Operational efficiency, profitability, supply chain resilience
4	Collaboration and integration	Coordinated stakeholder engagement	Enhance transparency and collective sustainability	Supplier collaboration, joint initiatives, shared information systems	Coordination, transparency, sustainability performance
5	Performance measurement and reporting	Monitoring and evaluating SSCM	Track progress and improve accountability	KPIs, audits, lifecycle assessment, reporting frameworks	Data-driven decisions, compliance, stakeholder trust
6	Innovation and technology	Leveraging technology for sustainability	Improve efficiency and reduce impact	Industry 4.0, AI analytics, digital twins, automation	Process optimization, environmental & social impact reduction
7	Risk management and resilience	Identifying and mitigating risks	Strengthen supply chain robustness	Risk assessment, contingency planning, supplier diversification	Resilience, reduced disruptions, stakeholder confidence
8	Circular economy practices	Closed-loop systems and resource recovery	Reduce waste and enhance resource efficiency	Recycling, remanufacturing, reverse logistics, product take-back	Waste reduction, resource efficiency, sustainability
9	Stakeholder engagement	Involving key stakeholders	Build trust and collaboration	Supplier audits, consumer engagement, partnerships	Stakeholder satisfaction, transparency, social impact
10	Ethical and regulatory compliance	Adherence to laws and standards	Ensure legal and ethical operations	Compliance monitoring, certifications, codes of conduct	Regulatory adherence, risk mitigation, reputation



Figure 1. Relationship between SCM, GSCM, and SSCM.

Table 2. Technology groups for Industry 4.0 in SSCM.

#	Technology group	Applications	SSCM relevance	Impact areas
1	IoT	Real-time monitoring, RFID, smart sensors	Enables transparency and resource efficiency	Traceability, operational optimization, and environmental performance
2	AI and ML	Forecasting, route optimization, predictive analytics	Supports sustainable sourcing and logistics decisions	Cost reduction, energy efficiency, risk management
3	Big data and analytics	Data integration, dashboards, and sustainability reporting	Identifies sustainability gaps and improves planning	Compliance, stakeholder engagement, and strategic decisions
4	Blockchain	Secure data sharing, smart contracts	Enhances transparency and accountability	Ethical sourcing, fraud prevention, supply chain integrity
5	Robotics and automation	Automated warehousing and production	Reduces errors and operational waste	Efficiency, environmental impact reduction
6	Cloud and edge computing	Centralized and real-time data management	Supports integrated and responsive SCM systems	Collaboration, resource optimization, agility
7	Digital twins and simulation	Virtual supply chain modeling	Predicts environmental, social, and operational impacts	Scenario planning, risk mitigation, resource optimization
8	3D printing	On-demand, localized production	Minimizes waste and shortens supply chains	Environmental impact, cost efficiency, and agility
9	AR/VR	Training, maintenance, and warehouse visualization	Enhances operational safety and efficiency	Safety, productivity, resource efficiency
10	Cyber-physical systems	Integration of physical and digital processes	Enables adaptive and responsive supply chains	Process efficiency, resilience, and sustainability monitoring
11	Smart sensors and wearables	Worker safety and environmental monitoring	Supports social and environmental sustainability	Safety, compliance, resource monitoring
12	5G and next-gen connectivity	High-speed data transfer, IoT support	Enables real-time monitoring and automation	Responsiveness, operational efficiency, and digital collaboration

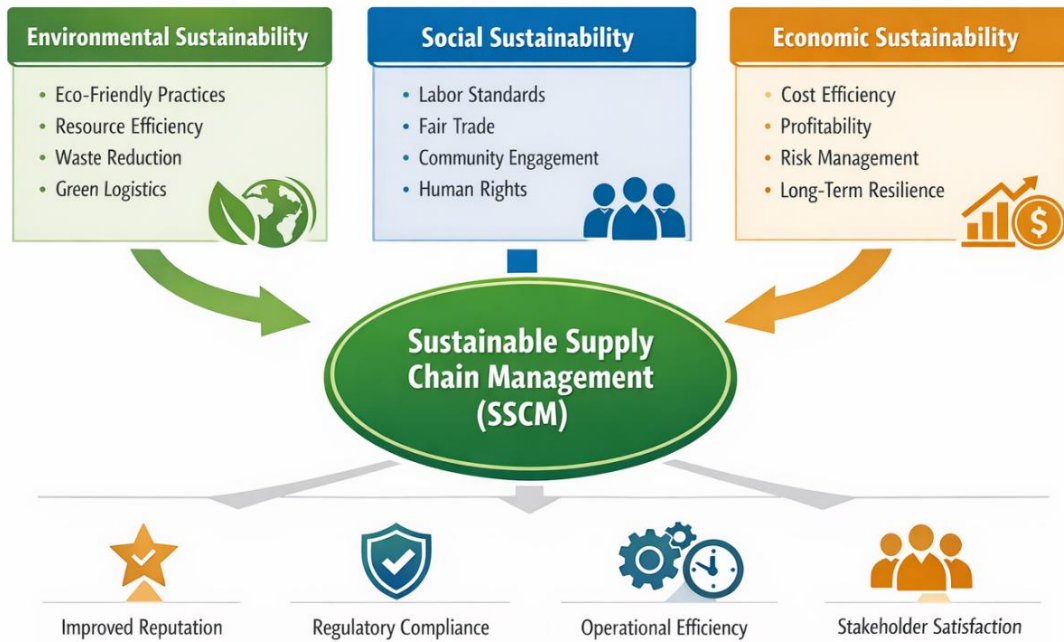


Figure 2. Sustainable supply chain management (SSCM) fundamentals.

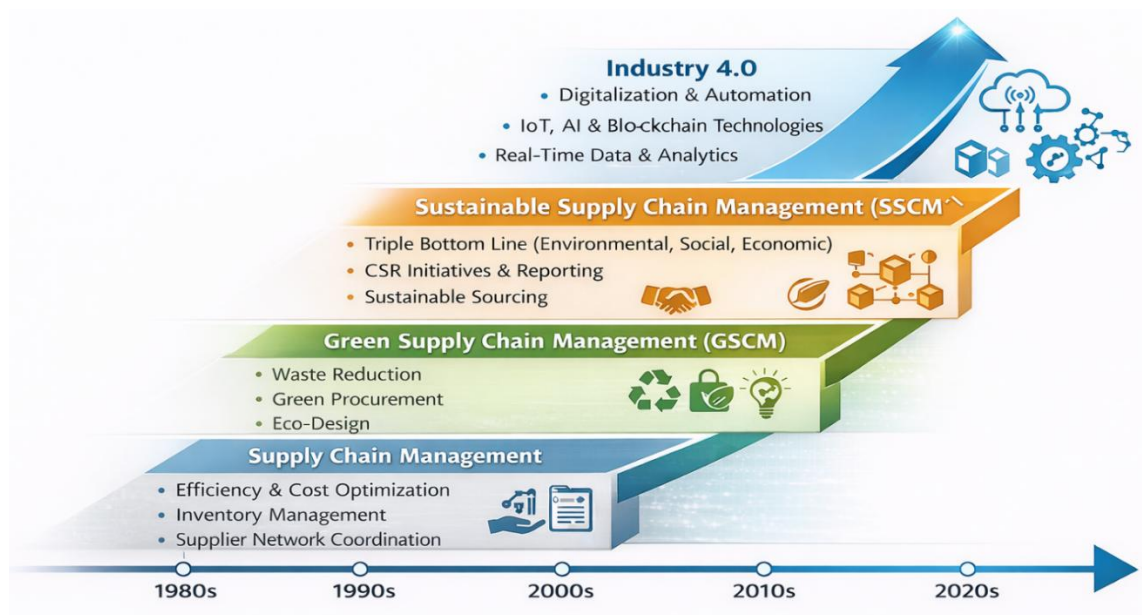


Figure 3. Milestone evolution map of SSCM integrating Industry 4.0.

2. Literature review on SSCM in the era of Industry 4.0

This study employs a systematic literature review (SLR) to investigate the integration of SSCM and Industry 4.0. Peer-reviewed articles published between 2010 and 2025 were retrieved from leading databases using Boolean keyword searches and screened through a four-stage process of identification, screening, eligibility, and inclusion. The final pool of studies was coded for bibliographic details,

methodological approaches, Industry 4.0 technologies, and sustainability dimensions, and analyzed through bibliometric mapping and thematic synthesis. The review consolidates existing knowledge, highlights critical research gaps, and proposes a conceptual framework that links Industry 4.0 technologies with SSCM enablers to advance sustainability outcomes and guide future research and practice.

Sustainable supply chain management (SSCM) extends traditional supply chain practices by embedding environmental, social, and economic considerations across all stages—from sourcing and production to distribution and end-of-life recovery. Practices such as green procurement, eco-design, energy efficiency, waste minimization, ethical labor compliance, and circular economy adoption not only mitigate risks but also enhance operational efficiency, innovation, resilience, and corporate reputation. Increasingly, SSCM is recognized as a strategic approach that balances the triple bottom line—people, planet, and profit—while creating long-term stakeholder value.

Over the past decade, SSCM has evolved from compliance-focused initiatives to a multidimensional paradigm shaped by institutional pressures, stakeholder expectations, and market demands. At the same time, Industry 4.0 technologies—AI, IoT, blockchain, big data analytics, and digital twins—have emerged as key enablers of sustainable, resilient, and high-performance supply chains. Table 3 synthesizes the literature, mapping conceptual foundations, drivers, barriers, performance outcomes, circular economy integration, Industry 4.0 enablers, sectoral and regional variations, and emerging research gaps. Adoption is primarily driven by leadership commitment, stakeholder influence, and risk mitigation, while barriers include limited supplier awareness, regulatory gaps, high costs, and cultural resistance. Evidence suggests that SSCM enhances competitiveness through operational efficiency, innovation, and dynamic capabilities, while circular economy principles and digital technologies strengthen resource efficiency, traceability, and predictive decision-making. Despite these advances, integration remains fragmented, with behavioral, multi-tier, and resilience dimensions underexplored—underscoring the need for empirically validated frameworks to develop adaptive, digitally enabled, and sustainable supply chains.

Conceptual foundations: SSCM has expanded traditional SCM's efficiency and cost-reduction focus to incorporate environmental, social, and economic objectives. Ahi and Searcy (2015) synthesized over 200 definitions to propose a unified, systems-oriented SSCM framework. Institutional pressures—regulation, market competition, and stakeholder expectations—drive adoption [19], while sustainability initiatives strengthen customer loyalty, brand equity, and risk management [20].

Drivers, barriers, and institutional pressures: SSCM implementation is shaped by both enablers and constraints. Top management commitment, stakeholder influence, and risk reduction facilitate adoption [21], whereas limited supplier awareness, weak governmental support, and high costs inhibit progress. Contextual factors, including firm size and national regulatory environments, modulate outcomes [22,23], and corporate culture and regulatory compliance further influence sustainability performance [24].

SSCM, performance, and dynamic capabilities: SSCM practices contribute to performance primarily through operational efficiency, innovation, and dynamic capabilities. Environmental and social initiatives enhance competitiveness indirectly by improving operational and process outcomes [25,26]. Internal SSCM practices support environmental and social goals, which in turn drive financial performance [27]. SSCM routines cultivate adaptability, knowledge sharing, and

responsiveness [28], and recent studies emphasize resilience-building amid disruptions such as COVID-19 [29,30].

Table 3. Key themes in SSCM literature and representative studies.

#	Theme	Key insights and contributions
1	Conceptual foundations	SSCM integrates environmental, social, and economic objectives, shaped by institutional pressures, regulations, and market expectations; it establishes a foundation for sustainability-oriented supply chains.
2	Drivers and barriers	Adoption driven by leadership commitment, stakeholder pressure, risk mitigation, and resource efficiency; barriers include low supplier awareness, weak regulation, cost concerns, and cultural resistance.
3	Performance and dynamic capabilities	SSCM enhances competitiveness and resilience indirectly through operational efficiency, innovation, knowledge sharing, and adaptability; dynamic capabilities mediate sustainability-performance links.
4	Circular economy integration	CE principles (reuse, redesign, reverse logistics) transform linear supply chains into regenerative systems; improve resource efficiency, reduce waste, and enhance transparency and resilience.
5	Industry 4.0 enablers	AI, IoT, blockchain, big data, and metaverse technologies enable traceability, predictive decision-making, and environmental performance; adoption for sustainability remains limited and fragmented.
6	Sectoral and regional insights	SSCM adoption and performance vary across industries and regions due to regulatory, structural, and resource differences; empirical evidence highlights context-specific strategies and outcomes.
7	Emerging directions and research gaps	Behavioral factors (motivation, collaboration), multi-tier performance assessment, digital-circular integration, and turbulence resilience are underexplored; few empirically validated frameworks exist.

Circular economy integration: Circular economy (CE) principles are increasingly central to SSCM, promoting resource efficiency, waste reduction, and closed-loop systems. CE-based supply chains outperform linear systems in emissions control, resource utilization, and transparency [31,32]. Modeling studies highlight optimal pricing, cost-sharing, and remanufacturing strategies that balance profitability with environmental sustainability [33,34].

Industry 4.0 as an enabler: Industry 4.0 technologies—such as IoT, AI, blockchain, digital twins, and cyber-physical systems—are reshaping SSCM by enabling real-time monitoring, predictive analytics, secure information exchange, and virtual simulation of supply chain processes. Blockchain strengthens transparency and accountability [35], IoT and big data drive digital environmental upgrading [2], AI enables adaptive sustainability decisions [36,37], and immersive tools like the metaverse improve collaboration and logistics efficiency [38]. However, integration remains fragmented, requiring structured frameworks.

Sectoral and regional insights: Sectoral and regional variations significantly influence SSCM implementation. Sustainability reporting in oil and gas firms remains inconsistent [39], whereas lean

and supply management enhance SSCM in manufacturing [40]. Textile and MSME sectors demonstrate distinct internal and demand-side practices [41,42].

Emerging directions and research gaps: Recent studies highlight underexplored SSCM dimensions, including managerial behaviors, emotions, and collaboration [43], as well as turbulence and uncertainty in global supply chains [44]. Cross-industry classifications provide systematic guidance for future research [45]. Persistent gaps remain in behavioral integration, multi-tier performance measurement, and digital–circular convergence.

In conclusion, SSCM has evolved into both a strategic imperative and a key performance driver. Its transformative potential is further strengthened by the integration of circular economy principles and Industry 4.0 technologies. However, effective adoption remains constrained by institutional, behavioral, and operational barriers that limit practical implementation. These challenges underpin this study’s comprehensive review, gap analysis, and the development of an integrated framework for enabling digitally driven, sustainable, and resilient supply chains [46–51].

3. Challenges and research gap analysis

The integration of sustainable supply chain management (SSCM) with Industry 4.0 technologies offers substantial potential for building resilient, environmentally responsible, and socially equitable supply chains. However, several challenges and research gaps limit the full realization of digitally enabled SSCM. Table 4 summarizes key obstacles and gaps, highlighting technological integration, data management, alignment with sustainability objectives, organizational and human factors, regulatory complexity, cybersecurity risks, and resource constraints. Research gaps include limited empirical evidence, fragmented frameworks, underexplored multi-tier networks, inconsistent performance metrics, insufficient circular economy adoption, limited studies on sustainability-driven innovation, and neglected socio-technical and behavioral dimensions. Addressing these issues is critical for designing holistic, resilient, and technology-enabled sustainable supply chains.

Implementation and operational challenges: Operational hurdles include high initial investments, limited resources (especially for SMEs), low transparency, supplier resistance, fragmented collaboration, inconsistent data management, regulatory complexity, and trade-offs between cost, quality, and sustainability. Industry 4.0 solutions—such as scalable IoT platforms, blockchain, AI-driven supplier assessment, cloud analytics, and predictive decision-support tools—enhance visibility, standardize performance monitoring, streamline collaboration, and optimize operational-sustainability trade-offs, enabling broader SSCM adoption.

Technological integration challenges: Integrating Industry 4.0 technologies across multi-tier supply chains is complex due to interoperability issues, legacy systems, and varied partner capabilities. High volumes of real-time data pose additional analytical challenges. Digital twins, cyber-physical systems, predictive analytics, and dashboards facilitate seamless connectivity, real-time coordination, and alignment with environmental, social, and economic objectives, promoting proactive and resilient SSCM.

Human, organizational, and knowledge gaps: Successful SSCM adoption depends on organizational culture, leadership commitment, and workforce capabilities. Resistance to change, skill gaps, weak collaboration, and cybersecurity vulnerabilities impede progress. AR/VR training, digital

learning platforms, collaborative tools, and secure blockchain systems enhance skills, engagement, and data security. Additionally, research gaps remain in empirical evidence, multi-tier network dynamics, circular economy operationalization, sustainability-driven innovation, and socio-technical factors. Industry 4.0 technologies—real-time monitoring, IoT-enabled reverse logistics, predictive modeling, and knowledge-sharing platforms—can help address these gaps, enabling regenerative, resource-efficient, and resilient supply chains while supporting evidence-based sustainable innovation.

Table 4. Challenges, Industry 4.0 enablers, and expected outcomes in SSCM.

Dimension	Challenges/research gaps	Industry 4.0 enablers	Expected SSCM outcomes
Implementation and operations	High initial investment, SME constraints	Scalable IoT, cloud platforms, modular digital solutions, automation	Cost-effective adoption; wider SSCM implementation
	Limited transparency and traceability	Blockchain, IoT sensors, RFID, cloud tracking	End-to-end visibility; enhanced accountability
	Supplier resistance and fragmented collaboration	AI supplier assessment, digital collaboration platforms	Aligned suppliers; integrated sustainability practices
	Data management and measurement issues	Big data analytics, standardized KPIs, integrated dashboards	Reliable monitoring; data-driven decisions
	Regulatory complexity and fragmented compliance	AI compliance monitoring, automated reporting	Simplified compliance; reduced legal/reputational risks
Technological integration	Trade-off management (cost, quality, sustainability)	Decision-support systems, predictive analytics, scenario modeling	Optimized trade-offs; aligned operational and sustainability objectives
	Multi-tier integration complexity	Digital twins, cyber-physical systems, interoperable IoT networks	Seamless connectivity; real-time coordination
	Data analytics challenges	AI and ML predictive/prescriptive modeling	Actionable insights; enhanced environmental, social, and economic performance
Human and organizational factors	Alignment with sustainability objectives	Integrated reporting, sustainability KPIs, dashboards	Strategic alignment with triple bottom line goals
	Resistance to change, limited skills, weak collaboration Cybersecurity and data privacy risks	AR/VR training, digital learning platforms, collaborative tools Blockchain security, encrypted cloud storage, access control	Enhanced skills, engagement, and SSCM adoption Secured data; mitigated cyber risks

Research and knowledge gaps	Limited empirical evidence on SSCM– Industry 4.0 integration	Longitudinal and multi-sector studies, simulations	Evidence-based guidance for SSCM strategy
	Fragmented frameworks and lack of holistic models	Integrated frameworks combining operations, technology, and strategy	Practical guidance for comprehensive SSCM implementation
	Multi-tier network complexity	Real-time digital platforms, networked monitoring, blockchain	Coordinated, resilient supply chains
	Circular economy adoption	IoT-enabled reverse logistics, digital twins, resource tracking	Closed-loop, resource-efficient, regenerative supply chains
	Sustainability-driven innovation	AI-assisted product/process design, predictive modeling	Green products, process innovations, sustainable business models
	Socio-technical and behavioral aspects	Knowledge-sharing platforms, collaborative tools, and change management programs	Improved trust, collaboration, and organizational readiness

4. Proposed conceptual framework for SSCM in Industry 4.0

The proposed conceptual framework integrates insights from the literature review (Section 2) and research gap analysis (Section 3) to provide a comprehensive and actionable model for implementing sustainable supply chain management (SSCM) within Industry 4.0 environments. It emphasizes the alignment of digital technologies, sustainability objectives, and operational excellence to develop supply chains that are resilient, adaptive, and high-performing, capable of responding effectively to dynamic markets, global disruptions, and evolving stakeholder expectations. By combining SSCM principles with Lean Six Sigma (LSS) methodologies and Industry 4.0 technologies, the framework enables measurable improvements across environmental, social, and economic dimensions, while fostering agility, transparency, stakeholder trust, and multi-tier collaboration.

The framework is structured around five interrelated pillars, reinforced by four complementary dimensions, and operationalized through the DMAIC methodology (*define, measure, analyze, improve, control*). These pillars represent the core operational capabilities of a technology-enabled sustainable supply chain, while the supporting dimensions provide the organizational, technological, and human-centric foundation necessary for successful implementation. Industry 4.0 technologies, including IoT, AI, blockchain, robotics, digital twins, and cloud platforms, enable real-time monitoring, predictive analytics, traceability, scenario-based optimization, and continuous improvement, ensuring SSCM objectives are achieved across multi-tier supply chains.

The five pillars define the primary operational capabilities of SSCM (Table 5). *Digital integration and connectivity* enables seamless multi-tier data flow among suppliers, manufacturers, distributors, and customers. IoT-enabled sensors, cloud platforms, ERP systems, and APIs allow automated data capture, predictive alerts, and rapid communication, reducing latency and preventing disruptions. *Intelligent decision-making* leverages AI, machine learning, and big data analytics to enable predictive

forecasting, process optimization, and proactive risk management. These tools allow organizations to identify inefficiencies, optimize production schedules, and reduce environmental impacts, supporting data-driven decision-making. *Transparency and traceability* provides end-to-end visibility and accountability, with blockchain, RFID, and digital twins verifying product origin, ethical sourcing, and regulatory compliance. This strengthens stakeholder confidence and enables proactive operational and environmental risk management. *Sustainability and circularity* embeds environmental stewardship, social responsibility, and circular economy principles into supply chain operations, including green logistics, energy-efficient operations, CSR alignment, life cycle assessment (LCA), recycling, and remanufacturing. Circular economy strategies extend product life cycles, recover value from end-of-life products, and minimize resource consumption, while social initiatives promote labor fairness, workplace safety, and stakeholder engagement. *Resilience and agility* equips supply chains to anticipate, respond to, and recover from disruptions. Scenario planning, simulations, and digital twins allow evaluation of alternative strategies and operational risks, enabling optimal responses to uncertainties such as supplier delays, port closures, or demand spikes.

Table 5. Framework for SSCM in Industry 4.0.

#	Pillar	Key components	Enabling technologies	Expected benefits
1	Digital integration and connectivity	Multi-tier integration, real-time monitoring, seamless data flow	IoT, cloud computing, ERP, APIs	Streamlined communication, reduced latency, actionable insights
2	Intelligent decision-making	Predictive analytics, AI-driven forecasting, process optimization	AI, machine learning, big data analytics	Improved forecasting, cost efficiency, and proactive risk management
3	Transparency and traceability	End-to-end visibility, ethical sourcing, compliance monitoring	Blockchain, RFID, digital twins	Enhanced trust, compliance, stakeholder confidence
4	Sustainability and circularity	Resource optimization, green logistics, CSR alignment	Life cycle assessment (LCA), circular economy tools	Lower environmental footprint, stronger social responsibility, long-term competitiveness
5	Resilience and agility	Risk monitoring, contingency planning, adaptive operations	Digital twins, simulation, scenario planning	Rapid disruption response, operational flexibility, robust supply chain performance

These pillars are reinforced by four complementary dimensions that ensure holistic implementation and long-term sustainability. *Strategic alignment and governance* embeds SSCM objectives into corporate strategy and global sustainability standards (SDGs, ESG), enhancing accountability, resource allocation, and cross-functional coordination through dashboards, audits, and KPI tracking. *Digital enablers* optimize resources, simulate operations, monitor sustainability impacts, and ensure interoperability, cybersecurity, and multi-tier data governance. *Operational and process*

integration embeds sustainability across sourcing, production, distribution, and end-of-life stages, applying continuous improvement and circular economy practices to improve efficiency, reduce waste, and maximize resource utilization. *Human-centric and socio-technical considerations* foster a culture of sustainability and digital adoption, using training, AR/VR simulations, and collaborative platforms to strengthen workforce skills, engagement, and innovation, aligning human capabilities with advanced technologies.

Table 6. LSS integration with SSCM using the DMAIC framework.

Phase	Objective	Key activities	Expected outcomes	Industry 4.0 tools
Define	Set SSCM's scope and identify challenges	<ul style="list-style-type: none"> • Develop project charter with critical to sustainability (CTS) • Map high-level processes • Engage stakeholders 	Clear objectives and aligned stakeholders	IoT, ERP, collaboration platforms
Measure	Evaluate current performance	<ul style="list-style-type: none"> • Collect operational and sustainability KPIs • Validate measurement systems • Identify process gaps 	Baseline understanding of performance	IoT sensors, data analytics, cloud platforms
Analyze	Determine root causes	<ul style="list-style-type: none"> • Conduct root cause analysis (RCA) • Identify key operational and sustainability drivers • Prioritize improvement opportunities 	Insights to guide targeted improvements	AI analytics, predictive modeling, process mining
Improve	Enhance efficiency and sustainability	<ul style="list-style-type: none"> • Implement green logistics, waste reduction, and energy optimization • Apply Lean tools (5S, Kaizen, VSM) • Use predictive analytics and real-time monitoring 	Measurable improvements in efficiency, sustainability, and collaboration	AI, digital twins, IoT, blockchain
Control	Maintain and sustain improvements	<ul style="list-style-type: none"> • Implement control plans • Establish SOPs and dashboards • Monitor KPIs via SPC • Conduct audits, training, and engagement 	Continuous improvement, sustained SSCM performance	IoT, SPC tools, dashboards, cloud analytics

Lean Six Sigma (LSS) provides a structured, data-driven methodology to optimize processes, reduce variability, and embed sustainability in SSCM. The DMAIC methodology operationalizes SSCM objectives by systematically identifying inefficiencies, prioritizing improvements, and sustaining performance [1,5]. Table 6 illustrates the DMAIC application: *Define* establishes project scope, identifies critical to sustainability (CTS) metrics, and engages stakeholders; *Measure* quantifies operational and sustainability performance, validates metrics, and identifies gaps; *Analyze* conducts root cause analysis, identifies drivers, and prioritizes improvement opportunities; *Improve* implements

interventions, including green logistics, energy optimization, Lean tools (5S, Kaizen, VSM), and Industry 4.0 technologies, piloting changes before full deployment; and *Control* ensures sustained improvements through SOPs, dashboards, SPC monitoring, audits, and training programs.

Table 7 aligns SSCM objectives, KPIs, and Industry 4.0 enablers across environmental, social, and economic dimensions. Environmental objectives target carbon footprint reduction, energy/resource optimization, and circular practices, monitored via CO₂ emissions per unit, energy intensity, and material recovery. Social objectives focus on ethical labor practices, workplace safety, stakeholder engagement, and equity, tracked through labor compliance, incident frequency, and employee satisfaction. Economic objectives aim to improve operational efficiency, reduce costs, foster innovation, and enhance competitiveness, measured via cost savings, inventory turnover, ROSI, and process cycle time. Industry 4.0 technologies—including IoT, AI, blockchain, digital twins, RPA, and cloud dashboards—enable real-time monitoring, predictive optimization, traceability, and data-driven decision-making across all dimensions, linking operational performance with sustainability outcomes.

Table 7. Key objectives, KPIs, and Industry 4.0 enablers in SSCM.

Dimension	Key objectives	KPIs	Industry 4.0 enablers
Environmental	Reduce carbon footprint; optimize energy and resource use; implement circular and regenerative practices	CO ₂ emissions per unit; energy intensity; material recovery rate; recycling efficiency	IoT for real-time monitoring; AI for predictive optimization; blockchain for traceability; digital twins for scenario analysis
Social	Ensure ethical labor practices and workplace safety; enhance stakeholder engagement; promote social equity	Labor compliance rate, workplace incident frequency, employee satisfaction, stakeholder engagement metrics	AR/VR training; collaborative digital platforms; AI-based social performance monitoring
Economic	Improve operational efficiency; reduce costs; foster innovation; enhance long-term competitiveness	Cost savings; inventory turnover; return on sustainability investment (ROSI); process cycle time	Predictive analytics; robotic process automation; cloud-based dashboards; AI-driven decision support

By integrating pillars, supporting dimensions, DMAIC methodology, and Industry 4.0 technologies, the framework ensures supply chains are efficient, resilient, sustainable, and socially responsible. Real-time monitoring, predictive analytics, scenario modeling, and iterative improvement cycles enable supply chains that are adaptive, future-ready, and ethically aligned.

Figure 4 presents the conceptual framework, illustrating the interactions of pillars, complementary dimensions, DMAIC phases, and Industry 4.0 enablers in achieving environmental, social, and economic objectives. It demonstrates how digital technologies, Lean Six Sigma, and

sustainability principles converge to drive operational excellence, transparency, resilience, and continuous improvement in SSCM.

In conclusion, this framework provides a holistic, data-driven, and actionable roadmap for organizations implementing SSCM in the digital era. It promotes continuous improvement, innovation, and long-term value creation, enabling multi-tier supply chains to operate in an adaptive, efficient, and sustainable manner while aligning operational performance with global sustainability standards and stakeholder expectations.

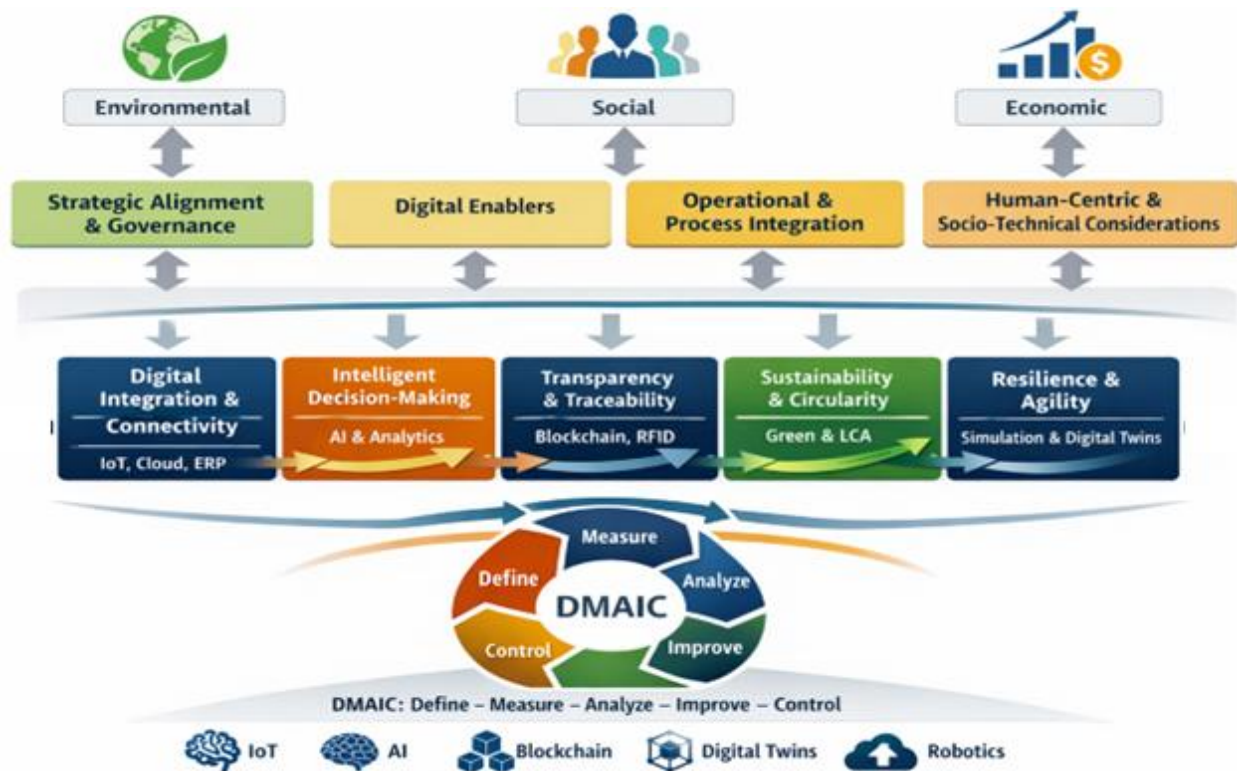


Figure 4. Conceptual framework for SSCM in Industry 4.0.

5. Conclusions and future work

This study examined sustainable supply chain management (SSCM) in the era of Industry 4.0, highlighting how digital technologies are reshaping the integration of sustainability across global supply chains. Through a comprehensive literature review, the study synthesized current knowledge, identified emerging trends, and revealed critical gaps in aligning digital transformation with environmental, social, and economic objectives. Key challenges include embedding advanced digital tools into sustainable practices, measuring sustainability performance across multi-tier networks, and operationalizing circular economy principles in both strategic and operational decision-making. These challenges underscore the need for integrated frameworks that bridge SSCM theory with practical, technology-enabled solutions.

To address these gaps, a comprehensive SSCM framework for Industry 4.0 is proposed, integrating digital technologies, Lean Six Sigma (LSS), and sustainability principles to enhance

operational, environmental, and social performance. The framework is organized around five interrelated pillars—*digital integration and connectivity, intelligent decision-making, transparency and traceability, sustainability and circularity, and resilience and agility*—reinforced by strategic alignment, digital enablers, process integration, and human-centric considerations. Applying the DMAIC methodology enables organizations to systematically identify inefficiencies, optimize processes, reduce waste, and implement continuous improvements across multi-tier supply chains. Leveraging Industry 4.0 technologies such as IoT, AI, blockchain, robotics, and digital twins facilitates real-time monitoring, predictive analytics, traceability, and operational optimization. The framework also aligns SSCM objectives with measurable KPIs across environmental, social, and economic dimensions, promoting resource efficiency, ethical practices, operational excellence, and long-term competitiveness.

Key contributions: This study makes several significant contributions. First, it bridges the gap between SSCM theory and practical implementation, demonstrating how digital technologies can be strategically integrated with sustainability objectives. Second, it advances theoretical understanding by combining Lean Six Sigma, DMAIC methodology, and Industry 4.0 concepts, providing a structured approach to operationalize sustainability in complex supply chains. Third, it offers actionable guidance for practitioners, enabling the design, implementation, and monitoring of SSCM strategies to improve efficiency, resilience, and stakeholder value. Fourth, it provides managers with a structured roadmap to align strategic and operational decisions with circular economy and sustainability goals, supporting evidence-based decision-making, risk mitigation, and cross-functional collaboration. Finally, the study identifies critical research gaps and future directions, laying the foundation for empirical validation, cross-industry application, and long-term evaluation of digital sustainability initiatives.

Theoretical implications: The framework integrates DMAIC methodology with SSCM in the Industry 4.0 context, demonstrating how operational excellence, process efficiency, and sustainability can be simultaneously addressed. It bridges sustainability theory, digital transformation, and process improvement literature, establishing a foundation for empirical testing and theoretical refinement.

Practical implications: For practitioners, the framework offers actionable guidance to design, implement, and monitor SSCM strategies. Linking DMAIC phases with sustainability objectives and leveraging Industry 4.0 tools allows organizations to identify inefficiencies, optimize processes, reduce impacts, and enhance resilience.

Managerial implications: Managers receive a structured roadmap for aligning strategic and operational decisions with circular economy and sustainability goals. The framework supports evidence-based decision-making, risk mitigation, and cross-functional collaboration, helping organizations improve competitiveness while meeting ESG and regulatory requirements.

Study limitations: The study is conceptual and based on a literature synthesis. Empirical testing across diverse industries, geographies, and technological contexts is required. Sector-specific adaptations may also be necessary to reflect differences in supply chain complexity, digital maturity, and sustainability priorities.

Future research directions: Future studies should empirically validate the SSCM-Industry 4.0 framework in diverse industrial sectors and global contexts, incorporating sector-specific adaptations and quantitative measurement of sustainability KPIs. Key directions include:

- 1) Empirical validation across sectors and contexts: Testing the framework in multiple industries and regions to evaluate effectiveness and practical relevance.
- 2) Integration of advanced Industry 4.0 technologies: Investigating how IoT, AI, blockchain, digital twins, and other tools enhance transparency, traceability, predictive analytics, and data-driven decision-making, while addressing implementation challenges.
- 3) Longitudinal and comparative studies: Examining sustained impacts, identifying contextual drivers and barriers, and determining best practices for digital sustainability strategies.
- 4) Cross-disciplinary collaboration: Engaging operation management, digital transformation, sustainability science, and policy to refine the framework, ensure theoretical rigor, and enhance practical applicability.
- 5) Circular economy and systemic sustainability: Exploring closed-loop logistics, resource recovery, and product lifecycle management to align digitalization with long-term environmental, social, and economic sustainability objectives.

Conflicts of interest

The authors declare no conflicts of interest.

Generative AI statement

The authors acknowledge that ChatGPT (OpenAI) was used exclusively for language editing and stylistic refinement of the authors' text, including improvements to clarity, grammar, and academic tone. The tool was not used to generate original scholarly content, data, analyses, or references. The authors have carefully reviewed and verified the final manuscript and accept full responsibility for its content.

Data availability statement

All data supporting this study are contained within the article.

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