Key Performance Operational Indicator for Sustainable Lean Supply Chain in Heavy Equipment Industry: Systematic Literature Review

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Abstract: The heavy equipment industry must balance operational efficiency with sustainability. Using the PRISMA approach, this study systematically reviews key operational performance indicators (KPOIs) for sustainable lean supply chain management. Analyzing over 220 papers, it identifies crucial KPIs, including cost efficiency, resource optimization, waste reduction, carbon emissions, and product quality. Integrating these indicators into supply chain processes enhances both performance and sustainability. The research provides a comprehensive KPOIs framework, aligning lean principles with environmental and economic goals, and offering valuable insights for optimizing supply chain management in the heavy equipment industry.

Keywords: heavy equipment; lean management; operational performance; supply chain; Sustainability

1. Introduction

The heavy equipment industry is a crucial contributor to the economy, supporting key sectors such as construction, mining, agriculture, and infrastructure development. However, it frequently encounters challenges such as unpredictable demand shifts, intense global competition, and the growing need to enhance quality, operational efficiency, and sustainability. The supply chain in this industry is highly complex, involving global suppliers, manufacturing processes, and distribution to various customer demand regions[1)]. Despite this importance, the industry frequently faces challenges such as unpredictable demand shifts, intense global competition, and increasing pressure to improve quality, operational efficiency, and sustainability[2)]. Its supply chain is particularly complex, involving global suppliers, multi-stage manufacturing, and distribution across diverse regional markets, making coordination far more difficult compared to other industries[3)].

Effective governance is therefore essential to address structural complexity, regulatory differences, and supplier visibility, ensuring the alignment of environmental, social, and economic objectives[4)]. The ability to manage this complexity also determines the availability of high-quality, efficient, and sustainable machinery that supports infrastructure development while addressing communication gaps and incentive misalignments among supply chain actors[5)]. A broader supply chain perspective (SCV) is essential for effective sustainability management, as traditional firm-centered approaches often overlook interconnected challenges[6)].

Compared to industries such as automotive or consumer electronics, where supply chains are often streamlined through high-volume, standardized production, the supply chains for heavy equipment must deal with low-volume, highly customized, and capital-intensive products with long lifecycles. This results in greater challenges in balancing efficiency, resilience, and sustainability[7)]. Sustainability concerns in the heavy equipment sector include the management of technical waste, the reduction of carbon emissions, and the efficient use of energy resources[3)]. These challenges are compounded by barriers such as a lack of sustainability expertise, weak top management commitment, limited technological readiness, and fragmented information flow, which hinder effective implementation of Sustainable Supply Chain Management (SSCM) strategies[2)]. In this context, lean operations have also been shown to positively moderate the relationship between supply chain integration and operational performance, reinforcing their strategic importance in improving both quality and inventory management[8)].

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The literature highlights that lean principles, which emphasize cost and waste reduction, often conflict with sustainability initiatives that require additional investment[9,10,11]. Without effective indicators, organizations struggle to reconcile these objectives, leading to suboptimal outcomes. At the same time, enabling factors such as customer engagement, collaboration, risk management, and supply chain design play a pivotal role in supporting SSCM effectiveness, particularly during disruptions[12]. The integration of sustainability and operational efficiency in Lean Supply Chain Management can further be enhanced by identifying barriers, formulating appropriate policy implications, and fostering stakeholder collaboration using Multi-Criteria Decision-Making (MCDM) approaches[13]. Similar barriers to Lean implementation, such as lack of long-term commitment, employee resistance to change, and unclear role definitions, have also been identified in SMEs, highlighting the need for structured change management strategies to ensure successful Lean adoption and sustainability[14]. Integrating these enablers requires comprehensive measurement tools that balance economic efficiency with environmental and social considerations[9].

The Lean Manufacturing (LM) approach aims to reduce waste and increase efficiency, while also converging with environmental, social, and economic sustainability goals[15]. Sustainable Value Stream Mapping (S-VSM) integrates economic, environmental, and social indicators to identify inefficiencies and enhance sustainability in manufacturing, demonstrating its effectiveness in improving operational efficiency, resource utilization, and worker well-being[16]. The proposed Walking Worker Assembly Line (WWAL) model can support heavy-duty manufacturing industries by reducing cycle time and improving productivity, thereby facilitating the development of lean-adopted manufacturing units[17].

Sustainability measurement in supply chains is increasingly supported by the use of Key Performance Indicators (KPIs), which enable organizations to align operational performance with sustainability goals through standardized indicator frameworks[24].

However, the absence of robust and adaptive KPIs undermines monitoring and improvement efforts, resulting in inefficient resource use and environmental degradation[26]. Organizations that fail to adopt measurable sustainability initiatives face greater scrutiny from stakeholders and may risk regulatory sanctions, with negative impacts on market competitiveness and brand reputation[25].

This underscores the need for systematic models that can integrate sustainability measurement into lean supply chain practices[27].

In parallel, the adoption of Industry 4.0 technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain—offers new opportunities to enhance sustainability within supply chains[18]. When effectively combined with lean tools such as Just-In-Time (JIT), Kanban, and KPI-based systems, these technologies enable real-time data visibility, enhance responsiveness, and support predictive analytics, thereby improving the operational performance of lean-oriented manufacturing systems[19]. Machine Learning further strengthens efficiency and profitability while supporting the development of data-driven KPIs that align lean principles with sustainability goals, enabling more adaptive decision-making[20]. However, their implementation is often driven by cost efficiency rather than environmental or social considerations, underscoring the need for a more structured integration strategy[18]. Without such integration, the risk of inefficiencies, waste, and higher long-term costs persists[21, 22].

Based on these challenges and gaps, this study aims to identify supply chain operational performance and assess Sustainable Lean Supply Chain Management (SLSCM) practices in the heavy equipment industry using existing literature. To achieve this, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method is employed, as it ensures transparency, minimizes bias, and allows systematic quality assessment for greater reliability and relevance[23]. This method also facilitates comprehensive literature identification, supports data integration, enables trend analysis, and strengthens the validity of conclusions[21, 22, 24, 25,26].

Furthermore, this study is expected to identify comprehensive Key Performance Operational Indicators (KPOIs), develop a theoretical framework, analyze gaps in prior research, and outline future directions for advancing sustainability practices. A comparative analysis is then conducted to measure and evaluate the effectiveness of SLSCM practices

2. Literature Review

2.1. Lean Supply Chain Management in the Heavy Equipment Industry

Lean Supply Chain Management (LSCM) focuses on eliminating waste, reducing lead times, and maximizing value by enhancing efficiency across the supply chain. In the heavy equipment sector, lean principles are applied to streamline processes and reduce unnecessary inventory, defects, and delays[9]. However, integrating lean principles with sustainability efforts is complex, as the objectives can often conflict—for example, cost reduction versus the investment required for environmental and social improvements[10,11]. In this context, segmented emission inventory modelling—based on vehicle type, survival rates, and annual usage—has proven effective in accurately projecting environmental impact in the heavy commercial vehicle sector, suggesting that strategic policy interventions such as stricter emission standards can deliver significant reductions even as fleet sizes grow[27].

2.2. Integration of Sustainability into Lean Practices

Although lean practices traditionally emphasize cost-efficiency, several studies have explored their convergence with sustainability goals under the framework of Sustainable Lean Supply Chain Management (SLSCM)[9]. Tools such as Sustainable Value Stream Mapping (S-VSM) have been introduced to integrate environmental and social dimensions into lean workflows, allowing for the identification of inefficiencies, better resource utilization, and enhanced worker well-being[28]. Furthermore, the importance of inter-organizational information processing in overcoming climate-related information asymmetries has been emphasized, as it is crucial for enabling firms to effectively engage supply chain partners in managing environmental performance, an essential component in aligning lean practices with sustainability[29].

Moreover, models like the Walking Worker Assembly Line (WWAL) contribute to operational optimization in heavy-duty manufacturing by reducing cycle times and improving productivity, aligning with the lean sustainability agenda[17]. The adoption of Industry 4.0 technologies—including IoT, AI, and blockchain—can further support SLSCM by enabling real-time visibility and predictive analytics. However, such technologies are often adopted for cost efficiency rather than sustainability enhancement, requiring a more structured integration approach[30, 31]. In addition, while battery-electric and fuel-cell heavy-duty trucks reduce fuel-cycle emissions, their overall sustainability impact is heavily influenced by the energy-intensive nature of components such as lithium-ion batteries and carbon fibre-reinforced hydrogen tanks, underscoring the importance of incorporating vehicle-cycle emissions into sustainability indicators[32]. By applying a triple bottom line (TBL) approach and multi-objective optimization, recent research demonstrates that integrating validated environmental and social indicators into supply chain models enables strategic decision-making that balances profitability with sustainability goals[33, 34].

2.3. Barriers to Sustainable Lean Implementation

Despite its potential, the implementation of SLSCM in the heavy equipment industry is hampered by several barriers. These include resistance to organizational change, insufficient long-term commitment, role ambiguity, and inadequate employee engagement. From a sustainability perspective, additional barriers include unclear definitions, high implementation costs, and regulatory uncertainty[2, 3]. Organizations also face challenges related to communication gaps and the absence of incentives across supply chain actors, which hinder the alignment of sustainability objectives[18]. In global supply chains, governance complexity, supplier visibility, and regulatory fragmentation further complicate sustainability initiatives[14]. Social factors, such as environmental consciousness and public policy support, play a significant role in advancing sustainable practices across industries, as reflected in the increasing adoption of electric vehicles in Indonesia[35].

2.4. The Role of Customer Engagement and Collaboration

Recent studies emphasize the strategic role of stakeholder and customer engagement in enhancing business continuity and sustaining supply chain resilience, especially in times of disruption like the COVID-19 pandemic[17]. Enablers such as collaboration, risk management, and strategic supply chain design are critical in ensuring supply chain adaptability and performance under pressure. The ability to share information efficiently, respond to customer demands, and align resources significantly contributes to SSCM goals[17].

2.5. Supply Chain Risk Management and Resilience

In the automotive sector, Honda demonstrates a comprehensive approach to risk management by leveraging capabilities such as financial strength and regional cluster participation to address critical risks in supply chains, including credit, macroeconomic fluctuations, and demand shifts[36]. Similarly, a validated framework in the forestry supply chain sector identifies five major risk categories—supply, manufacturing, logistics and transport, demand/market, and environmental risks—underscoring the need for industry-specific risk mitigation strategies to enhance supply chain resilience and sustainability[37]. Performance indicators based on sustainable supply chain strategies—particularly those measuring economic efficiency, operational-social resilience, and environmental impacts—are essential for formulating effective lean-agile approaches in complex and dynamic industries such as construction and heavy equipment[38]. The application of Lean/Agile management principles in supply chain fleet composition enables organizations to evaluate multiple operational criteria—including cost, safety, delivery time, and environmental impact—thereby supporting the development of robust key performance operational indicators for sustainable decision-making in logistics-intensive industries[39]. Effective sustainability-related risk management in multi-tier supply chains requires companies to adopt both direct and indirect monitoring and collaboration practices to mitigate environmental, social, and economic risks beyond first-tier suppliers[40].

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2.6. The Need for Key Performance Operational Indicators (KPOIs)

In light of the discussed challenges, the development of the best and most adaptive Key Performance Operational Indicators (KPOIs) becomes vital. KPOIs serve as tools to evaluate and monitor sustainability performance in a lean-oriented supply chain[10]. Without such indicators, organizations may struggle to align their operations with sustainability goals, risking environmental degradation, regulatory penalties, and reputational damage[12, 11]. The recent scientometric analysis highlights a growing research emphasis on sustainability-focused supply chain strategies, with attention to a circular economy, blockchain integration, big data analytics, and critical success factors in SCM[41] For the heavy equipment industry, these strategic shifts directly influence the development of KPOIs by requiring indicators that measure resource circularity, data transparency across global suppliers, and traceability in complex multi-tier supply chains. The SCOR-based performance measurement framework provides a comprehensive structure for evaluating supply chain effectiveness, integrating key process areas such as planning, sourcing, making, delivering, and returning, which is crucial for developing operational indicators in sustainable lean supply chains[42]. When applied to the heavy equipment sector, SCOR-based KPOIs must address long product lifecycles, high capital intensity, and the need for closed-loop logistics systems that capture sustainability outcomes such as remanufacturing rates, energy intensity, and lifecycle cost efficiency.

Moreover, the integration of Industry 4.0 technologies into Lean Supply Chain Management (LSCM) significantly enhances real-time data visibility, process automation, and operational efficiency—factors that are essential in developing accurate and responsive KPOIs in complex industrial environments such as the heavy equipment sector[43].

In this context, KPOIs related to digitalization, such as predictive maintenance effectiveness, IoT-enabled energy monitoring, and automation-driven defect reduction, are critical for aligning sustainability and lean objectives in capital-intensive operations. Effective KPOIs must bridge the gap between lean efficiency and sustainability targets, capturing economic, environmental, and social dimensions in a measurable and actionable manner[22, 44]. Furthermore, incorporating data-driven technologies such as machine learning can improve KPI relevance and support better decision-making in complex and dynamic supply chain environments[22]. AI-enabled KPOIs such as predictive energy demand forecasting, risk-aware supply chain resilience scores, and optimized logistics energy use offer practical pathways to balance cost efficiency with sustainability imperatives for the heavy equipment industry.

3. Methodology

This study employed a systematic literature selection process to identify relevant research on performance measurement in sustainable lean supply chain management. Initially, a total of 254 articles were retrieved from two major academic databases—152 from Scopus and 102 from Web of Science (WoS). After removing 82 duplicate records, 144 unique articles remained for further screening. At this stage, 58 articles were excluded because they were review papers, conference reports, or published before 2014. The eligibility assessment was then conducted on the remaining 128 full-text articles, resulting in the exclusion of 79 articles that did not specifically address performance measurement in the context of lean supply chain management and sustainability. Ultimately, 50 articles were selected and included in the analysis, focusing on the identification and development of Key Performance Indicators (KPIs) relevant to sustainable supply chain operations.

The article selection process followed the PRISMA methodology (Figure.1), ensuring a structured approach to identifying, screening, and selecting relevant studies. A systematic search was conducted using predefined criteria and keywords. The final selection underwent thorough analysis, contributing to a comprehensive evaluation of SLSCM performance indicators. The search strategy, selection criteria, and analytical framework were documented, enabling future studies to replicate the methodology and validate findings.

4. Results and Discussion

The discussion of KPOIs in SLSCM is very relevant in the context of the heavy equipment industry. The complexity of the supply chain in this industry, involving global suppliers, large-scale manufacturing, and cross-regional distribution, creates unique challenges in integrating lean principles with sustainability[2]. The lean approach, focused on waste reduction, can clash with sustainability initiatives that require investment in waste management, carbon emission reductions, and more efficient energy consumption[15,45]. In this case, developing and implementing measurable and adaptive KPIs becomes very important to balance operational efficiency and achieve sustainability goals[9].

4.1. Descriptive analysis

An overview of papers on KPOIs in Sustainability, Supply Chain Management (SCM), SSCM, and LSCM can be illustrated in the literature analysis graph, which shows the number of studies from 2015 to 2024. Figure 2 illustrates the number of papers published each year from 2014 to 2024. The trend shows a significant increase in publication activity in recent years, peaking in 2023 with over 50 papers. Notably, a sharp rise began in 2021, followed by

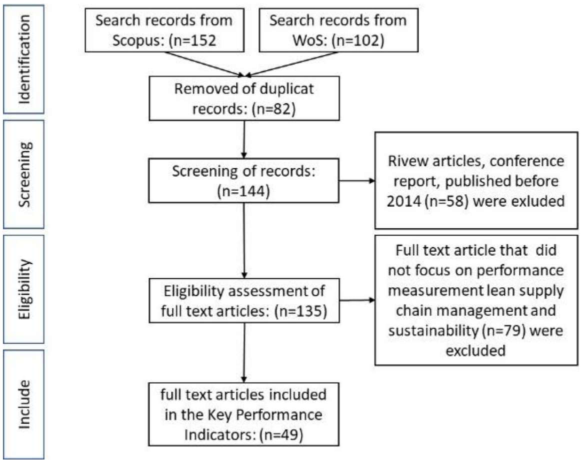

Fig. 1: Systematic Literature Review Process (adapted from the PRISMA method)

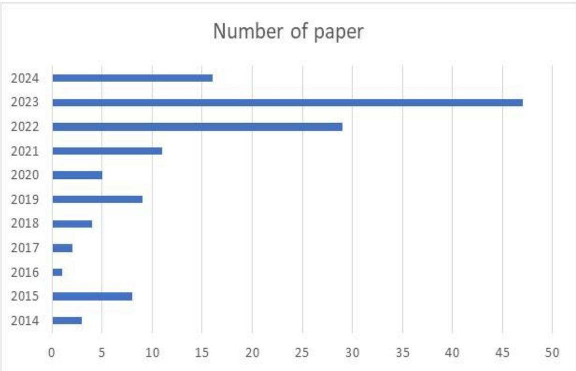

Fig. 2: Publication of papers from 2014 to 2024

Table 1: Distribution of Research by Industry Scope

Scope Industries	Counts	Percentage
Manufacture	39	25%
Food	18	11%
Automotive	17	11%
Textile	10	6%
Construction	10	6%
Heavy Duty/Equipment	9	6%
Logistics	9	6%
Chemistry & Pharmacy	8	5%
Services	8	5%
Electronik	7	4%
Ritel	6	4%
Oil, Gas & Energy	6	4%
Forest&Agriculture	6	4%
Printing/paper & Pulp	4	3%
Textile	39	25%

substantial growth in 2022 and a peak in 2023. Although there is a slight decline in 2024, the number of papers remains higher than in most previous years. This suggests a growing interest in the topic, particularly during the last three years.

The overall trend highlights the growing importance of sustainability, lean supply chain management, and performance indicators in the heavy equipment industry, particularly in recent years. Table 1. Presents the journal to our dataset.

Table 1 shows the distribution of research across different industries. The manufacturing sector dominates, accounting for 25% of studies, followed by the food and automotive sectors (11% each). Textile, construction, heavy-duty equipment, and logistics each contribute 6%. Other sectors, including chemistry and pharmacy, services, electronics, retail, oil & gas, forestry and agriculture, and printing/paper & pulp, have smaller shares, ranging from 3% to 5%. Overall, the table illustrates that research is highly concentrated in the manufacturing sector, while other industries, though less represented, provide valuable insights into sector-specific supply chain and sustainability practices.

Beyond the industry scope, the analysis also examines the distribution of 135 academic publications across 64 journals, conference proceedings, and other academic sources. Each row in the subsequent table represents a source (publisher) along with its corresponding number of publications. The journals and proceedings contributing the highest number of publications are as follows:

- *Evergreen* – 16 publications
- Operations and Supply Chain Management – 9 publications
- Journal of Cleaner Production – 6 publications
- Procedia Computer Science – 6 publications
- Cleaner Logistics and Supply Chain – 6 publications
- IFAC PapersOnLine – 5 publications
- Supply Chain Analytics – 5 publications

Several journals contributed a moderate number of papers (2 or 3 each), and the majority of journals (more than 40) contributed only one publication each. This table demonstrates a broad disciplinary range with an interdisciplinary focus, encompassing journals that address topics such as:

- Supply Chain and Operations Management
- Sustainability and Environmental Science
- Industrial and Manufacturing Engineering
- Logistics and Transportation
- Technology and Artificial Intelligence
- Business and Management

This publication list demonstrates a diverse and well-distributed base of literature sources, with a strong emphasis on sustainability, operations, logistics, and supply chain management. The high frequency of publications from *Evergreen* and *Operations and Supply Chain Management* suggests that these may be key sources in this field of research. Meanwhile, the inclusion of many journals with one or two entries indicates a broad academic reach and interdisciplinary engagement.

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4.2. Categorization of Literature on Performance Indicators in Sustainable Lean Supply Chains

To provide a comprehensive understanding of the research landscape, this section synthesizes findings from 47 academic sources that have been systematically reviewed. These studies span a range of disciplines and address various aspects of sustainable supply chain management (SSCM), particularly concerning performance measurement and operational efficiency. The literature reveals a growing integration of sustainability principles—economic, environmental, and social—with lean management practices. Moreover, it highlights the importance of technological innovation, industry-specific approaches, and resilience in supply chain systems.

For clarity and structure, the reviewed literature has been categorized into eight thematic areas, each reflecting a distinct but interconnected focus:

i. The study proposes that effective Lean Supply Chain Management (LSCM) depends on aligning lean performance objectives with specific supply chain challenges and selecting lean approaches accordingly, emphasizing a contextual-contingent perspective to tailor lean practices to the operational environment[46)].
ii. Developing quantitative performance indicators that reflect the resilience of on-time delivery to standard supply chain failure modes, such as capacity and material shortages, is critical for assessing and enhancing sustainable operational practices in complex, lean-oriented industries like automotive and heavy equipment[22)].
iii. Performance Measurement in Sustainable Supply Chain Management: developed a framework and analyzed metrics used to assess SSCM performance, including economic, social, and environmental dimensions.

Table 2 presents a thematic classification of selected literature on Sustainable Supply Chain Management (SSCM) performance measurement, highlighting the key focus areas and contributions across different research streams. The first theme, SSCM Performance Measurement, covers studies that develop frameworks and metrics for evaluating sustainability within supply chains. The second theme, Lean, Green, Agile, and Resilient (LARG), emphasizes the integration of lean and green practices as well as the broader LARG framework and its implications for SSCM performance. The third category, Technology and Industry 4.0, includes works that examine the role of digital technologies such as IoT, big data, and automation in enhancing sustainable supply chain operations. The Circular Supply Chain and Reverse Logistics theme explores the implementation of closed-loop systems, reverse logistics, and sustainability through product returns and material recovery processes.

Table 2: Classification of Themes and Contributions in SLSCM Performance Measurement Literature

Key Themes	Focus and Contribution	Authors
SSCM Performance Measurement	SSCM Framework and Metrics	9, 10, 30, 47, 48, 49, 50)
Lean, Green, Agile, Resilient (LARG)	Lean-green integration, LARG framework, and its impact on SSCM	51, 52, 53, 54, 55, 56, 57)
Technology and Industry 4.0	The impact of digitalization, big data, IoT, and other technologies on SSCM	2, 7, 12, 58, 59)
Circular Supply Chain & Reverse Logistics	Closed-loop, product returns, reverse logistics, sustainability	2, 3, 31, 60)
Collaboration, Information, and Resilience	The role of information, stakeholder collaboration, and supply chain resilience	61, 62, 63, 64, 65)
Sectoral Case Studies	Applications of SSCM and performance measurement in construction, automotive, food, etc., sectors.	12, 28, 30, 48, 49, 66, 67, 68, 69, 70, 71)
Framework & Evaluative Model	Analytical approaches: AHP, ISM-MICMAC, DEA, systematic performance evaluation	66, 72, 73, 74)
Challenges & Solutions for SSCM Implementation	Barriers, drivers, and strategies for SSCM implementation	69, 75)
Local Studies in Indonesia	Case studies and supply chain performance measurement in the Indonesian context	28, 62, 71, 76, 77)

In the area of Collaboration, Information, and Resilience, researchers have studied how information sharing, stakeholder engagement, and supply chain resilience contribute to sustainable outcomes. The Sectoral Case Studies theme reflects empirical applications of SSCM practices across various industries, including construction, automotive, and food sectors. The theme of Frameworks and Evaluative Models focuses on analytical methods such as AHP, ISM-MICMAC, DEA, and other tools for systematic performance evaluation in SSCM. Additionally, the Challenges and Solutions for SSCM Implementation category identifies key barriers, drivers, and strategic responses to implementing SSCM effectively. Lastly, Local Studies in Indonesia include research specific to the Indonesian context, particularly case studies that assess SSCM performance in local supply chains.

4.3. Bibliometric analysis

Figure 3 presents a keyword co-occurrence network visualization using VOSviewer, illustrating key relationships in SSCM. The nodes represent frequently occurring keywords, while the connecting lines indicate the strength and frequency of co-occurrences, reflecting how closely these concepts are related within the literature. Different colors signify distinct clusters, each representing a thematic area in SLSCM research.

- The **red cluster** centers around "time," "efficiency," "waste," "manufacturer," "productivity," and "digital twin." This grouping highlights research focused on optimizing manufacturing processes, minimizing waste, and improving operational efficiency through digital innovations like digital twins. These concepts are closely linked to lean management principles, which emphasize process efficiency and waste reduction.
- The **blue cluster** includes "impact," "activity," and "LSCM" (Lean Supply Chain Management), signifying studies that analyze the effects of lean strategies on supply chain performance. This cluster evaluates how lean principles improve productivity, reduce costs, and influence overall supply chain efficiency.
- The **green cluster** revolves around "sustainability," "disruption," and "resilience," addressing challenges related to environmental responsibility, supply chain risks, and adaptability. This cluster emphasizes integrating sustainable practices into supply chain operations, ensuring long-term viability despite disruptions such as economic fluctuations or global crises.
- The **yellow cluster** features "blockchain technology" and "barrier," pointing to the role of emerging technologies in supply chain management and the obstacles to their adoption. Blockchain is increasingly being explored for its potential to enhance transparency and traceability in sustainable supply chains, though challenges like cost, implementation complexity, and regulatory concerns remain significant barriers.

Overall, the figure provides a comprehensive visualization of the interconnections among key concepts in sustainable lean supply chain management. It highlights the balance between lean efficiency, sustainability, and resilience, while also identifying technological advancements and challenges that influence supply chain optimization in the heavy equipment industry.

The Collaboration Planning Tool (CPT), an ICT-based decision support system, enhances sustainability in supply chains by integrating economic, environmental, and social objectives, facilitating multi-tier collaboration, optimizing logistics, and improving decision-making while identifying challenges such as data integrity, resistance to change, and complexity in 3BL integration[78]. This aligns with the discussion on Key Performance Operational Indicators (KPOIs) for a Sustainable Lean Supply Chain in the Heavy Equipment Industry, where digital tools play a crucial role in supporting lean and sustainable operations through data-driven decision-making and strategic collaboration.

Table 3 presents a synthesized mapping of key performance indicators derived from a comprehensive review of 47 academic references, categorized under the TBL dimensions—Economic, Environmental, and Social.

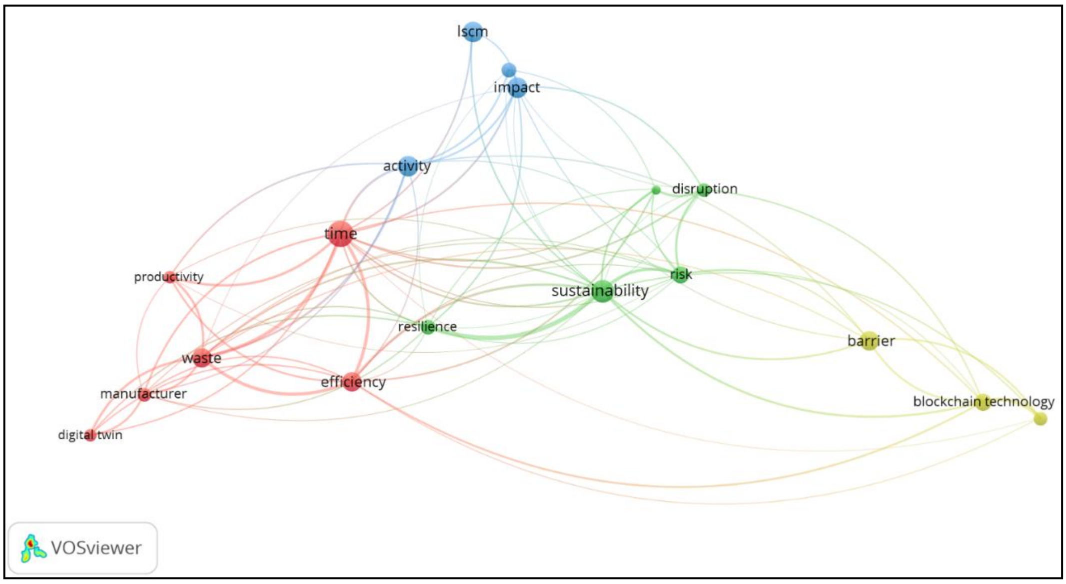

Fig. 3*:* Bibliometrics with keyword Lean Supply Chain Managemen

4.4. Integration of Literature-Based Indicators and TBL Dimensions

This synthesis is specifically tailored to the operational context of sustainable lean supply chains within the heavy equipment industry. Each indicator is aligned with relevant variables and performance factors to ensure a holistic evaluation framework. By integrating established theoretical insights with practical metrics, this table aims to support both researchers and practitioners in assessing and enhancing sustainability performance across the supply chain. In addition, the mapping considers common organizational challenges such as managerial and design complexity, limited top management commitment, and insufficient supplier integration, which can significantly affect the successful implementation of sustainability initiatives in supply chain operations[79)]. Furthermore, the integration of environmental safety indicators—such as emission levels, waste reduction, and ecosystem impact—has been emphasized in regional sustainability efforts as essential components of effective environmental management frameworks[80)]. In line with this, sustainable waste management approaches that incorporate local knowledge and community participation have also proven effective in enhancing environmental and economic performance, especially in resource-intensive sectors[81)]. These indicators will be used as the foundation for developing operational performance metrics in SLSCM.

4.5. Results

In the fast-changing world of the heavy equipment industry, sustainability has become a key driver of both operational and strategic choices. As supply chains become increasingly complex, the need for comprehensive performance metrics to assess sustainability has never been greater. This framework introduces a holistic set of indicators designed to evaluate the sustainability of lean

Table 3: Integration of Literature Indicators and TBL Dimensions for Heavy Equipment Supply Chain Operational Performance Assessment

Reference	Relevant TBL Dimensions	Key Contribution to Performance Indicators
Tajbakhsh & Hassini (2015)	Economic, Environmental, Social	Developed an integrated framework covering ROI, emission metrics, and social compliance.
Ahi & Searcy (2015)	Economic, Environmental, Social	Identified TBL-aligned KPIs and challenges in measurement across sectors.
Ng et al. (2015)	Economic, Environmental	Lean-green synergy for cost efficiency and energy/resource optimization.
Chavez et al. (2016)	Economic	Linked lean practices to cost efficiency, inventory turnover, and ROI.
Govindan et al. (2015)	Environmental	Defined closed-loop and reverse logistics as indicators of waste and resource recovery performance.
Kamble & Gunasekaran (2020)	Economic, Technological	Highlighted big data and digital KPIs (data accuracy, automation, traceability).
Hebaz et al. (2022)	Economic	Integrated LARG indicators into the TBL framework for resilience, efficiency, and sustainability.
Shekarian et al. (2021)	Technological	Focused on digital tools and tech adoption rates in performance monitoring.
Wang & Rogge (2018)	Economic	Used the DEA model to measure cost, efficiency, and capacity utilization.
Saleheen & Habib (2022)	Economic, Environmental, Social	Presented metrics for sustainability reporting, emissions, and social welfare.
Roldán Bravo et al. (2021)	Economic, Technological	Connected lean initiatives to Industry 4.0 for performance, defect rate, and automation.
Kankam et al. (2022)	Social	Defined indicators for stakeholder engagement and employee satisfaction.
Xu et al. (2022)	Environmental	Highlighted circular economy practices through waste management and water usage metrics.
Lahane et al. (2020)	Environmental, Social	Identified drivers/barriers in implementing SSCM and relevant social/environmental indicators.
Adhim & Mulyono (2022)	Social	Case study highlighting employee safety and community engagement indicators.
Contini et al. (2020)	Technological	Measured smart technology use and automation in food and ceramic supply chains.
Baliga et al. (2022)	Economic, Environmental	Assessed lean-green cost benefits and emission reductions.
Carissimi et al. (2022)	Social, Resilience	Suggested resilience KPIs: delivery reliability, risk mitigation, adaptive capacity.
Demirkıran & Öztürkoğlu (2021)	Technological	Proposed maturity model indicators for digital readiness and tech integration.

Table 4: Triple Bottom Line Indicators for SLSC in the Heavy Equipment Industry

Variable	Indicator	Explanation	Ref.
Economic Dimensions			
Cost & Investment Efficiency	Cost Efficiency	Savings from lean and sustainable practices in heavy equipment production.	10, 50, 75)
	ROI on Sustainability	Financial returns from sustainability-related investments.	7, 72)
Operational Efficiency	Inventory Turnover Rate	Efficiency in managing spare parts and components	30, 49, 70)
	Process Efficiency	Streamlined production and resource utilization	53, 54, 55)
	Lead Time Reduction	Time form order placement to final delivery	7, 51, 56
	Capacity Utilization	Optimal use of production and storage facilities	48, 49)
Quality & Reliability	Defect Rate	Percentage of defective or nonconforming products	30, 52)
	On-Time Delivery	Percentages on deliveries completed as scheduled	67, 70)
Flexibility & Adaptability	Supply Chain Flexibility	Ability to respond to changing demand or disruption.	53, 61, 65)
Technology Integration	Technology Adoption Rate	Implementation of rate digital technologies	30, 45, 85)
	Automation & Industry 4.0 Integration	Level of automated systems in manufacturing	7, 12, 58)
	Data Accuracy & availability	Reliability and usability of logistics/production data	2, 58)
Risk Management	Risk Mitigation Strategies	Measures the prevention or recovery from supply chain risks	58, 61, 63)
Resilience	Supply Chain Resilience	Evaluate the ability to recover from a disruption in the supply chain	22, 61, 63, 86)
Environmental Dimensions			
Emission Management	Carbon Emission Reduction	Reduction of CO_2 emissions across production and logistics	3, 50, 75)
Resources Efficiency	Energy Consumption Efficiency	Energy used per unit of output	10, 26, 45, 74)
	Water Usage	Water usage in cooling, cleaning, and production	9, 66)
Circularity	Waste Management Efficiency	Percentage of waste recycled or reused in operations	3, 60)
Social Dimensions			
Worker Health & Safety	Employee Health & Safety	Number of workplace incidents, safety compliance	25, 69)
	Occupational Safety	Frequency and level of work accidents that cause lost time.	61, 69)
Employee Well-being	Workforce Training	Training hour per Employee and percentage in upskilling programs	28, 69)
Human Capital Practices	Labor Practices	Compliance with labor standards; employee satisfaction	61, 63, 76)
Stakeholder Engagement	Stakeholder Collaboration	Depth of cooperation with suppliers, customers, and partners	52, 55, 68)
	Community engagement	Impact of operations on surrounding communities	28, 77)
Transparency & Governance	Sustainability Reporting Compliance	Conformance with Global Reporting Initiative (GRI) or national sustainability standards	73, 74, 75)
	Transparency & Accountability	Openness in sustainability-related disclosures and governance	45, 72, 74)
	Stakeholder Feedback	Public and stakeholder perception of SSCM practices	9, 25, 73)
Learning and Improvement	Continuous Improvement Initiatives	A regular improvement program, such as Kaizen or Six Sigma	51, 54, 56)

supply chains, focusing on key areas such as environmental impact, economic efficiency, social responsibility, technological advancement, and resilience. Effective Lean Supply Chain Management requires the contextual alignment between performance objectives and operational challenges, thus informing the development of more responsive and context-specific KPOIs in heavy equipment industries[46]. To further support sustainability evaluation, a structured method integrating sustainability indicators into Value Stream Mapping (VSM) has been developed, enabling real-time assessment and visualization of sustainability performance in manufacturing systems. Value Stream Mapping (VSM), when integrated with innovative and sustainable indicators such as energy consumption, carbon emissions, and digitization rate, enables industries to improve production efficiency while aligning with TBL goals—economic, environmental, and social sustainability[82]. This integration provides operational managers with a standardized approach to identify inefficiencies, reduce waste, and enhance sustainability across economic, social, and environmental dimensions[83]. Long-term modelling of strategic energy demand and carbon emissions, such as those applied in Indonesia's electricity sector, further highlights the importance of incorporating energy intensity, renewable mix, and emission projections as operational sustainability indicators in large-scale industrial systems[84]. Integrating sustainability indicators in the heavy equipment industry has generated significant environmental, economic, and social benefits. Energy-efficient technologies and optimized logistics have reduced carbon footprints and energy use[1]. Lean practices and sustainability initiatives have improved cost efficiency, inventory management, and profitability. Greater transparency in sustainability reporting has strengthened stakeholder trust and accountability[74]. Transparency of information within the firm and across firm boundaries underpins these sustainability issues. The shift toward this transparency is also fundamental in any lean organization, as it supports internal governance practices[7]. Enhanced safety measures and stronger community engagement have also been observed[3]. Industry 4.0 technologies have boosted process efficiency and data accuracy, enabling informed decision-making[7].

Additionally, companies have increased resilience to supply chain disruptions through improved delivery rates and risk mitigation[22]. AI-driven supply chain risk management fosters organizational resilience and aligns sustainability goals with economic strategy, thereby offering a data-driven framework for mitigating disruptions and enhancing overall supply chain performance[74]. The integration of AI-based Supply Chain Risk Management (SCRM) frameworks has been shown to enhance operational resilience, sustainability, and decision-making efficiency across global heavy industry organizations[87]. Effective Supply Chain Risk Management (SCRM) depends on the integration of risk identification, assessment, and mitigation strategies, supported by emerging technologies such as AI and blockchain, to enhance supply chain resilience and performance in complex global operations[88]. Moreover, a comparative analysis of lean and agile supply chain strategies during the COVID-19 pandemic revealed that while lean strategies reduced logistics costs, agile approaches provided greater rollout speed and adaptability under disruption, offering valuable insights for building responsive and sustainable supply chains in high-pressure contexts[89]. Furthermore**,** a fuzzy-TISM-based study identified 14 critical barriers to effective Supply Chain Disaster Management (SCDM) in the automotive sector, emphasizing the complex interrelationships between upstream constraints and supply chain resilience and sustainability[90]. One of the key success factors for businesses is their ability to maintain a complete, accurate, and up-to-date vision of their supply chain environment, including risks and opportunities associated with it[91].

Despite these advancements, research has primarily focused on environmental and economic impacts, with limited attention to energy efficiency strategies in the heavy equipment industry. Existing studies lack a comprehensive analysis of Key Performance Operational Indicators (KPOIs) in driving energy reduction within Sustainable Lean Supply Chain Management (SLSCM). Moreover, while Industry 4.0 technologies are recognized for improving efficiency, their direct role in energy conservation remains underexplored. The integration of Green Supply Chain Management (GSCM) with Multi-Criteria Decision Making (MCDM) methods, such as AHP-ELECTRE, enables optimal energy distribution planning by balancing sustainability, cost efficiency, and infrastructure constraints in complex regional environments[92, 93]. This study addresses these gaps by identifying measurable KPOIs and proposing innovations such as optimized cooling systems and automation to enhance energy efficiency.

4.6. Implications

The implications of SSCM include identifying key operational performance indicators, addressing implementation challenges, and leveraging digitalization strategies such as ERP, IoT, and AI/ML to enhance sustainability, resilience, and efficiency in lean supply chains. The integration of Industry 4.0 technologies—such as IoT, big data analytics, and cyber-physical systems—with lean tools enhances real-time data visibility, supports faster decision-making, and improves operational responsiveness, thereby enabling higher performance across lean supply chains [23, 94]. The integration of Lean Supply Chain and Industry 4.0 practices creates synergistic effects that enhance operational efficiency, waste minimization, and supply chain responsiveness by aligning digital technologies with lean principles[95]. Digital capability positively influences green innovation performance through enhanced green supply chain collaboration, emphasizing the strategic integration of digital tools, information sharing, and environmental awareness for sustainable supply chain management[96]. SLSCM plays a critical role in reducing energy consumption while maintaining operational efficiency. Lean principles, emphasizing waste reduction and process optimization, contribute to energy conservation when combined with sustainability efforts such as carbon reduction, energy-efficient processes, and renewable energy adoption.

Balancing these efforts and cost efficiency requires adaptive KPOIs to align energy strategies with business and sustainability goals. A cost-based decision support system offers a scalable method to compare different supply chain configurations, providing insights that support KPI development and performance optimization in lean and digitalized supply chains[97]. The study highlights that optimizing shipment frequency and cost-sharing ratios between manufacturers and retailers can significantly improve operational efficiency and cost control within two-echelon supply chains[98]. Metaheuristic algorithms offer a practical optimization approach for sustainable supply chain management by balancing economic, environmental, and social performance goals through flexible, multi-objective modelling[99]. The integration of SSCM with adaptive KPOIs, digitalization, and Industry 4.0 technologies enhances energy efficiency, sustainability, and resilience in lean supply chains while balancing cost efficiency and environmental responsibility[100].

Enhancing production efficiency is a key energy-saving strategy. Just-In-Time (JIT) production reduces idle machine operations, while automation and digital twin technologies enable real-time energy monitoring. In logistics, route optimization and the use of fuel-efficient or electric heavy-duty vehicles further cut energy waste and emissions. Energy-efficient innovations, such as repositioning cooling fans to absorb hot air from hydraulic tanks, lowering the temperature, reducing the cooling system's workload, and extending component lifespan while cutting energy demand.

Industry 4.0 technologies optimize energy consumption through IoT-enabled monitoring and AI-driven predictive analytics, identifying inefficiencies and refining usage patterns. Circular economy practices, including remanufacturing and waste heat recovery, further enhance resource efficiency. These strategies reduce operational costs, ensure regulatory compliance, and strengthen supply chain resilience. Leveraging KPOIs in SLSCM enables the integration of lean efficiency with sustainability, achieving substantial energy savings while maintaining economic viability and environmental responsibility.

In practical terms, the model offers managers clear guidance for monitoring sustainability performance while also supporting policymakers in designing regulatory frameworks that promote energy efficiency, resilience, and social responsibility in heavy industries. This dual perspective enhances the research's industry relevance.

4.7. Limitations

This study is specific to the heavy equipment industry, limiting its generalizability. It relies on secondary data, requiring empirical validation. The focus on KPOIs may not fully capture long-term energy efficiency impacts, and regional differences in lean and sustainability implementation affect applicability. Social impacts are minimally discussed, and global disruptions such as geopolitical tensions and energy price fluctuations are not considered, which may influence supply chain sustainability and energy reduction strategies.

5. Conclusions and Future Research

This study underscores the importance of Sustainable Lean Supply Chain Management (SLSCM) in addressing efficiency, sustainability, and resilience challenges within the heavy equipment industry. By identifying six KPOI dimensions and 28 measurable indicators, the proposed model provides a structured approach to assessing performance across economic, environmental, social, lean, technological, and resilience dimensions. Integrating sustainability indicators into Value Stream Mapping (VSM) enables real-time evaluation of energy use, carbon emissions, and operational efficiency, aligning supply chain practices with Triple Bottom Line (TBL) objectives.

This study highlights the strategic importance of Sustainable Lean Supply Chain Management (SLSCM) in the heavy equipment industry, where operational complexity, long product lifecycles, and high capital intensity demand a balanced approach to efficiency and sustainability. By identifying six Key Performance Operational Indicator (KPOI) dimensions economic, environmental, social, lean, technological, and resilience the research offers a comprehensive framework for evaluating supply chain performance aligned with Triple Bottom Line (TBL) principles.

This study underscores the importance of Sustainable Lean Supply Chain Management (SLSCM) in addressing efficiency, sustainability, and resilience challenges within the heavy equipment industry. By identifying six KPOI dimensions and 28 measurable indicators, the proposed model provides a structured approach to assessing performance across economic, environmental, social, lean, technological, and resilience dimensions. Integrating sustainability indicators into Value Stream Mapping (VSM) enables real-time evaluation of energy use, carbon emissions, and operational efficiency, aligning supply chain practices with Triple Bottom Line (TBL) objectives.

Despite the growing body of literature, several critical gaps remain. Most existing studies emphasize environmental and economic metrics, while energy efficiency strategies, particularly those tailored to heavy equipment operations, are insufficiently addressed. Furthermore, although Industry 4.0 technologies are widely recognized for enhancing operational performance, their direct role in driving energy conservation and sustainability outcomes is still underexplored. Social dimensions such as workforce well-being, stakeholder engagement, and community impact also receive limited empirical attention, especially in developing country contexts.

Future research should examine the sector-specific application of adaptive KPOIs, particularly in integrating Industry 4.0 technologies with energy conservation strategies. Comparative studies across different heavy industries and cross-country contexts would validate the model more broadly. In addition, incorporating advanced simulation tools and multi-criteria decision-making approaches may strengthen the scalability and predictive capabilities of sustainable lean supply chain management.

To advance the field, future research should:

- Explore the integration of adaptive KPOIs with energy-saving innovations
- Conduct cross-sector and cross-country comparative studies to validate the proposed KPOI framework and assess its applicability across different industrial and regulatory environments.
- Investigate the role of Industry 4.0 technologies, including AI, IoT, and blockchain.
- Expand the analysis of social sustainability indicators, focusing on labor practices, occupational safety, and community engagement, particularly in regions with limited infrastructure and regulatory support.
- Apply advanced simulation and multi-criteria decision-making models (e.g., AHP, fuzzy, etc) to optimize trade-offs between cost, sustainability, and resilience in lean supply chain configurations.

By addressing these gaps, future research can contribute to more holistic, data-driven, and context-sensitive models for sustainable supply chain management in the heavy equipment sector and beyond.

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Nomenclature

Subscripts

GRI	Global Reporting Initiative
GSCM	Green Supply Chain Management
IoT	Internet of Things
JIT	Just In Time
LARG	Lean-Agile-Resilience-Green
LSCM	Lean Supply Chain Management
KPOIs	Key Performance Operational Indicators
LSC	Lean Supply Chain
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
SSCM	Sustainability Supply Chain Management
SLSCM	Sustainability Lean Supply Chain Management
LM	Lean Manufacturing
Sus-VSM	Sustainability Value Stream Mapping
TBL	Triple Bottom Line
VSM	Value Stream Mapping
WoS	Web of Science
WWAL	Walking Worker Assembly Line

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