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Review

Smart Supply Chain Management Integrating Lean Six Sigma and Industry 4.0–5.0: Framework, Applications, and Challenges for Sustainability and Resilience

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ABSTRACT: Despite rapid digital transformation, modern supply chains remain vulnerable, facing demand volatility, supply disruptions, operational inefficiencies, fragmented digital adoption, limited human–AI collaboration, and growing sustainability pressures. Conventional strategies focused on cost reduction and process standardization are no longer sufficient to ensure resilience, adaptability, and long-term value creation. This study presents a Smart Supply Chain Management (SSCM) framework that integrates Lean Six Sigma (LSS) with Industry 4.0 (I4.0) digital technologies and Industry 5.0 (I5.0) human-centric innovations. Implemented through the DMAIC (Define–Measure–Analyze–Improve–Control) methodology, the framework enables predictive, data-driven decision-making, operational excellence, ESG-aligned performance, and enhanced human–AI collaboration. It leverages I4.0 technologies—including AI, IoT, big data analytics, digital twins, and robotics—for real-time visibility, automation, and predictive insights, while embedding I5.0 innovations—such as collaborative robots, AR/VR, human digital twins, and emotional AI—to enhance workforce engagement, creativity, ethical decision-making, and ergonomic safety. Sustainability and social responsibility are integrated across operations, fostering resilient, adaptable, and socially responsible supply chains. By addressing critical digital, human, and operational bottlenecks, this framework delivers novel theoretical insights, actionable guidance for practitioners, and a foundation for future empirical research, offering organizations a roadmap to achieve long-term competitiveness while aligning technology adoption with human-centric and sustainable practices.

Keywords: Smart supply chain management; Lean six sigma; Industry 4.0; Industry 5.0; Digital transformation; Operational excellence; Resilience; Sustainability

1. Introduction

Modern supply chains are increasingly complex, global, and digitally interconnected, spanning multiple tiers of suppliers, manufacturers, distributors, and customers. This complexity exposes them to demand volatility, supply disruptions, quality inconsistencies, inventory inefficiencies, and growing ESG

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pressures [1–3]. Rapid technological advancements, globalization, and evolving customer expectations further intensify these challenges, requiring supply chains to become more agile, resilient, adaptive, and sustainable. Traditional strategies focused solely on cost reduction or process efficiency are no longer sufficient. To remain competitive, organizations must adopt integrated approaches that combine operational excellence, advanced digital technologies, and human-centric practices, enabling intelligent and future-ready supply chains [4–6].

1.1. Problem Statement

Despite significant advancements in supply chain management, critical challenges persist in integrating process improvement methodologies, digital technologies, and human-centric practices. Existing approaches remain fragmented, resulting in siloed implementations, limited interoperability, and weak alignment between operational excellence and digital transformation. These gaps lead to fragmented digital adoption, constrained human–AI collaboration, and insufficient integration of sustainability and ESG objectives. Consequently, supply chains struggle to achieve efficiency, resilience, adaptability, and social responsibility simultaneously. A unified and structured framework integrating Lean Six Sigma (LSS), Industry 4.0 (I4.0), and Industry 5.0 (I5.0) is therefore required to enable next-generation Smart Supply Chain Management (SSCM).

1.2. SCM Functions and Frameworks

Effective Supply Chain Management (SCM) depends on structured frameworks that align operational activities with strategic objectives. Core functions include demand and supply planning, production and operations, logistics, digitalization, human capital, risk and compliance, sustainability, performance measurement, finance, service delivery, and organizational agility [7]. These functions drive measurable outcomes such as inventory optimization, process efficiency, regulatory compliance, technology adoption, collaboration, sustainability, and market responsiveness. Table 1 presents a comprehensive SCM framework linking functions to actionable objectives, supporting continuous improvement, digital transformation, and the development of smart, resilient, and sustainable supply chains [6,8].

Table 1. SCM Functions Framework.

#	Cluster	Category	Key Functions	Objective
1	Demand & Supply Management	Demand & Supply Planning	Demand Forecasting	Accurately predict demand to optimize production and inventory levels
			Inventory & Warehouse Management	Maintain optimal stock levels and efficient storage
			Strategic Sourcing & Supplier Development	Ensure reliable suppliers and supply continuity
		Customer & Market Management	CRM & Demand Alignment	Align supply chain operations with customer needs and market trends
2	Operations & Production Management	Operations & Production	Manufacturing & Process Optimization	Achieve efficient, high-quality production
			Product Lifecycle Management	Manage products from design to end-of-life efficiently
		Cost & Profitability Management	Operational & Production Cost Optimization	Monitor and control costs, margins, and resources
3	Logistics & Distribution	Transportation & Logistics	Movement of Goods	Plan, optimize, and track transportation across the supply chain
		Order Management & Customer Service	Order Fulfillment	Ensure timely and accurate order processing

		Reverse Logistics & Returns	Returns & Product Recovery	Collect, repair, recycle, and redistribute products efficiently
4	Digitalization & Technology	Digital Transformation	Digital Enablement	Integrate intelligent, connected, and automated processes
		Innovation & Future Readiness	Emerging Technology Adoption	Apply AI, robotics, predictive analytics, and advanced digital tools
		Knowledge & Information Management	Data Governance & Analytics	Ensure reliable, standardized data and actionable insights
5	Human Capital & Collaboration	Workforce & Collaboration	Human-Centric Practices	Develop workforce skills, engagement, and an innovation culture
		Ecosystem Collaboration	Supplier & Partner Integration	Foster collaboration, co-creation, and network coordination
6	Risk, Resilience & Compliance	Risk & Resilience	Disruption Management	Identify and mitigate risks to ensure continuity
		Regulatory & Compliance	Legal & Regulatory Adherence	Ensure compliance across operations and regions
		Security & Ethics	Cybersecurity & Ethical Sourcing	Safeguard supply chain integrity, data, and ethics
		Global Trade Management	Global Sourcing & Compliance	Navigate tariffs, sanctions, and international trade effectively
7	Sustainability & ESG	Sustainability & ESG	Environmental & Social Responsibility	Reduce environmental footprint and implement sustainable practices
		Circular & Regenerative Supply Chains	Closed-Loop Operations	Reuse, recycle, remanufacture, and regenerate resources
8	Performance & Continuous Improvement	Performance Measurement	KPI Tracking & Benchmarking	Monitor performance and benchmark against best practices
		Lean Six Sigma & Continuous Improvement	Process Optimization	Reduce waste, improve quality, and standardize operations
		Strategic Planning & Decision Support	Strategic Alignment	Align operations with organizational strategy for long-term success
9	Financial & Supply Chain Finance	Financial Management	Cash Flow & Cost Optimization	Optimize working capital, trade financing, and cost-to-serve
10	Service & After-Sales Management	Service & After-Sales	Post-Sale Support	Manage warranties, maintenance, and repairs to enhance customer satisfaction
11	Agility, Flexibility & Responsiveness	Adaptive Supply Chains	Dynamic Response	Rapidly adjust operations to market changes and evolving demand

1.3. Lean Six Sigma for Process Excellence

Lean Six Sigma (LSS) integrates Lean's waste-elimination principles with Six Sigma's defect-reduction focus, enabling organizations to improve efficiency, reduce lead times, minimize errors, and lower costs [5,9]. Beyond operational gains, LSS enhances delivery reliability, scalability, supplier collaboration, and sustainable resource utilization. Tools such as DMAIC, Value Stream Mapping, and root-cause analysis provide structured approaches for process improvement and strategic alignment. Table 2 presents a 13-cluster LSS-driven SCM framework, mapping tools to applications and demonstrating how LSS supports efficiency, quality, resilience, responsiveness, and sustainability [5,7,10,11].

Table 2. LSS-Driven SCM Framework.

#	Cluster/Group	Purpose/Focus	Representative LSS Tools	SCM Applications/Impact
1	Structured Problem Solving & Root Cause Analysis	Systematically identify, analyze, and resolve supply chain issues	DMAIC, A3 Problem Solving, Six Sigma Project Charter, RCA, RCCA, FMEA, Fishbone/Ishikawa Diagram	Optimize order fulfillment, reduce defects, enhance production quality, and prevent logistics disruptions
2	Process Visualization & Workflow Mapping	Map, analyze, and optimize end-to-end processes	Value Stream Mapping (VSM), Process Mapping, SIPOC, Spaghetti Diagrams	Streamline procure-to-pay, order-to-cash, warehouse layouts, transportation flows, and overall process efficiency
3	Waste Elimination & Operational Efficiency	Eliminate waste, prevent errors, and enhance efficiency	5S, TIMWOOD, Kanban/Pull Systems, SMED, Poka-Yoke, Bottleneck Analysis	Optimize inventory, production scheduling, warehouse operations, transportation, and JIT replenishment
4	Statistical Analysis & Quality Control	Monitor, measure, and improve process performance	SPC, Control Charts, Cp/Cpk, Histograms, Box Plots, Pareto Analysis, Scatter Plots, DOE, Hypothesis Testing	Track supplier quality, production consistency, inventory accuracy, defect reduction, and delivery reliability
5	Customer Insight & Alignment	Align supply chain operations with customer requirements	Voice of the Customer (VOC), Quality Function Deployment (QFD)	Improve demand forecasting, service levels, order fulfillment accuracy, and customer satisfaction
6	Performance Measurement & Financial Management	Measure and optimize operational and financial performance	Lean Accounting, KPI Dashboards, Benchmarking, Strategic KPI Tracking	Reduce cost-to-serve, optimize cash flow, monitor supplier and logistics performance, and enhance SCM efficiency
7	Risk Management & Predictive Analysis	Anticipate and mitigate supply chain risks	Monte Carlo Simulation, Failure Tree Analysis, Scenario Planning	Predict demand variability, inventory shortages, supplier disruptions, and transportation delays
8	Continuous Improvement & Knowledge Sustainability	Standardize, sustain, and embed improvements	Kaizen, Control Plans, Process FMEA	Maintain excellence across procurement, production, logistics, and supplier management; preserve operational knowledge
9	Digital & Data-Driven Integration	Enable connected, intelligent, and predictive supply chains	Digital Twins, IoT Monitoring, ERP Analytics, Big Data Analytics, AI Forecasting	Achieve real-time visibility, predictive maintenance, smart inventory, automated logistics, and data-driven decisions
10	Supplier & Ecosystem Collaboration	Strengthen supplier performance and strategic partnerships	Supplier Scorecards, Joint KPIs, Collaborative Platforms	Enhance supplier reliability, co-innovation, and joint process optimization
11	Regulatory Compliance & Sustainability	Ensure legal, ethical, and environmental compliance	ESG Reporting Tools, Compliance Dashboards, Sustainability KPIs	Support circular supply chains, green logistics, regulatory adherence, and ESG alignment
12	Agile & Adaptive Supply Chains	Enhance responsiveness and flexibility	Scenario Modeling, Dynamic Planning, Rapid Reconfiguration Tools	Quickly adapt to demand fluctuations, market changes, and operational disruptions
13	Service Excellence & After-Sales Management	Optimize post-sale support and customer experience	Service Management Software, Warranty Tracking, Spare Part Analytics	Improve warranty management, repair operations, after-sales efficiency, and customer satisfaction

1.4. Industry 4.0–5.0 Technologies for Digital and Human-Centric Supply Chains

Industry 4.0 (I4.0) and Industry 5.0 (I5.0) technologies are transforming supply chains by embedding intelligence, connectivity, automation, and human-centric innovation. I4.0 technologies—including IoT, AI, machine learning, big data analytics, digital twins, cloud computing, and robotics—enable real-time monitoring, predictive analytics, autonomous decision-making, and improved operational efficiency [2,4,12].

I5.0 extends this paradigm by emphasizing human creativity, ethical governance, and resilience, leveraging collaborative robots (Cobots), AR/VR, human digital twins, blockchain, and emerging technologies such as quantum computing and brain–computer interfaces [6,13]. Table 3 outlines 15 technology groups, linking technologies to supply chain capabilities and applications, showing how I4.0 drives automation and intelligence while I5.0 enables human-centric and sustainable practices [4,6,14–16].

Table 3. Technology Groups for Industry 4.0–5.0 Smart Supply Chain Management.

#	Technology Group	Key Technologies	SCM Capabilities	Representative SCM Applications
1	Digital Connectivity & Infrastructure	IoT, Edge Computing, Cloud Computing, Cyber–Physical Systems (CPS)	Real-time data capture, seamless integration, end-to-end visibility	Shipment tracking, inventory monitoring, cold-chain management
2	Intelligent Analytics & Decision Support	AI, Machine Learning, Big Data Analytics, Prescriptive Analytics, Explainable AI (XAI), Federated Learning	Predictive and prescriptive analytics, optimization, data-driven decision-making	Demand forecasting, inventory optimization, supplier performance evaluation
3	Simulation & Autonomous Optimization	Digital Twins, Multi-Agent Systems, Swarm Intelligence, Quantum-Inspired Optimization	Scenario modeling, network optimization, autonomous decision-making	Disruption simulation, adaptive routing, decentralized logistics
4	Automation & Operational Execution	Advanced Robotics, Autonomous Vehicles, Drones, Cognitive Automation	Process automation, material handling, operational execution	Automated warehousing, autonomous transport, last-mile delivery
5	Collaboration & Ecosystem Integration	Blockchain, Smart Contracts, Digital Platforms, Marketplaces	Multi-tier coordination, traceability, inter-organizational trust	End-to-end traceability, automated contracting, collaborative planning
6	Human-Centric & Industry 5.0 Technologies	Collaborative Robots (Cobots), AR/VR, Human Digital Twins, Emotional AI, Human–Machine Collaboration	Workforce augmentation, human–AI collaboration, co-created decision-making	Assisted picking, immersive training, ergonomic optimization, and safety improvement
7	Sustainability & Circularity	ESG Analytics, Circular Economy Platforms, Green AI, Energy-Aware AI	Sustainability management, circular supply chain enablement, and regulatory compliance	Carbon footprint tracking, green logistics, closed-loop supply chains
8	Resilience, Risk & Governance	Resilience Analytics, Cybersecurity Systems, Ethical AI Governance Frameworks	Risk anticipation, disruption management, governance assurance	Supply chain stress-testing, cyber-risk mitigation, regulatory monitoring
9	Supply Chain Finance & Smart Contracting	FinTech Platforms, Blockchain-Based Finance, AI-Driven Credit Analytics	Financial flow optimization, liquidity management, risk mitigation	Dynamic discounting, supplier financing, automated payments
10	Sensing & Intelligent Monitoring	Computer Vision, Smart Sensors, RFID, Image/Video Analytics	Quality inspection, condition monitoring, anomaly detection	Automated defect detection, damage inspection, and asset condition monitoring
11	Knowledge & Cognitive Systems	Knowledge Graphs, Neuro-Symbolic AI, Cognitive Automation	Knowledge integration, reasoning, and organizational learning	Intelligent exception handling, hybrid rule-based and learning-driven planning
12	Control Towers & Orchestration Platforms	Digital Control Towers, AI-Orchestration Engines	End-to-end coordination, real-time exception management	Integrated SCM orchestration, alert-driven decision-making
13	Advanced Planning, Forecasting & Market Intelligence	Advanced Planning & Scheduling (APS) Systems, Demand Sensing, Sentiment Analytics	Strategic and tactical planning, market responsiveness	Short-term demand sensing, market-driven production, and distribution planning

14	Additive & Distributed Manufacturing	3D Printing, Distributed Manufacturing Platforms	Production flexibility, localization, and rapid response	On-demand spare parts, decentralized and localized manufacturing
15	Emerging Frontier & Industry 6.0–Ready Technologies	Quantum Computing, AGI, Brain–Computer Interfaces (BCI)	Hyper-optimization, cognitive interaction, system-level intelligence	Ultra-complex network optimization, advanced human–AI collaboration

1.5. Integrating LSS with I4.0–5.0 for Smart Supply Chain Management

Integrating LSS with I4.0–5.0 provides a holistic approach to Smart Supply Chain Management (SSCM). LSS ensures structured process optimization and performance measurement; I4.0 enables real-time visibility, predictive analytics, and automation; and I5.0 fosters human-centric collaboration and ethical governance [1,4,6]. This integration enables supply chains that are efficient, resilient, sustainable, and adaptive, bridging the performance-driven focus of I4.0 with the human-centered vision of I5.0 [17–19].

Figure 1 illustrates the phased evolution of smart supply chain capabilities from Phase 1 (2023–2025) to Phase 5 (2029–2030), integrating LSS, I4.0, I5.0, sustainability, and resilience. Key milestones include process optimization, IoT-enabled visibility, predictive analytics, digital twins, collaborative robots, AR/VR engagement, ethical decision-making, and circular economy integration. The roadmap highlights temporal progression and interdependencies, demonstrating how integrated adoption addresses digital fragmentation, limited human–AI collaboration, operational inefficiencies, and sustainability challenges, while guiding the transformation toward intelligent and socially responsible supply chains.

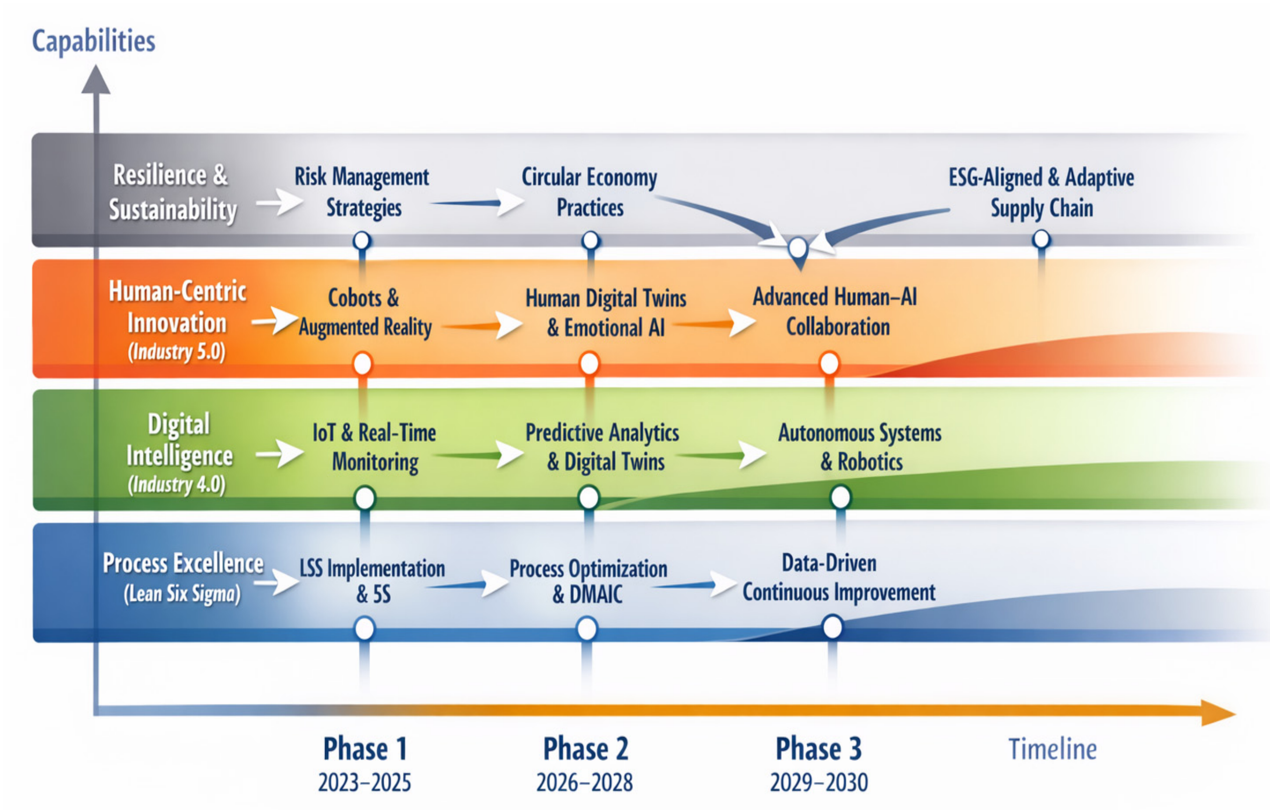

Figure 1. Milestone Evolution Map of Smart Supply Chain Management (SSCM).

1.6. Study Objectives and Contribution

Despite extensive research, critical technical bottlenecks persist in integrating and operationalizing Lean Six Sigma (LSS), Industry 4.0 (I4.0), and Industry 5.0 (I5.0) within supply chain systems. Existing studies highlight fragmented adoption, weak alignment between process improvement and digital transformation, limited human–AI collaboration, insufficient ESG integration, and a lack of comprehensive frameworks for adaptive and resilient operations.

This study addresses these gaps by proposing a Smart Supply Chain Management (SSCM) framework that integrates LSS with I4.0–5.0 technologies. The framework combines process excellence, digital intelligence, and human-centric innovation to deliver a structured roadmap for operational improvement, predictive decision-making, and sustainable performance. It bridges the performance-driven paradigm of I4.0 with the human-centered vision of I5.0, offering both theoretical and practical contributions.

The paper is organized as follows: Section 2 reviews Lean Six Sigma (LSS), Industry 4.0–5.0 technologies, and sustainable supply chain management (SCM); Section 3 identifies research gaps and technical bottlenecks; Section 4 develops the SSCM framework; Section 5 provides a discussion of the findings; and Section 6 concludes with key insights and recommendations.

2. Literature Review

Effective Supply Chain Management (SCM) is critical for manufacturing competitiveness, enabling organizations to deliver high-quality products efficiently, reliably, and cost-effectively. In today's volatile and globalized markets, continuous optimization and strategic alignment of supply chain processes are essential for sustaining competitive advantage. Flexible, responsive, and cost-efficient supply chains reduce operational costs, enhance customer satisfaction, and improve long-term organizational performance [1,4,20,21].

This study reviews literature from 2011 to 2025, indexed in Scopus, Web of Science, and ScienceDirect, focusing on the integration of Lean Six Sigma (LSS) methodologies with Industry 4.0 and 5.0 technologies to enhance supply chain performance, resilience, and sustainability. Modern supply chains are complex, globally dispersed, and digitally interconnected, facing challenges such as demand volatility, operational disruptions, geopolitical risks, and rising environmental and social pressures. Traditional cost- and efficiency-focused approaches are increasingly insufficient, driving the adoption of Smart Supply Chain Management (SSCM), which integrates process excellence, digital intelligence, and sustainability-oriented practices.

SSCM is redefining traditional supply chains through Industry 4.0 technologies, including artificial intelligence (AI), the Internet of Things (IoT), robotics, big data analytics, cloud computing, and digital twins [22,23]. These technologies enable real-time monitoring, seamless data exchange, and predictive analytics, providing end-to-end visibility, operational transparency, and enhanced responsiveness across manufacturing, logistics, and distribution networks. By embedding these digital capabilities, SSCM supports distributed production, mass customization, and customer-centric value creation, allowing organizations to respond rapidly to dynamic market demands and shifting consumer preferences [24].

Through intelligent automation and advanced analytics, SSCM enhances operational efficiency, reduces unplanned downtime, ensures consistent product quality, and optimizes resource utilization. Decision-making is strengthened by predictive analytics, cyber-physical systems, and digital twins, facilitating proactive planning, risk mitigation, and continuous performance improvement [25–27]. These capabilities enable manufacturers to simulate scenarios, anticipate disruptions, and implement agile responses without interrupting ongoing operations, thereby improving flexibility and resilience.

Furthermore, SSCM drives strategic cost reduction, waste minimization, and faster production cycles through flexible, reconfigurable, and synchronized operations [28–32]. Beyond operational and financial benefits, SSCM supports sustainability and long-term resilience by optimizing energy and resource usage, reducing environmental impacts, and promoting circular supply chain practices. By bridging the efficiency-driven paradigm of Industry 4.0 with the human-centric, resilient, and sustainability-focused vision of Industry 5.0, SSCM fosters adaptive, agile, and globally competitive supply chains that thrive in complex, dynamic, and uncertain global environments [4].

2.1. Lean Six Sigma in Supply Chain Management

Lean Six Sigma (LSS) is a cornerstone methodology for enhancing SCM, providing a structured approach to reduce waste, minimize variability, and improve operational performance. By integrating Lean principles—focused on process efficiency and elimination of non-value-added activities—with Six Sigma methodologies—emphasizing defect reduction, statistical rigor, and process reliability—LSS enables holistic optimization of supply chain performance. Its implementation consistently improves lead times, inventory management, product quality, and responsiveness [33].

When aligned with strategic planning, LSS connects operational improvements with long-term organizational goals such as profitability, quality, sustainability, and customer satisfaction. This alignment enhances agility, risk management, and cross-functional collaboration, enabling supply chains to adapt dynamically to market volatility and global disruptions [34]. Incorporating sustainability into LSS initiatives allows firms to optimize energy use, reduce carbon emissions, and implement circular economy practices while maintaining operational efficiency.

Empirical and bibliometric studies underscore LSS's growing significance in SCM. Gera et al. [35] synthesized empirical studies highlighting the impact of lean practices, quality management, green supply chain initiatives, innovation, and Industry 4.0 technologies on operational, environmental, and economic performance. Mahdikhani [5] identified key trends and research gaps, particularly in integrating sustainability and digitalization into LSS-driven supply chains. Barbosa et al. [1] proposed frameworks for Green LSS adoption and highlighted challenges such as cultural resistance and technology integration.

Integration of LSS with digital technologies further strengthens its strategic value. AI, IoT, predictive analytics, and automation enhance LSS by enabling real-time monitoring and data-driven optimization [36,37]. Lean Six Sigma combined with Industry 4.0—often referred to as LSS 4.0—has been shown to reduce waste, defects, and lead times while improving resilience and flexibility [38]. Overall, LSS has evolved from a process improvement methodology into a strategic enabler of supply chain excellence.

2.2. Industry 4.0 and Industry 5.0 Technologies in Supply Chain Management

Industry 4.0 has reshaped SCM by enabling digitally integrated, automated, and real-time decision-making systems. Through cyber-physical systems and intelligent automation, traditional supply chains are transformed into adaptive, interconnected networks capable of responding dynamically to disruptions and demand fluctuations. Core technologies such as AI, IoT, digital twins, big data analytics, cloud computing, and robotics enhance visibility, agility, and operational responsiveness [4,39].

IoT and cyber-physical systems enable continuous data collection and decentralized decision-making, improving traceability, predictive maintenance, and operational monitoring across supply chain networks [40,41]. Blockchain integration further strengthens transparency, traceability, and trust by enabling secure and immutable data sharing [42]. AI, big data analytics, and digital twins enhance predictive and prescriptive decision-making, supporting demand forecasting, risk analysis, and scenario planning [43–45].

Digital twins provide virtual representations of supply chain systems for simulation, optimization, and disruption forecasting. Cloud and edge computing enable scalable real-time data processing, while robotics and collaborative robots improve flexibility and human–machine interaction [46]. Integrating Lean principles with Industry 4.0 technologies (Lean 4.0/LSS 4.0) enhances operational efficiency through real-time optimization and automation [38].

Industry 5.0 builds on this foundation by introducing a human-centric paradigm that emphasizes creativity, ethics, and sustainability. Unlike Industry 4.0's automation focus, Industry 5.0 integrates human intelligence with advanced technologies to co-create value in socio-technical systems [47,48]. It prioritizes workforce empowerment, ethical governance, and resilience, ensuring that digital transformation aligns with societal and environmental goals.

Empirical studies confirm that Industry 5.0 technologies improve supply chain efficiency, visibility, responsiveness, and ESG performance [49,50]. Supply chain integration plays a critical role in translating technological adoption into performance outcomes by aligning material, financial, and informational flows [51–53]. However, challenges such as high costs, cybersecurity risks, and workforce skill gaps remain significant barriers to implementation [54–56].

3. Challenges and Research Gaps Analysis

The convergence of Lean Six Sigma (LSS), Industry 4.0 (I4.0), and Industry 5.0 (I5.0) offers substantial potential to enhance supply chain efficiency, resilience, and sustainability. However, organizations continue to face technological, operational, organizational, and socio-environmental challenges, revealing critical research gaps that must be addressed to develop fully integrated Smart Supply Chain Management (SSCM) frameworks capable of delivering operational excellence, agility, sustainability, and human-centric value.

3.1. Challenges in Lean Six Sigma Implementation

While LSS remains a cornerstone for operational efficiency and quality improvement, its application in modern, multi-tier supply chains faces notable constraints:

(1) Limited digital integration: Traditional LSS relies on historical data and manual monitoring, with minimal real-time IoT, predictive analytics, or automated decision support, limiting agility in dynamic supply networks [5,7].
(2) Sustainability alignment gaps: LSS initiatives rarely embed ESG principles or circular economy practices systematically, due to measurement complexity and competing operational priorities [1,21].
(3) Organizational and cultural barriers: Resistance to change, siloed structures, and weak strategic alignment hinder cross-functional collaboration and scaling of LSS initiatives [21,57].
(4) Scalability and network complexity: Multi-tier global supply chains challenge coordination, variability reduction, and disruption management, which conventional LSS approaches cannot fully address [58,59].
(5) Dynamic performance measurement limitations: LSS KPIs typically focus on historical efficiency, lacking predictive, resilience-oriented, and sustainability-linked metrics.

3.2. Challenges in Industry 4.0 Adoption

I4.0 technologies—including AI, IoT, digital twins, cloud computing, and robotics—enable real-time, data-driven supply chain management, yet adoption faces several hurdles:

(1) High investment costs: Implementation requires substantial capital and operational expenditure, particularly for SMEs [49].
(2) Technical complexity and interoperability: Integration across heterogeneous legacy systems and multi-tier networks demands standardization and robust IT infrastructure [39,43].
(3) Data governance and cybersecurity risks: Interconnected supply chains are vulnerable to cyberattacks, data breaches, and regulatory non-compliance, requiring strong governance frameworks [23].
(4) Workforce capability gaps: Successful adoption depends on digital literacy, analytical expertise, and automation skills, which are often insufficient [60].
(5) Operational complexity in multi-tier networks: Coordinating predictive analytics, automation, and IoT-enabled processes across distributed supply chains remains challenging [61].

3.3. Challenges in Industry 5.0 Integration

I5.0 emphasizes human-centricity, ethical governance, and sustainability, introducing additional implementation challenges:

(1) Human–technology collaboration: Effective co-working between humans and intelligent systems requires organizational redesign, leadership development, and updated operational routines [48,62].
(2) Institutional and regulatory constraints: Weak or fragmented institutions hinder infrastructure, skill development, and technology diffusion, especially in emerging economies [63,64].
(3) Integration with SCI and sustainability: Translating I5.0 adoption into measurable ESG and operational outcomes relies on effective Supply Chain Integration (SCI), which remains underexplored [65,66].
(4) Ethical and systemic risks: AI-driven decisions may introduce bias, accountability challenges, and systemic vulnerabilities, requiring robust ethical frameworks [67–69].
(5) Workforce capability development: Skills in creativity, ethical reasoning, and strategic decision-making are essential but often underrepresented in adoption strategies [70,71].

3.4. Research Gaps in Smart Supply Chain Management

Despite significant advances, substantial research gaps remain that constrain the creation of fully integrated, resilient, and sustainable SSCM frameworks. Table 4 summarizes the key challenges, research gaps, and strategic implications, grouped into four dimensions: Technology & Digitalization, Human & Organizational Factors, Sustainability & Governance, and Performance Measurement & Sectoral Coverage [2,72–80].

Table 4. Challenges, Research Gaps, and Strategic Implications in SSCM.

#	Dimension	Key Challenges	Research Gaps	Strategic Implications
1	Technology & Digitalization	Fragmented LSS–I4.0/I5.0 adoption; Limited resilience metrics; Platform heterogeneity; AI ethics underexplored	Few integrated frameworks; Lack of interoperability standards; Limited resilience measurement; AI governance underexplored	Develop integrated SSCM; Standardize platforms; Embed predictive resilience metrics; Implement AI governance
2	Human & Organizational	Skill gaps; Resistance to change; Limited human–AI collaboration	Weak research on creativity, ethics, and collaboration; Underdeveloped change management; SCI's mediating role unclear	Invest in training; Promote cultural change; Leverage SCI for operational, social, and environmental outcomes
3	Sustainability & Governance	ESG and circular economy gaps; Cybersecurity/compliance issues	ESG/circular practices rarely embedded; Limited secure, compliant SSCM practices, especially in SMEs/emerging economies	Integrate ESG and circular economy principles; Strengthen governance and cybersecurity; Align sustainability with strategy
4	Performance & Coverage	Limited predictive KPIs; Short-term studies; SMEs and emerging markets underrepresented	Few frameworks link operational, digital, human-centric, and sustainability performance; Limited longitudinal and cross-sectoral evidence	Develop predictive metrics; Conduct longitudinal, cross-sectoral studies; Adapt SSCM for SMEs and diverse sectors

(1) Technology & Digitalization: This dimension highlights the need for holistic integration of digital and operational capabilities. Few frameworks combine LSS with I4.0/I5.0 technologies, human-centric practices, and sustainability principles. Measurement and management of supply chain resilience under volatility, disruptions, and geopolitical risks are underdeveloped. Integration of heterogeneous platforms, legacy systems, and multi-tier networks remains challenging, while ethical considerations, transparency, and accountability in AI-driven decisions are underexplored.
(2) Human & Organizational Factors: The impact of collaborative intelligence, creativity, and ethical decision-making on supply chain performance and sustainability is insufficiently studied. Change management and workforce readiness strategies are limited, and the mediating role of SCI in translating technology adoption into operational, environmental, and social outcomes across multi-tier networks remains largely unexplored. Addressing these gaps is crucial for developing adaptive, resilient, and innovative supply chains.

(3) Sustainability & Governance: Sustainability and governance considerations are often fragmented from operational and digital initiatives. ESG metrics, carbon footprint monitoring, and circular economy practices are rarely embedded in LSS or I4.0/I5.0 frameworks. Similarly, comprehensive approaches to data governance, cybersecurity, and regulatory compliance remain underdeveloped, particularly for SMEs and emerging economies. Integrating sustainability principles alongside technological adoption ensures long-term performance, ethical alignment, and regulatory compliance.

(4) Performance Measurement & Sectoral Coverage: Key gaps exist in performance measurement and contextual applicability. Few studies link operational efficiency, digital adoption, human-centric practices, and sustainability to predictive KPIs, limiting strategic monitoring. Most research emphasizes short-term outcomes, with limited longitudinal evidence on the long-term effects of LSS, I4.0, or I5.0 adoption. Moreover, SMEs, service industries, emerging markets, and non-traditional sectors remain underexplored, highlighting the need for broader, cross-sectoral studies.

In summary, addressing these gaps is critical for developing holistic, adaptive, human-centric, and sustainable SSCM frameworks. Future research should focus on creating empirically validated models that integrate operational excellence, digital technologies, human creativity, ethical governance, and sustainability, while also conducting longitudinal, cross-sectoral, and multi-geographical studies to assess long-term impacts. Additionally, practical implementation challenges—such as digital integration, workforce readiness, ESG alignment, and Supply Chain Integration (SCI) adoption—must be addressed. By combining LSS with I4.0/I5.0 technologies and sustainability-driven human-centric practices, SSCM frameworks can bridge the efficiency-oriented focus of Industry 4.0 with the resilient, ethical, and sustainable vision of Industry 5.0, enabling adaptive, future-ready, and globally competitive supply chains.

4. Integrated Smart Supply Chain Management (SSCM) Framework

The Integrated Smart Supply Chain Management (SSCM) Framework provides a comprehensive and actionable roadmap for modern supply chains by systematically integrating core SCM functions, Lean Six Sigma (LSS) methodologies, and Industry 4.0–5.0 technologies. By combining operational excellence, advanced digital intelligence, and human-centered practices, the framework transforms strategic objectives into measurable outcomes and practical applications, enabling organizations to achieve efficiency, agility, resilience, and sustainability across complex and dynamic supply chain networks.

Figure 2 illustrates the SSCM ecosystem, highlighting the synergy among LSS, Industry 4.0 (I4.0), and Industry 5.0 (I5.0). LSS provides the operational foundation, driving process optimization, quality improvement, and waste reduction. I4.0 technologies—including AI, IoT, big data analytics, digital twins, cloud computing, and robotics—enable real-time monitoring, predictive insights, and adaptive decision-making. I5.0 complements these capabilities with human-centered, ethical, and collaborative practices, fostering supply chains that are not only efficient and resilient but also socially responsible. Cross-cutting enablers such as supply chain integration, institutional support, workforce capability, and cybersecurity ensure that operational and technological initiatives are strategically aligned, promoting continuous improvement and innovation.

Modern supply chains face increasing complexity, including demand volatility, supply disruptions, operational inefficiencies, intricate logistics networks, regulatory pressures, and rising sustainability expectations. Traditional approaches focused solely on cost reduction or standardization are no longer sufficient. The SSCM framework addresses these challenges by integrating Lean-driven process optimization, predictive automation, real-time analytics, and human-centered innovation. Table 5 maps twenty-two critical supply chain functions—including demand and supply planning, inventory and warehouse management, sourcing, production, logistics, product lifecycle management, customer service, reverse logistics, workforce collaboration, risk and resilience management, compliance, sustainability, finance, and performance measurement—to corresponding LSS tools, enabling technologies, and operational applications. LSS methodologies—DMAIC, Kaizen, FMEA, Value Stream Mapping, SIPOC, and Voice of the Customer (VOC)—support continuous improvement, quality enhancement, and waste reduction, ensuring alignment with organizational strategy and long-term operational goals.

Figure 2. Integration of LSS, Industry 4.0–5.0 for SSCM.

Table 5. Integrated SSCM Framework.

#	SCM Function	Representative LSS Tools	Enabling Technologies (Industry 4.0–5.0)	Applications/Impact
1	Demand & Supply Management	DMAIC, VOC, QFD, Value Stream Mapping	AI/ML, Big Data Analytics, Digital Twins, IoT	Accurate demand forecasting, optimized inventory, supplier performance monitoring, adaptive production planning
2	Inventory & Warehouse Management	5S, Kanban, SMED, Process Mapping	IoT, Edge Computing, Cloud, Autonomous Robotics, RFID, Smart Sensors	Real-time inventory visibility, automated warehousing, JIT replenishment, cold-chain monitoring
3	Strategic Sourcing & Supplier Development	Supplier Scorecards, Joint KPIs, RCA, FMEA	Blockchain, AI, Predictive Analytics, Digital Platforms	Supplier evaluation, risk mitigation, collaborative planning, automated contracting
4	Customer & Market Management	VOC, QFD, SIPOC, Spaghetti Diagram	Big Data Analytics, APS Systems, Sentiment Analytics	Align operations with customer demand, improve service levels, enhance order fulfillment accuracy
5	Operations & Production Management	DMAIC, Kaizen, Control Plans, Bottleneck Analysis	Advanced Robotics, Autonomous Vehicles, Digital Twins, 3D Printing	Optimize production processes, improve efficiency, enhance quality, enable on-demand manufacturing
6	Product Lifecycle Management	Process FMEA, Value Stream Mapping, Process Mapping	Digital Twins, ERP Analytics, AR/VR	End-to-end product oversight, predictive maintenance, lifecycle tracking from design to disposal
7	Cost & Profitability Management	Lean Accounting, KPI Dashboards, Benchmarking	AI, Big Data Analytics, FinTech Platforms	Optimize cost-to-serve, manage cash flow, improve operational efficiency, mitigate financial risks
8	Transportation & Logistics	Kanban, SMED, Bottleneck Analysis, Process Mapping	Autonomous Vehicles, Drones, IoT, Cloud, Digital Control Towers	Route optimization, real-time shipment tracking, automated transport, last-mile delivery

9	Order Management & Customer Service	VOC, SIPOC, Service Management Software	AI Forecasting, ERP Analytics, IoT	Timely order processing, demand alignment, improved customer satisfaction, predictive service
10	Reverse Logistics & Returns	DMAIC, Kaizen, FMEA	IoT, Digital Platforms, AR/VR	Efficient returns handling, repair, and recycling operations, closed-loop supply chains
11	Digital Transformation & Innovation	Value Stream Mapping, Process FMEA, Kaizen	IoT, Cloud, Edge Computing, AI, Robotics, AR/VR, Digital Twins	Smart, connected operations, predictive planning, human–AI collaboration, data-driven decision-making
12	Knowledge & Information Management	Knowledge Graphs, Cognitive Automation, Control Plans	Neuro-Symbolic AI, Big Data Analytics, AI Forecasting	Knowledge integration, organizational learning, intelligent exception handling, data-driven SCM decisions
13	Workforce & Collaboration	Kaizen, SIPOC, 5S	Cobots, Human Digital Twins, AR/VR, Emotional AI	Workforce augmentation, immersive training, ergonomic and safety optimization, human–AI co-created decision-making
14	Ecosystem Collaboration	Supplier Scorecards, Joint KPIs, Collaborative Platforms	Blockchain, Digital Platforms, Marketplaces	Multi-tier coordination, trust building, joint process optimization, collaborative planning
15	Risk & Resilience	FMEA, Monte Carlo Simulation, Scenario Planning	Resilience Analytics, Cybersecurity Systems, AI	Anticipate disruptions, stress-testing, continuity planning, cyber-risk mitigation
16	Regulatory & Compliance	Compliance Dashboards, ESG Reporting Tools	ESG Analytics, Blockchain, AI	Ensure regulatory compliance, sustainability reporting, and ethical sourcing
17	Security & Ethics	Control Plans, FMEA, Ethical AI Frameworks	Cybersecurity Systems, Ethical AI	Maintain supply chain integrity, protect against cyber threats, support ethical decision-making
18	Sustainability & Circular Supply Chains	Kaizen, Control Plans, ESG KPIs	ESG Analytics, Circular Economy Platforms, Green AI	Reduce carbon footprint, implement green logistics, enable closed-loop operations, and circular supply chains
19	Performance Measurement & Continuous Improvement	KPI Dashboards, Lean Accounting, DMAIC, Kaizen	AI Analytics, Digital Twins, Big Data	Track operational performance, benchmark processes, reduce waste, and enable continuous improvement
20	Financial Management & Supply Chain Finance	Lean Accounting, KPI Dashboards, Blockchain Finance	FinTech Platforms, Blockchain, AI	Dynamic discounting, liquidity optimization, automated payments, and financial risk management
21	Service & After-Sales Management	Service Management Software, Warranty Tracking	AI Forecasting, IoT, ERP Analytics	Manage warranties, predictive maintenance, and optimize after-sales service
22	Agility, Flexibility & Adaptive Supply Chains	Scenario Modeling, Dynamic Planning, Kaizen	AI, Digital Twins, IoT, Robotics	Rapidly respond to market changes, dynamically adjust operations, and maintain resilient logistics

The framework harnesses Industry 4.0 and 5.0 technologies to enable transformative supply chain capabilities. I4.0 tools—including AI, machine learning, big data analytics, digital twins, IoT, cloud/edge computing, autonomous robotics, drones, and additive manufacturing—provide operational visibility, predictive insights, automation, and advanced decision support. I5.0 innovations—including collaborative robots (Cobots), AR/VR, human digital twins, emotional AI, and brain–computer interfaces—introduce human-centered intelligence, enhancing workforce engagement, collaboration, creativity, and ergonomic safety. Integrating I4.0 and I5.0 enables data-driven decision-making, predictive maintenance, intelligent exception handling, and scenario-based planning, ensuring supply chains are technologically advanced, human-centered, and socially responsible.

The SSCM framework delivers multi-dimensional benefits. Operational efficiency is improved through streamlined processes and optimized production, inventory, and logistics management. Customer-centricity is strengthened via accurate demand fulfillment, predictive services, and responsive operations. Agility allows rapid adaptation to market fluctuations and disruptions, while sustainability and ESG compliance are advanced through green logistics, circular operations, and ethical sourcing. Risk management and governance are reinforced through proactive disruption anticipation, cyber-risk mitigation, and regulatory compliance. Human–AI collaboration enhances workforce productivity, decision-making, and ergonomic safety, bridging technological advancement with human-centered innovation. Strategically, the framework provides a roadmap for designing future-ready supply chains that can dynamically respond to technological, market, and societal pressures while fostering continuous improvement and sustainable innovation.

The DMAIC framework—Define, Measure, Analyze, Improve, Control—offers a structured, data-driven methodology for process optimization, quality enhancement, and waste reduction. Applied to SSCM, DMAIC enables adaptive, resilient, and sustainable supply chains by systematically aligning operational processes with digital technologies, human-centered practices, and ESG objectives. Table 6 demonstrates how each DMAIC phase integrates with I4.0 technologies, I5.0 human-centered innovations, and sustainability principles, providing a practical roadmap for implementing structured improvements across all supply chain functions.

Table 6. Integration of Lean Six Sigma DMAIC Framework into SSCM.

DMAIC Phase	SSCM Objectives	Industry 4.0 Enablement	Industry 5.0/Human-Centric Focus	Sustainability Integration	Strategic Benefits
Define	Identify critical supply chain processes, bottlenecks, and improvement opportunities	Digital twins, process mapping, and network visualization	Cross-functional collaboration, ethical decision-making	Align ESG goals and circular economy targets	Strategic clarity, stakeholder alignment, prioritized improvement opportunities
Measure	Quantify current performance, variability, and sustainability metrics	IoT sensors, AI-powered data collection, cloud analytics	Workforce engagement for accurate interpretation	Monitor energy use, emissions, and resource efficiency	Real-time visibility, reliable baselines, data-driven insights
Analyze	Determine root causes of inefficiencies, delays, and environmental/social impacts	Predictive analytics, AI-based anomaly detection	Collaborative problem-solving, human creativity	Assess environmental footprint and circularity gaps	Evidence-based strategies, risk reduction, process innovation
Improve	Optimize processes, enhance quality, reduce waste, and implement sustainable practices	Automation, AI-assisted simulations, process optimization	Human–machine collaboration, ethical and inclusive decision-making	Reduce carbon footprint, optimize resource use, implement circular practices	Efficiency gains, resilience, innovation, and sustainability improvements
Control	Sustain improvements, monitor performance, and ensure compliance	Real-time dashboards, predictive KPIs, automated alerts	Continuous learning, adaptive workforce development	Track ESG compliance, lifecycle impacts, circularity metrics	Operational stability, continuous improvement, and long-term performance alignment

In the Define phase, organizations clarify supply chain objectives, identify critical processes, and align initiatives with ESG and circular economy principles. Digital twins and process-mapping platforms provide end-to-end visibility, supporting scenario modeling, risk assessment, and informed strategic decision-making. Human-centered practices emphasize cross-functional collaboration, ethical governance, and stakeholder engagement, establishing a foundation for resilient, sustainable operations. The Measure phase captures operational, environmental, and human-centered performance data to establish a baseline. IoT sensors, AI analytics, and cloud platforms deliver real-time insights, while workforce engagement ensures accurate interpretation. Key metrics—including energy consumption, emissions, resource utilization, and workforce performance—enable informed, data-driven decisions.

During the Analyze phase, predictive analytics, simulations, and collaborative problem-solving uncover root causes of inefficiencies, quality deviations, and sustainability gaps. The Improve phase implements targeted interventions—including AI-driven optimization, automation, robotic collaboration, and human–machine interaction—to enhance efficiency, quality, and sustainability while fostering creativity, ethical decision-making, and ergonomic safety. The Control phase sustains improvements through continuous monitoring, dashboards, predictive KPIs, ESG-aligned performance tracking, and workforce training, embedding long-term operational resilience and sustainability.

By integrating DMAIC into SSCM, organizations create a holistic, adaptive framework where operational excellence, predictive intelligence, human creativity, and sustainability converge. Each DMAIC phase aligns with I4.0/5.0 technologies, human-centered practices, and circular economy principles, transforming supply chains into intelligent, resilient, and socially responsible systems. Predictive analytics, digital twins, and collaborative robotics optimize planning, inventory, sourcing, production, logistics, and customer service, ensuring competitiveness and ESG alignment.

Figure 3 illustrates the integration of the Lean Six Sigma (LSS) DMAIC framework within Smart Supply Chain Management (SSCM), highlighting how each phase—Define, Measure, Analyze, Improve, and Control—is enabled by Industry 4.0/5.0 technologies and sustainability principles. Define sets objectives, ESG targets, and digital twin models; Measure captures real-time operational, environmental, and workforce data; Analyze applies root cause analysis and predictive analytics; Improve implements AI-driven optimization, automation, Cobots, AR/VR, and Lean tools; and control ensures continuous monitoring, ESG compliance, and risk management. Together, these elements create a data-driven, adaptive, resilient, and socially responsible supply chain capable of addressing complex operational, environmental, and societal challenges.

In conclusion, DMAIC-driven SSCM establishes a future-ready, integrated framework that unites structured process improvement, advanced digital technologies, and human-centered sustainability. By linking each DMAIC phase with Industry 4.0/5.0 capabilities and ESG objectives, organizations can develop supply chains that are efficient, adaptive, resilient, and socially responsible, bridging operational excellence with ethical and sustainable practices. This approach enhances process efficiency, enables predictive decision-making, fosters human-centered innovation, and provides a strategic roadmap for next-generation supply chain management.

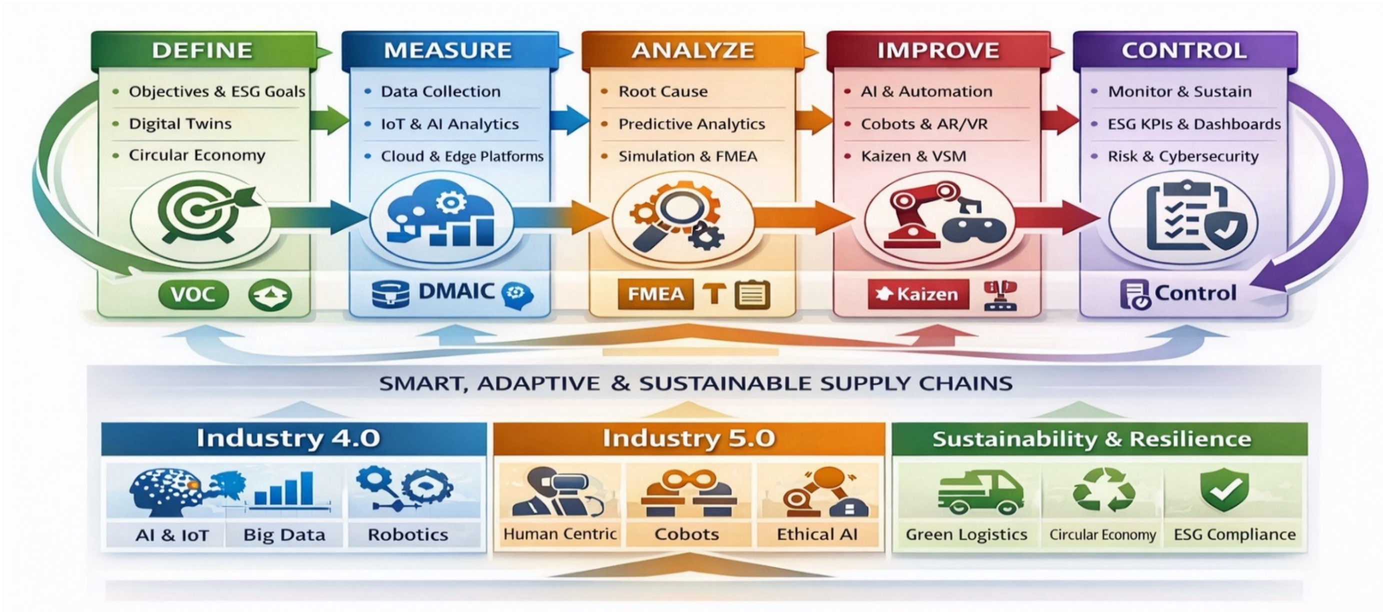

Figure 3. Integration of LSS DMAIC Framework for SSCM.

5. Discussion

This study presents an integrated Smart Supply Chain Management (SSCM) framework that systematically combines Lean Six Sigma (LSS), Industry 4.0 (I4.0) digital technologies, and Industry 5.0 (I5.0) human-centric innovations. The framework addresses operational, technological, organizational, and socio-environmental challenges by providing a structured methodology for achieving efficiency, resilience, agility, and sustainability. Unlike existing models, it operationalizes interactions across layers, showing how process optimization, predictive intelligence, and human-centered practices work together to generate actionable outcomes.

Theoretical Significance: The SSCM framework contributes to supply chain theory by formalizing a multi-paradigm integration. LSS provides the operational foundation, driving process optimization, waste reduction, and quality improvement. I4.0 technologies—including AI, IoT, digital twins, cloud computing, and robotics—enable predictive analytics, real-time monitoring, and adaptive decision-making. I5.0 innovations, such as Cobots, AR/VR, human digital twins, and emotional AI, facilitate human-centered creativity, ethical governance, and collaborative decision-making. By embedding resilience, ESG principles, and circular economy practices alongside operational excellence, the framework extends digital supply chain literature beyond efficiency and automation, incorporating human-centric and sustainable dimensions.

Operationalization and Layer Integration: The framework provides practical guidance for implementation. LSS tools identify inefficiencies and quality gaps, I4.0 technologies provide predictive insights and automation, and I5.0 practices enhance workforce engagement, creativity, and ethical decision-making. ESG and circular economy objectives are integrated into processes to ensure alignment with organizational strategy and societal expectations. Operationalization occurs through continuous feedback loops: predictive analytics from I4.0 inform LSS-driven improvements, human-centered practices validate decisions, and real-time monitoring sustains adaptive performance. This transforms the SSCM framework from a conceptual model into an actionable roadmap for integrated, resilient, and socially responsible supply chains.

Strategic Benefits: Organizations adopting this framework can enhance agility and resilience through scenario planning, cross-functional coordination, and predictive insights, enabling rapid adaptation to disruptions. Competitive advantage is strengthened by combining operational excellence, predictive intelligence, and human-centric innovation, improving efficiency, service quality, and sustainability performance. The framework formalizes inter-layer interactions: the process layer (LSS) standardizes operations and identifies improvements, the technology layer (I4.0) provides real-time insights and automation, and the human-centric layer (I5.0) guides ethical decision-making, creativity, and collaboration. Together, these layers create continuous feedback loops connecting operational, strategic, and sustainability objectives, enabling adaptive and resilient supply chains.

DMAIC Implementation in SSCM: The DMAIC methodology operationalizes the framework. In the Define phase, organizations clarify objectives, identify critical processes, and align initiatives with ESG and circular economy principles. Measure captures operational, environmental, and human-centered performance using IoT, AI analytics, and workforce engagement. Analyze applies predictive analytics, simulations, and collaborative problem-solving to uncover inefficiencies and sustainability gaps. Improve implements AI-driven optimization, automation, Cobots, AR/VR, and Lean tools, while Control sustains improvements via real-time dashboards, predictive KPIs, ESG tracking, and workforce development. This structured approach transforms supply chains into intelligent, resilient, and socially responsible systems.

Limitations and Future Directions: While the framework offers theoretical and practical contributions, empirical validation is needed to assess scalability and effectiveness across industries. Longitudinal studies are required to evaluate sustained impacts on performance, resilience, and sustainability. Implementation challenges—including workforce readiness, multi-tier coordination, and human–digital integration—must be addressed. Ethical governance, AI accountability, and transparency mechanisms also need further development to ensure responsible adoption.

In conclusion, the proposed SSCM framework formalizes the integration of process optimization, predictive intelligence, and human-centric practices, offering both theoretical and practical guidance for next-generation supply chains. By linking operational excellence with ethical and sustainable practices, it enables organizations can develop adaptive, resilient, and globally competitive supply chains that are future-ready and socially responsible.

6. Conclusions and Future Research Directions

This study presents an integrated Smart Supply Chain Management (SSCM) framework that aligns Lean Six Sigma (LSS) methodologies with Industry 4.0 (I4.0) digital technologies and Industry 5.0 (I5.0) human-centric innovations, enabling supply chains that are intelligent, adaptive, resilient, and sustainable. The framework translates strategic objectives into actionable mechanisms and measurable outcomes, linking process excellence, digital intelligence, and human-centered value creation across complex supply networks. LSS provides the structured foundation for process optimization, quality improvement, and waste reduction. I4.0 technologies—including AI, IoT, digital twins, robotics, and cloud computing—enable real-time visibility, predictive analytics, and intelligent decision-making. I5.0 innovations, such as collaborative robots, AR/VR, human digital twins, and emotional AI, embed ethical, inclusive, and collaborative principles, enhancing workforce engagement, creativity, safety, and ergonomic performance. Cross-cutting enablers—supply chain integration, workforce development, institutional support, and cybersecurity—ensure alignment, scalability, and continuous improvement.

The framework operationalizes the DMAIC (Define–Measure–Analyze–Improve–Control) methodology to integrate process improvement with digital technologies, human-centric practices, and ESG objectives. In Define, critical processes and improvement opportunities are identified and aligned with sustainability targets. Measure captures operational, environmental, and workforce data through IoT, AI, and cloud platforms. Analyze applies predictive analytics and collaborative problem-solving to uncover inefficiencies and sustainability gaps. Improve implements AI-assisted optimization, automation, and human–machine collaboration. Control sustains improvements via predictive KPIs, ESG-aligned monitoring, and workforce training. This approach clarifies how LSS, I4.0, and I5.0 layers interact, operationalizing a multi-layered strategy that connects process excellence, digital intelligence, and human-centered value creation.

Theoretical Contributions: This study contributes to supply chain theory by conceptualizing a unified, multi-paradigm framework integrating LSS, I4.0, and I5.0. It extends operational excellence and digital supply chain literature by embedding human-centricity, ethical governance, resilience, and sustainability within a structured methodology, providing a foundation for empirical validation and formal theoretical development.

Practical Implications: For practitioners, the framework provides a structured roadmap for designing and implementing smart, resilient, and sustainable supply chains. It supports process optimization, predictive decision-making, quality improvement, waste reduction, and ESG alignment, translating strategic objectives into operational results.

Managerial Implications: Managers can use the framework to guide technology adoption, organizational transformation, and workforce empowerment. It enhances human–AI collaboration, strengthens risk and resilience management, and institutionalizes sustainability in multi-tier supply chains.

Study Limitations: The study is conceptual, based on literature and secondary data. Empirical validation is needed to assess effectiveness, adaptability, and performance impacts across industries, organizational sizes, and geographical regions.

Future Research Directions: Future research should empirically test and refine the framework through case studies, surveys, experiments, and longitudinal studies. Key areas include developing quantitative metrics for I5.0 adoption, exploring advanced human–AI collaboration, and assessing long-term impacts on sustainability, resilience, and operational performance. Further studies should examine applicability in emerging economies, high-risk or regulated industries, and culturally diverse supply chains. Advancing these directions will strengthen theoretical generalization and provide evidence-based guidance for intelligent, ethical, resilient, and sustainable supply chains in dynamic environments.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

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

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