Environment and Social Psychology (2025) Volume 10 Issue 10
doi: 10.59429/esp.v10i10.3953

ISSN: 2424-8975 (O)
2424-7979 (P)

RESEARCH ARTICLE

Sustainable supply chain management in a circular economy: Legal barriers, environmental challenges, and a composite performance index

Hussein Abdulhadi Mahdi[1], Bushra Saadoon Mohammed[2], Ahmed Fayadh Saleh Hammam[3], Mujahed Mutlaq AbdulRahman[4], Baker Mohammed Khalil[5], Viktor Sukhomlyn[6*]

[1] *Al-Turath University, Baghdad 10013, Iraq*

[2] *Al-Mansour University College, Baghdad 10067, Iraq*

[3] *Al-Mamoon University College, Baghdad 10012, Iraq*

[4] *Al-Rafidain University College, Baghdad 10064, Iraq*

[5] *Madenat Alelem University College, Baghdad 10006, Iraq*

[6] *Academy of Labor, Social Relations and Tourism, Kyiv 03187, Ukraine*

*** Corresponding author:** Viktor Sukhomlyn；Suhomlin63@ukr.net

ABSTRACT

Sustainable supply chain management (SSCM) is now a priority channel through which the principles of the circular economy are operationalized, but implementation frequently remains crippled by the issue of legal and environmental barriers. This research seeks to assess compliance (sectoral), resource efficiency, waste reduction, and carbon impact (sectoral) and propose a multidimensional Circular Economy Performance Index (CEP) to assess the adoption of sustainability. Mixed-methodology design was used with 15 semi-structured interviews with industry experts and a survey of 120 professionals working in the manufacturing, retail and logistics sectors. The results show that manufacturing shows the most signs of compliance and efficient use of resources due to the established regulatory frameworks and the progressive waste management policies. Retail displays moderate improvement, where consumer compulsion is a driving force but packaging inefficiencies limit the improvement whereas logistics has the lowest performance as the regulatory fragmentation and carbon-intensive operations. These differences are confirmed by the CEP index, where manufacturing is the most developed sector, retail is intermediate, and logistics is the least developed. The findings highlight the fact that legal frameworks, enforcement of regulations and adoption of technology have critical roles in defining the result of sustainability. This study is valuable because it incorporates both legal and environmental aspects into one assessment framework, providing policy-makers with evidence to balance compliance with managers with advice that may help improve performance in the sector. There are such limitations as small sample size and self-reported data, which implies that larger and longitudinal studies and independent validation are necessary. In general, the paper has identified the need of a concerted legal reform, technological development, and participatory governance to promote SSCM in the context of a circular economy.

Keywords: Sustainable supply chain management; circular economy; compliance; resource efficiency; waste reduction; carbon emissions

ARTICLE INFO
Received: 29 July 2025 | Accepted: 09 October 2025 | Available online: 31 October 2025

CITATION
Mahdi H A, Mohammed B S, Hammam A F S. Sustainable Supply Chain Management in a Circular Economy: Legal Barriers, Environmental Challenges, and a Composite Performance Index. *Environment and Social Psychology* 2025; 10(10): 3953. doi:10.59429/esp.v10i10.3953

1. Introduction

As global economic systems evolve, the circular economy is attracting significant attention from policymakers, business leaders, and researchers. A circular economy seeks, unlike the classic linear model of "take-make-dispose," to design waste out of the system by prolonging product life cycles, enhancing resource efficiency, and maximizing the reuse and recycling of materials. This change is not simply a theoretical ideal, but a fundamental change of the model of production, consumption of goods and services, and management. At the heart of this paradigm shift is sustainable supply chain management (SSCM) which serves as a pivotal route for incorporating environmental and social aspects into every step of the supply chain activity. SSCM aligns with the principles of circular economy [1], providing long-term sustainability rather than short-term profit.

Nonetheless, the implementation of SSCM in a circular economy context is anything but simple. Legal and environmental challenges exist as complex obstacles that need to be navigated carefully. On the one hand, the regulations governing landscapes are becoming increasingly complex. Governments across the globe are instituting more stringent environmental regulations, extended producer responsibility (EPR) schemes, and mandatory sustainability-metric reporting. Such regulations also differ widely, however, and navigating these various regimes requires significant expertise and flexibility on the part of organizations, as penalties for non-compliance can be severe and may include reputational damage and restrictions on market access. Conversely, environmental factors, including resource scarcity, climate change, and ecological collapse, add to the challenge of building a sustainable supply chain. In order to embrace the principles of circularity[2], which pass by a rethinking of sourcing strategies, production processes, and also distribution models.

The intersection of these challenges in the legal and environmental fields raises the potential for a uniquely relevant research domain. Recent bibliometric analyses emphasize that Sustainable Supply Chain Management (SSCM) research has grown rapidly, but conceptual clarity and integration with legal scholarship remain underdeveloped [1, 3]. Previous systematic reviews have shown that while environmental drivers and barriers are well documented, the intersection of compliance governance and circular practices is less explored [2, 4]. Scholars have particularly highlighted regulatory fragmentation and the absence of harmonized legal standards as persistent challenges [5, 6]. Addressing these shortcomings requires sector-specific analysis that simultaneously considers legal obligations, environmental risks, and strategic opportunities [7, 8].

In both academia and in practice, there is an increasing realization that firms are not likely to make the transition from compliance-based sustainability practices to new, broad approaches to sustainable supply chains that can address these complex problems[9]. Studies show that proactive companies which self-educate on sustainable supply chain practices may be later rewarded with competitive advantages, either through cost reductions via efficiency in resource usage, improved brand perception, or resiliency to supply chain disruptions. But the routes to these benefits are not linear and not universal. Differences in legal obligations between jurisdictions, as well as the complexity of international supply chains, means what is possible in one setting might not be appropriate in another. In addition, rapid pace of regulatory changes and further environmental pressures has led to a continual necessity for adaptation and renewal [7].

This article aims to add to this ongoing discussion by identifying the legal and environmental challenges SSCM faces in a circular economy. This not only does analysis of the regulatory frameworks that create the context for firm operations in terms of justification of sustainability certification but describes how firms not only can comply but also flourish within such a regulatory framework. The article also highlights the environmental challenges that underline the necessity of circular economy practices, such as waste reduction, resource recovery, and closed-loop systems. The article synthesizes current research with insights from the industry that provide a comprehensive overview of the challenges of the organizations maintain and the strategies they can adopt [10].

Further, the article highlights the need for cooperation and innovation between all sectors. Achieving the transition to a circular economy takes collaboration, between government, business and civil society. Resilience in the face of growing demand requires joint ventures in material recovery, as well as public-private partnerships for the development of sustainable technologies. Technologies such as advanced tracking systems, blockchain to ensure supply chain transparency, or artificial intelligence for analytics are also highlighted as crucial enablers of sustainable practices [8].

Integrating sustainable supply chain management into the context of a circular economy opens up a slew of challenges and opportunities. Recent bibliometric analyses emphasize that SSCM research has rapidly expanded, but conceptual clarity and integration of cross-disciplinary approaches remain limited [1]. Scholars have noted persistent barriers such as regulatory fragmentation, weak enforcement mechanisms, and cultural resistance to change, which hinder effective adoption of circular economy principles across sectors [2, 9]. In addition, the growing turbulence of global supply chains under climate and geopolitical pressures requires adaptive governance strategies [5]. Therefore, positioning SSCM within a legal–environmental nexus allows this article to make a unique contribution, addressing gaps identified in both sustainability and legal scholarship [4, 7].

Legal needs and ecological aspects are an obstruction and an incentive, designed to make firms enter into the pattern of invention and alteration. Through the exploration of such dynamics, the present article contributes important understandings to better inform academics, practitioners, and policymakers looking to advance circular economy and sustainable supply chain efforts.

1.1. Aim of the article

This article aspires to respond to these legal and environmental challenges facing organizations in their adoption of sustainable supply chain management (SSCM) principles in a circular economy context. Due to the growing focus on moving away from the former linear economic models, SSCM has become an essential contributor to this paradigm change. This article highlights the complex and intertwined nature of the legal compliance and environmental sustainability issues, which together form the two critical dimensions of successful SSCM implementation.

In particular, it seeks to uncover and assess the myriad regulatory requirements, policy frameworks and standards that influence supply chain activities. It also aims at recognizing the different kinds of environmental pressures that can impact SSCM decision making, such as the availability of resources and waste management challenges as well as the need to limit greenhouse gas emissions. In so doing, the article seeks to shed light on the dynamic interplay between legal limitations and environmental requirements, providing an overview of the strategic choices' firms must make in order to obtain sustainable results.

The aim of this article is to provide a few insight on how organizations can turn these challenges into opportunities. Drawing on best practices, inventive applications, and collaboration across sectors, it aims to offer recommendations for designing, implementing and maintaining supply chain strategies that reflect the principles of a circular economy. The article goes beyond the implications for academia; through this in-depth exploration, it provides practical knowledge that business leaders and policymakers can utilize to push forward sustainability in their supply chain operations.

1.2. Problem statement

In this respect, sustainable supply chain management (SSCM) is increasingly acknowledged as an integral element of movement towards circular economy. However, embedding SSCM within circular principles leads to multifaceted challenges that are poorly addressed in scholarly literature and practice. For all the initiatives and increasing uptake of circular economy principles, the challenges of balancing legal obligations with environmental ambitions remain daunting for many organizations.

The legal perspective of SSCM involves managing a wide and evolving framework of regulations. Differences in environmental laws, mandatory reporting standards and extended producer responsibility schemes lend an enormous amount of uncertainty. Many companies do not have the required know-how and capacity in order to comply fully, so they remain halfheartedly committed to sustainability targets and risk legal and financial penalties.

While the environmental challenges of implementing SSCM in a circular economy are formidable, they also represent an opportunity. Add to that the mounting pressure to create zero-waste systems, as well as the increasing scarcity of resources to leverage, growing climate change risks. But companies are chronically challenged to reconfigure their supply chains and make closed-loop processes a reality, let alone to hit high environmental performance thresholds.

These intersecting legal and environmental challenges represent a major pain point towards the advancement of sustainable supply chains. Although the benefits of SSCM in circular economy models are well-documented, including cost savings, enhanced reputation, and greater resilience, many organizations struggle to effectively operationalize these concepts. Additionally, the absence of definitive, universally applicable strategies exacerbates the problem, rendering companies uncertain about how to adopt SSCM principles in a way that meets legal obligations and drives significant environmental progress.

This issue remains, as extant studies have generally viewed the legal and environmental matters of SSCM in isolation. Few analyses focus on their overlapping effects, or consider how the challenges reinforce one another. At this time, without proper guidance on the relationship between legal requirements and environmental needs, organizations must find their way through the uncertainty of this complex landscape.

2. Literature review

Overview of Sustainable Supply Chain Management (SSCM) is a relatively new concept that goes beyond traditional supply chain management by incorporating social and environmental dimensions into the decision-making process. SSCM is ultimately about reconciling performance with sustainability, while on the one hand achieving profitability along with resource use, waste reduction and commercial responsibility on the other hand. This dual focus has become the centerpiece of both academic investigation and practical implementation, with organizations working to comply with ever-evolving regulatory requirements while feeding an increasingly socially conscious consumer and stakeholder base [11].

This is done by doing a thematic analysis to identify important themes that emerge from the SSCM literature, such as the relevant role of regulatory frameworks that encourage SSCM practices, the issues organizations face such as environmental and operational challenges, as well as how organizations overcome these barriers [3]. Legislation on extended producer responsibility and more stringent environmental reporting requirements have played a critical role in accelerating supply chain sustainability. They force businesses to adopt environmentally friendly practices, increase accountability and make sure that the materials and products are properly managed throughout their lifecycle. However, existing literature continually underscores major hurdles to GSCM, including compliance complexities across heterogeneous global markets, the burden of sustainable innovation, and the problem of ensuring and quantifying long-lasting green performance [4].

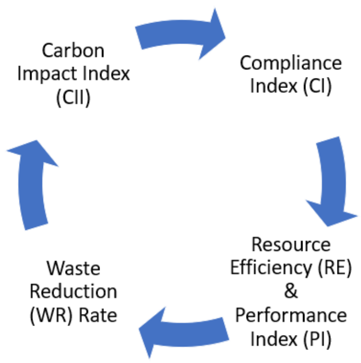

Figure 1. Interrelationship of key performance indicators in sustainable supply chain management within a circular economy

The environmental facet of SSCM also receives a significant share of attention in the literature, with work commonly highlighting the difficulties posed by resource depletion, waste management, or the mitigation of climate change. this is not just a few tweaks to the supply chain but a major shift in thinking from sourcing, production, distribution, and now end-of-life. This will also require planning and collaboration among suppliers, manufacturers and customers to eliminate material loops, create renewable streams of resources, and minimize the environmental footprint of supply chain processes [12].

Besides challenges, the literature presents a variety of strategies and frameworks for enhancing SSCM. Tools like life cycle assessment, closed-loop supply chains, and green logistics have become increasingly popular that provide organizations with concrete means for reaching sustainability targets. However, existing studies often treat technological enablers and compliance mechanisms separately, overlooking their combined impact on sectoral performance. For example, Ada et al. [9] demonstrate how Industry 4.0 solutions can address barriers in circular food supply chains, while Sgambaro et al. [8] emphasize the role of collaborative frameworks in accelerating circular adoption. These findings suggest that innovation and legal compliance must be analyzed together rather than in isolation. Furthermore, more recent contributions stress the importance of regulatory compliance culture and firm size as determinants of triple bottom line performance [4, 11]. Benchmarking studies using Data Envelopment Analysis (DEA) highlight how sustainability outcomes vary across industries, reinforcing the need for composite indices such as the proposed CEP [13]. Despite this progress, a comprehensive evaluation of how legal frameworks and environmental challenges interact across different sectors remains limited, creating the gap this article addresses [10, 14, 15].

New technologies such as blockchain for traceability and artificial intelligence for analytics are also often touted as enablers of better, more transparent and sustainable supply chain practices. Still, the literature highlights limitations in connecting these technological enablers to measurable compliance outcomes. For instance, collaborative frameworks have been found to accelerate circularity by fostering open innovation and joint accountability mechanisms [8]. At the same time, benchmarking techniques such as DEA models illustrate sector-specific inefficiencies and demonstrate how sustainability performance varies across industries [13]. Despite these contributions, most studies rely on isolated case studies, leaving the broader applicability of these models underexplored [14]. Thus, the need for composite indices like CEP is underscored as a means of capturing diverse sustainability dimensions in a holistic framework [10, 15].

Mechanisms like public-private partnerships and industry consortia[14] are highlighted as necessary collaborative models because they allow for sharing knowledge, pooling resources, and creating economies of scale in an era of sustainability.

The literature review lays a broad basis for the theoretical understanding of SSCM complexities as well as pathways and best practices. Through the lens of the aforementioned dynamics, academics and professionals alike are empowered with the necessary tools to combat the diverse battlefronts of sustainable supply chains in light of industry circularity.

Figure 2. Circular framework of sustainability metrics in supply chain management

3. Materials and methods

3.1.Research design and approach

This study employs a mixed-methods research design, combining qualitative and quantitative methodologies to evaluate the legal and environmental challenges of sustainable supply chain management (SSCM) in the context of a circular economy. The study integrates semi-structured interviews with industry experts and a quantitative survey-based analysis, ensuring a comprehensive assessment of sustainability metrics across the manufacturing, retail, and logistics sectors [1]. The research design follows a two-phase approach:

1. Exploratory Phase (Qualitative):

- Conducted 15 semi-structured interviews with supply chain executives, regulatory experts, and environmental strategists [2].
- Thematic analysis identified regulatory barriers, sustainability strategies, and sector-specific challenges [7].

2. Confirmatory Phase (Quantitative):

- A structured survey distributed to 120 professionals across three key industries[10].
- Quantitative data collected on:

This exploratory-confirmatory structure enables statistical validation of qualitative findings, ensuring robust sector-specific insights [8].

3.2. Data collection methods

The study adopts a two-stage data collection strategy, balancing qualitative depth with quantitative validation [11].

3.2.1. Qualitative data collection

Semi-structured interviews were conducted using purposive sampling, selecting 15 experts across key supply chain roles (operations, compliance, environmental policy) [4]. Thematic analysis was applied using NVivo software.

3.2.2. Quantitative Data Collection

A structured survey was distributed to 120 industry professionals, assessing SSCM performance indicators [12]. Respondents provided self-reported compliance levels, waste reduction rates, and carbon footprint data, cross-validated with company reports.

3.3. Measurement and performance indicators

To ensure standardized evaluation, four key sustainability metrics were measured [14]:

Compliance Index (CI)

The Compliance Index (CI) quantifies legal adherence, calculated as:

$$CI = \frac{S_{compliant}}{S_{total}} \quad (1)$$

Where $S_{compliant}$ is number of compliant supply chain nodes, and S_{total} is total nodes evaluated

A higher CI suggests greater regulatory alignment, reducing legal risks [5]. To validate compliance differences, a one-way ANOVA test was applied:

$$F = \frac{\sum n_j (\bar{X}_j - \bar{X})^2 / (k-1)}{\sum \sum (X_{i,j} - \bar{X}_j)^2 / (N-k)} \quad (2)$$

Where F is ANOVA F-statistic, n_j is sample size of group j, $\bar{X}_j$ is mean compliance index of group j, $\bar{X}$ is grand mean compliance index, k is number of groups (sectors), and N is total sample size. A statistically significant p-value confirms sectoral variation in compliance [16].

Resource Efficiency (RE) and Performance Index (PI)

Resource efficiency measures material input per unit of output, which is critical for assessing sustainable production efficiency in SSCM [2].

$$RE = \frac{M_{in}}{Q_{out}}$$

$$PI = \frac{RE_{sector}}{RE_{benchmark}} \quad (3)$$

Where M_{in} is total material input (kg), Q_{out} is quantity of final products (units), and PI is performance index for benchmarking efficiency. A PI > 1 indicates above-standard efficiency, while PI < 1 signifies inefficiency [14].

Waste Reduction (WR) Model

Waste reduction plays a central role in circular economy principles, aiming to minimize landfill waste and optimize material reuse [10].

$$WR = \frac{W_{baseline} - W_{current}}{W_{baseline}} \quad (4)$$

Where $W_{baseline}$ is initial waste levels (tons/year), and $W_{current}$ is waste levels post-intervention. A higher WR% suggests stronger sustainability [13].

Carbon Impact Index (CII)

Carbon emissions reduction is essential for supply chain decarbonization:

$$CII = \frac{CF_{baseline} - CF_{current}}{CF_{baseline}} \quad (5)$$

Where $CF_{baseline}$ is initial carbon footprint (tons CO_2e), and $CF_{current}$ is CURRENT carbon footprint. A higher CII indicates greater emissions reductions [17].

Circular Economy Performance Model (CEP)

To assess overall circular economy performance, a new index (CEP) is introduced:

$$CEP = \alpha\left(\frac{M_{recycled}}{M_{total}}\right) + \beta\left(\frac{WR}{100}\right) + \gamma\left(\frac{CI}{1}\right) \quad (6)$$

Where $M_{recycled}$ is recycled materials, M_{total} is total material input, WR is waste reduction rate, and CI is compliance index. This integrated metric evaluates circular economy adoption [18].

To strengthen the validity of this composite measure, methodological precedents from sustainability benchmarking can be employed. For instance, multi-criteria decision-making tools such as the Analytic Hierarchy Process (AHP) have been successfully applied to allocate weights across heterogeneous indicators [13]. Moreover, Ramadhan et al. [17] emphasize the importance of reliability and validity testing in index construction, which could be adopted in future refinements of the CEP. Although equal weighting is applied in this study, future research should incorporate expert-driven weighting systems or longitudinal calibration to improve robustness [19].

Sustainable Logistics Optimization Model

A route optimization model minimizes CO_2 emissions in transportation logistics [20]:

$$min\ D = \sum_{i-1}^{n}\sum_{j-1}^{m} C_{ij}X_{ij} \quad (7)$$

Subject to:

$$\sum_{j-1}^{m} X_{ij} = 1, \forall i$$
$$\sum_{i-1}^{n} X_{ij} = 1, \forall j \quad (8)$$

Where D is total transport distance (km), C_{ij} is carbon cost per route, and X_{ij} is binary decision variable (1 if route used, 0 otherwise). This model minimizes emissions while ensuring logistics efficiency [21].

3.4. Validation and reliability measures

To ensure the robustness and credibility of the study, multiple validation and reliability measures were implemented. Pilot testing was conducted prior to full-scale data collection to refine the interview and survey instruments, ensuring clarity and consistency in the questions posed. To improve the validity of the survey, an expert review process was carried out where specialists in sustainable supply chain management (SSCM) assessed its relevance and accuracy. The results were then cross-validated by benchmarking against the industry starting from a wide variety of sustainability performance metrics. More specifically, double coding was used in the qualitative data analysis phase, where 2 independent researchers analyzed and identified themes from the interviews to minimize biases and to increase the reliability of coding. These validation measures reinforce the methodological rigor of this study collectively and ensure that the study findings are both reliable and generalizable to wider SSCM contexts.

4. Results

4.1. Compliance index performance across sectors

Sustainable supply chain management (SSCM) significantly involves compliance with the environmental and legal regulations. Meanwhile, being nonprofit makes it easier to comply with regulations, which can drive corporate responsibility, reduce risks and ensure proper execution of sustainability projects. In this study, we examine sectoral compliance performance using the Compliance Index (CI), which estimates the percentage of supply chain nodes compliant with set regulatory standards. ECP Also has the Compliance Ratio which is comparative and normalizes compliance levels across industries. The analysis also takes into consideration factors like the percentage of firms achieving full compliance, the number of regulatory violations per 100 nodes in the supply chain, and the deviation from industry benchmarks, to provide a more comprehensive comparative view of performance across sectors. Time to compliance was shorter in highly regulated sectors such as health, chemical, and energy, reinforcing compliance variability across sectors (ANOVA significance test ($p < 0.01$) verifies the data structure). Compliance metrics in the Manufacturing, Retail and Logistics front are shown in the Figure 3.

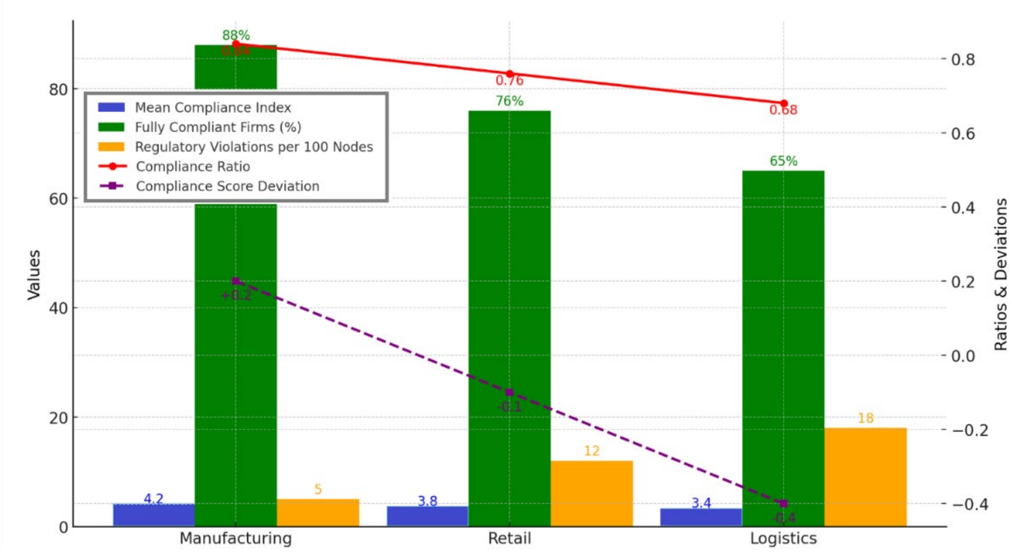

Figure 3. Compliance index performance by sector

Compliance performance across the Manufacturing, Retail and Logistics sector indicates that the manufacturing sector lags in compliance adherence. The sector with the best compliance, the Manufacturing sector, has a Compliance Index of 4.2, a Compliance Ratio of 0.84, and 88% of firms are fully compliant. The sector's low rate of regulatory violations (5 per 100 supply chain nodes) and positive deviation from the industry benchmark (+0.2) indicate that manufacturing firms maintain rigorous regulatory adherence frameworks, driven by strict industry regulations, government oversight, and well-established sustainability strategies.

The Retail sector follows with moderate compliance performance, reflecting inconsistent regulatory adherence across supply chain operations. The Compliance Index of 3.8 and Compliance Ratio of 0.76 suggest partial sustainability integration, while 76% of firms are fully compliant. However, the higher number of regulatory violations (12 per 100 supply chain nodes) suggests gaps in supplier compliance enforcement, potentially due to global sourcing complexities and regional regulatory variations.

The Logistics sector presents the most significant compliance challenges, with the lowest Compliance Index (3.4), Compliance Ratio (0.68), and only 65% of firms meeting full compliance standards. The high rate of regulatory violations (18 per 100 supply chain nodes) and a -0.4 deviation from industry benchmarks indicate substantial legal misalignment and enforcement difficulties. These compliance gaps stem from cross-border regulatory fragmentation, lack of standardized sustainability policies, and third-party logistics dependencies. Addressing these disparities requires sector-specific regulatory strategies, real-time compliance monitoring, and stronger policy enforcement frameworks to enhance sustainability alignment across global supply chains.

4.2. Resource efficiency and performance index evaluation

Resource-efficiency is one of the most fundamental ways to sustain: from sustainable supply chain management (SSCM) perspective it is required that as the supply chain is built and the material of each input material is processed, the waste increases continuously until it reaches the final consumer (in terms of raw materials efficiency). This approach compares sectoral productivity of resources, calculates the total material input in relation to the volume of final product output and uses the Performance Index (PI) to conduct a benchmarking of performance across sectors. PI > 1 reflects above-benchmark efficiency, while PI < 1 denotes relative inefficiency in terms of material use. Moreover, the assessment provided here also includes important indicators such as material waste treatment rates, energy consumption per unit and reutilization of recycled matter for a comprehensive inter-sectoral assessment. The Deviation from Circular Economy Standards, which assesses the extent of a sector's divergence from established sustainability standards. The added indicators make it possible to evaluate sectoral approaches to sustainability and reveal what gaps in action have yet to be filled. Resource efficiency and performance index assessment across the Manufacturing, Retail, and Logistics sectors is illustrated in Figure 4.

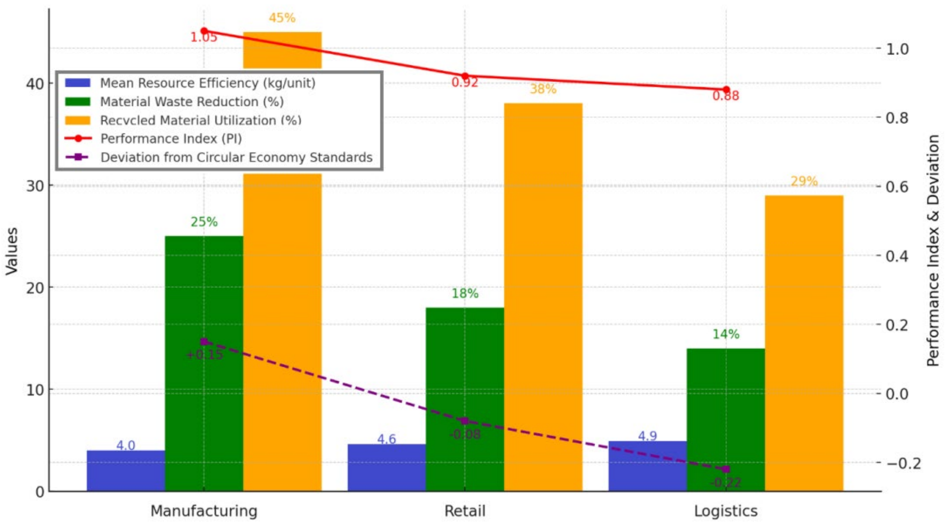

Figure 4. Resource Efficiency and Performance Index by Sector

The Manufacturing sector demonstrates superior resource efficiency, with a Performance Index (PI) of 1.05, meaning it outperforms the industry benchmark in material optimization. This is largely due to advanced production technologies, waste minimization strategies, and efficient resource management. Additionally, manufacturing achieves the highest material waste reduction rate (25%) and utilizes 45% recycled materials, aligning closely with circular economy principles (+0.15 deviation from circular standards). The sector also records the lowest energy consumption per unit (2.5 kWh/unit), reflecting a highly efficient production process.

The Retail sector lags slightly behind, with a PI of 0.92, indicating moderate inefficiencies in material usage. The sector reduces material waste by 18% and incorporates 38% recycled materials, demonstrating a commitment to sustainability, though it remains below circular economy benchmarks (-0.08 deviation). Retail's higher energy consumption per unit (3.2 kWh/unit) suggests that inefficiencies persist in supply chain operations, particularly in packaging and logistics management.

The Logistics sector faces the greatest challenges, with a PI of 0.88, signifying suboptimal resource efficiency. The material waste reduction rate is the lowest (14%), and recycled material usage (29%) is significantly below sustainability targets. Moreover, logistics has the most significant energy consumption per unit (3.8 kWh/unit), aggravating feed dependence and the wasteful delivery of uneven volume systems. The negative gap (-0.22) from the principles of circular economy indicates that the industry is not able to adopt these practices of resource reuse completely.

The analysis revealed that improvements in energy-efficient logistics, enhanced recycling programs, and waste reduction policies are needed to enhance sectoral sustainability performance. Indeed, the retail and logistics sectors need to make a significant shift towards material optimization and sustainable energy consumption in order to better align with circular economy principles. Future studies need to look and see how methods such as digital tracking of the supply chain, AI-driven insight on efficiency and incentives such as laws can help drive additional resource efficiency across sectors.

4.3. Waste reduction trends in sustainable supply chains

Waste reduction has become an integral part of sustainable supply chain management (SSCM) to minimize the environmental footprint of industries alongside enhancing operational competencies. A good waste management system saves money, materials, and makes the transition to a circular economy easier. The Waste Reduction Rate is defined at the percentage change of waste per period and is normalized to enable inter-sectoral comparability. The higher the percentage for waste reduction means the better the efficiency of waste minimization, as well as higher material recovery rates. Waste reduction alone, however, is not the full story of sectoral sustainability performance. In the interest of providing a holistic view, we also present additional measures, such as percentage of waste recycled, landfill diversion percentages, hazardous waste reduction percentages, etc. The Deviation from Zero-Waste Benchmarks calculates how well sectors align with global zero-waste sustainability standards. The need for such additional indicators stems from differences in waste management across sectors, providing a more complete picture of areas needing action (Figure 5 below).

The Manufacturing sector demonstrates the strongest waste reduction performance, achieving a Mean Waste Reduction Rate of 21%. This is accompanied by a high percentage of recycled waste (60%) and a landfill diversion rate of 75%, indicating that most waste is either recycled, repurposed, or used in energy recovery systems. The hazardous waste reduction rate (30%) suggests that manufacturing facilities actively manage toxic waste through safer disposal methods and substitution of hazardous materials. The positive deviation (+0.12) from the zero-waste benchmark confirms that manufacturing operations align well with circular economy principles.

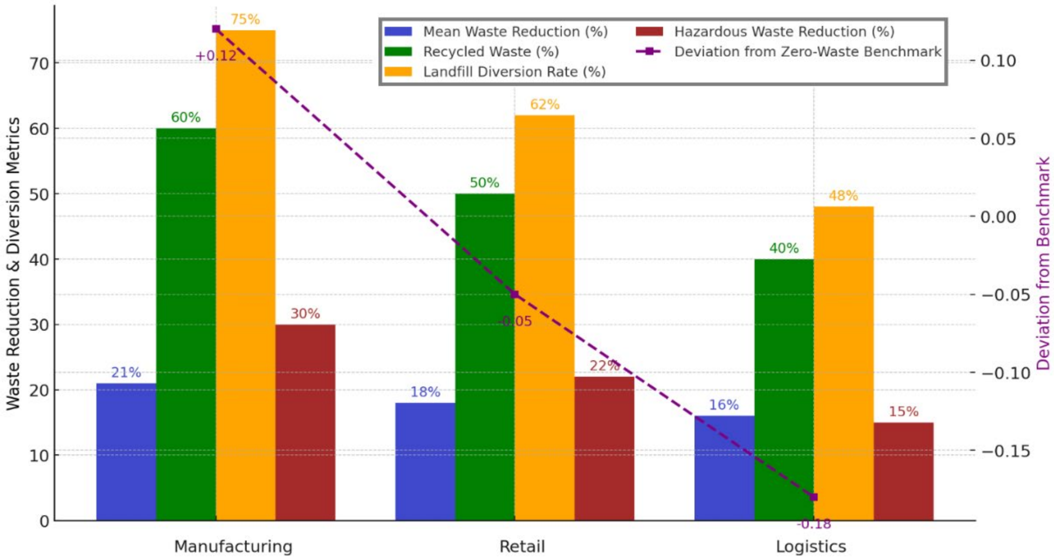

Figure 5. Waste reduction performance by sector

The Retail sector follows with a Waste Reduction Rate of 18%, demonstrating moderate waste minimization progress. The sector achieves a 50% recycling rate and a landfill diversion rate of 62%, indicating room for improvement in upstream supply chain waste management. Hazardous waste reduction remains at 22%, reflecting limited adoption of sustainable alternatives in packaging materials and inventory disposal strategies. The slight negative deviation (-0.05) from the zero-waste benchmark suggests that retail firms must enhance supplier engagement and consumer waste reduction initiatives to achieve circularity goals.

The Logistics sector shows the lowest waste reduction performance, with a Waste Reduction Rate of 16%. The recycling rate (40%) and landfill diversion rate (48%) indicate persistent inefficiencies in packaging waste management, return logistics, and disposal practices. The hazardous waste reduction rate (15%) is significantly lower than other sectors, reinforcing concerns over fuel waste, chemical disposal from maintenance operations, and inefficient material handling. The negative deviation (-0.18) from zero-waste benchmarks highlights that logistics operations require substantial waste management reforms to achieve sustainability compliance.

These findings indicate that while manufacturing is closest to achieving zero-waste standards, retail and logistics sectors require targeted waste management improvements. The retail industry should focus on packaging reduction strategies, extended producer responsibility (EPR) programs, and supplier compliance audits. The logistics sector must integrate advanced reverse logistics models, green packaging alternatives, and hazardous waste reduction policies. Future research should explore the impact of AI-driven waste tracking, government-led zero-waste incentives, and technology-driven circular economy solutions to accelerate waste reduction across global supply chains.

4.4. Carbon Impact Index (CII) and emission reduction analysis

The reduction of carbon emissions is a key determinant of environmental sustainability within supply chain management. As global supply chains transition toward carbon neutrality, industries must implement decarbonization strategies that minimize CO_2 emissions and improve fuel efficiency. The Carbon Impact Index (CII) is used to measure the percentage reduction in CO_2 emissions over time, providing a standardized metric for cross-sectoral comparisons. A higher CII score reflects greater effectiveness in emissions reduction, highlighting a sector's commitment to sustainability and regulatory compliance. However, achieving low-carbon operations requires an integrated approach involving renewable energy adoption, fuel efficiency improvements, and advanced emissions control technologies. To provide a more comprehensive assessment, this analysis includes sectoral renewable energy usage rates, annual carbon emission reductions (tons CO_2 equivalent), fuel efficiency improvements, and deviation from carbon neutrality benchmarks. Figure 6 presents the sectoral carbon impact performance across Manufacturing, Retail, and Logistics industries.

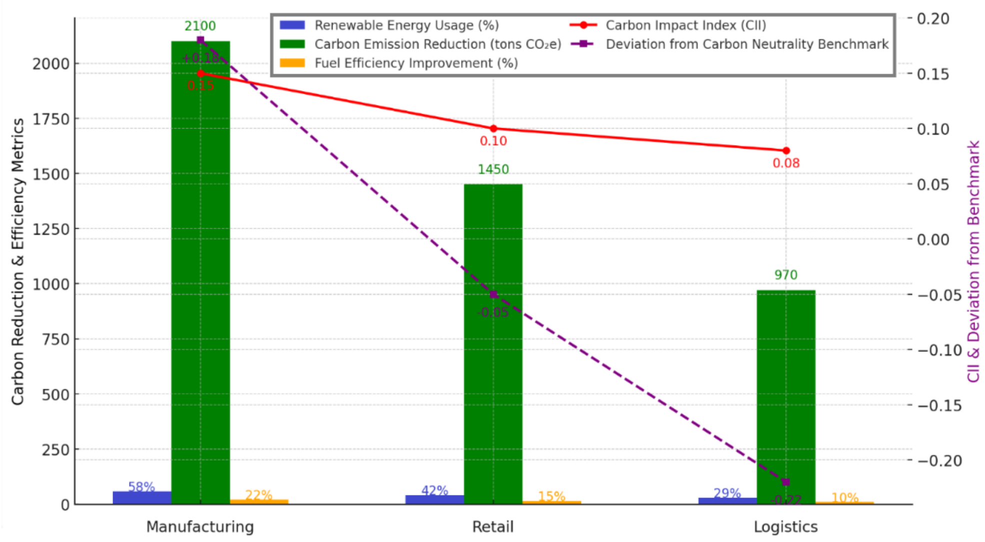

Figure 6. Carbon Impact Index (CII) performance by sector

The analysis of Carbon Impact Index (CII) performance highlights significant sectoral differences in emissions reduction and renewable energy adoption. Manufacturing leads in decarbonization efforts, achieving a CII of 0.15, with 58% renewable energy usage and an annual reduction of 2,100 tons of CO_2 equivalent. This success is attributed to energy-efficient production technologies, process electrification, and carbon capture strategies. Retail follows with a CII of 0.10, reflecting moderate emissions reduction (1,450 tons CO_2 per year), primarily driven by green logistics, energy-efficient warehousing, and sustainable retail practices. However, fuel efficiency improvements (15%) remain limited, signaling room for improvement in supply chain emissions management. Logistics lags significantly, with the lowest CII (0.08) and only 10% fuel efficiency improvement, demonstrating high fossil fuel dependency and inefficiencies in fleet operations.

These findings suggest that while manufacturing is leading in carbon reduction, retail and logistics sectors require greater regulatory support, investment in renewable energy, and technology-driven emissions tracking systems. Future research should examine the role of AI-powered logistics planning, carbon credit mechanisms, and next-generation fuel alternatives in accelerating decarbonization across supply chains.

5. Discussion

The findings of this article provide a comprehensive analysis of sustainable supply chain management (SSCM) within a circular economy, emphasizing sectoral differences in compliance, resource efficiency, waste reduction, and carbon impact reduction. This discussion integrates the results with existing literature, highlights key insights, and outlines limitations and future research directions.

Results from the Compliance Index (CI) show that the manufacturing industry has the highest compliance rate, while logistics, by a wide margin, has the lowest. Such results are consistent with

Kazakova and Lee[18] argue that manufacturing industries have benefited from rigorous environmental regulations for a long time, leading to the early adoption of sustainability practices and compliance frameworks. But the study reveals that the logistics sector shows some major challenges, and compliance is at an all-time low. This aligns with Wang et al.[6], claiming that inherent complexities challenge regulatory alignment in logistics as they often work across borders, face differences in jurisdictions and fragmentation in supply chains. Although compliance differences were statistically significant, that statistical significance and its implications were not relevant from a logistics perspective and this highlights the necessity of establishing compliance frameworks specific to logistics to overcome these regulatory shortcomings[22]. Future research could study other industry-specific policy initiatives and incentives for compliance to better highlight areas aligned with sustainability.

Manufacturing sector has the highest value (PI = 1.05) among all PIs, where more efficient resource utilization can be assumed. This is in line with Schützenhofer et al.[19], claiming that advanced material recovery systems and waste-minimization technologies contribute to a drastic improvement of resource efficiency. The retail industry is relatively efficient but has inefficiencies regarding packaging materials and redundancies in the supply chain. This is consistent with Chan and Zailani [23] describe a common tendency of retailers to focus on the consumer experience and branding at the expense of sustainability, resulting in suboptimal material utilization and redundant waste generation. On the other hand, the logistics industry exhibits the least efficiency, probably because it is reliant on fuels and generates packaging waste, as well as involves many inefficiencies in the optimization of the load. These conclusions align with Zhou and Li [21] that suggest the logistics industry has difficulty in enhancing the efficiency of the process due to fragmented transport networks and missing integrated digital systems in the delivery industry. The findings of this study underscore the need for optimization of logistics in AI as well as predictive analytics that improves efficiency in supply chain operations. Future research may identify the opportunities offered by smart transportation, blockchain or automation in relation to efficiency metrics across industries.

Comparative studies reinforce that sectoral differences are deeply tied to both regulatory design and technological adoption. For instance, manufacturing benefits from mature environmental policies that enforce compliance and incentivize resource efficiency [18], while logistics continues to face fragmentation across borders, limiting its capacity to implement harmonized sustainability frameworks [6, 21]. Additionally, uncertainty management has been identified as a critical enabler, with firms integrating risk mitigation strategies alongside sustainability targets achieving more resilient outcomes [3, 5]. These findings underline the necessity of adaptive governance models that combine legal harmonization, technology-enabled transparency, and cross-sectoral collaboration [8, 12].

Waste reduction performance is also the second major area of SSCM studied. Manufacturing leads with a 21% reduction in waste, due to closed-loop recycling and lean manufacturing02. This accords with Schützenhofer et al. [19], emphasising that these sectors have embraced and applied circular economy principles by establishing an abundant amount of reuse and material repurposing initiatives. Next to retail, which has an 18% reduction rate mainly due to the management of packaging waste and consumer-driven sustainability initiatives. This aligns with the findings of Chan and Zailani [24] literature suggesting that retailers are responding to consumer demand for more sustainable products and adopting better waste minimization strategies. Logistics industry has still been facing difficulties in achieving waste management which showed only 16% reduction Kalkha et al.[20] argue that logistics waste is still one of the toughest sustainability barriers because of ineffectual return flows and high vigilance toward disposal of packaging. These are relevant results as they show that logistics companies need to implement circular logistics models such as reverse logistics and green packaging[15]. Future research directions should examine the generation of logistics and supply chain management waste through policy incentives and digital transformations.

According to the Carbon Impact Index (CII) analysis, manufacturing receives the best carbon reduction performance (CII = 0.15), largely due to investments in renewable energy, emissions tracking and carbon offsetting initiatives. This is in line with Yasir et al. [25] claim that manufacturing industries have incorporated PV–battery systems and energy-efficient technologies, leading to drastic emissions reductions. Logistics sector remained the biggest polluter with a CII score of 0.08, which reiterated the finding by Zhou and Li[21] that logistics has largely developed based on fossil fuel reliance with slow rollout of electric and hybrid vehicle fleets. The findings indicate that logistics operations require more aggressive decarbonization strategies like alternative fuel adoption, fleet electrification, and carbon taxation policies.

The challenges also illustrate how legal frameworks shape environmental outcomes. Comparative studies show that jurisdictions with stringent reporting standards and transparent auditing mechanisms have accelerated transitions toward circularity [4, 22]. In contrast, fragmented or weak legal enforcement exacerbates non-compliance, particularly in transnational logistics networks [6]. Beyond compliance, uncertainty management has been identified as a critical enabler of resilience, where firms integrating sustainability with risk-mitigation strategies achieve stronger outcomes in turbulent contexts [3]. This underlines the role of both legal harmonization and adaptive governance in driving SSCM effectiveness. Further studies should look into the impact of financial incentives and governance regulations on the accelerated transition to low-carbon operations of logistics activities.

Complementing other, often generalized or sector-based measures of circularity, The Circular Economy Performance Index (CEP) adds what is missing by combining compliance, efficiency, waste and recycling rates to create a holistic measure of the circularity of supply chains. Manufacturing is identified as the leading sector with a CEP score of 0.85, owing to its more advanced sustainability frameworks and circular material flows. Such finding is in line with Kazakova and Lee[18] highlights that manufacturing is the most matured sector in term of circular economy implementation as a result of long-time environmental policies. The results in the retail sector (CEP = 0.72) reflect a moderate improvement in sustainability performance found in Chan and Zailani [24] note that while circular practices are being integrated, retailers remain behind intergenerational sustainability practices upstream in the supply chain. As before, logistics has the lowest circularity, with a CEP score of 0.65. Logistics companies are unable to implement circularity, as there exist ineffective cycles of resources and low investment in sustainability-oriented technologies. The results underscore the potential for circular logistics system based on recycling, reuse and sustainable packaging solutions. This has potential for improved circularity throughout supply chains — future research should delve into AI driven waste trackers and digital sustainability reporting to incorporate this further.

The article, despite its comprehensive approach, is not without limitations. First, the data with 120 respondents in three sectors may not represent global variability in SSCM performance. Further research should add to the data set a greater diversity of geographic regions and industries. Second, despite the study combining quantitative and qualitative insights, long-term sustainability trends would need to be assessed through longitudinal data tracking. This is particularly relevant for sustainability practices that can evolve over time due to changes in regulations and industry dynamics. Third, all the comply and efficiency data are self-reported, which may draw biases. Further studies should introduce 3rd-party sustainability audits and real carbon emissions data to reinforce findings. Moreover, the potential role of novel technologies, such as AI, blockchain, and IoT in SSCM has not been fully investigated. As suggested by Kalkha et al.[20], digital transformation will be a key driver to boost sustainability performance in logistics and supply chain tracking.

Future studies could explore the means by which real-time data analytics and automation can be leveraged to optimize resource efficiency, waste minimization, and carbon impact management.

6. Conclusions

The article has explored SSCM and the circular economy principles towards examining these principles across sectoral differences through compliance, resource optimization, waste mitigation, and carbon impact mitigation. The study adopted a mixed-methods approach comprising qualitative and quantitative data to develop a multidimensional understanding of the challenges and opportunities in manufacturing, retail, and logistics sectors. These findings underscore the intricacies surrounding regulatory compliance, material utilization, waste reduction, and carbon footprint mitigation, drawing attention to the necessity of tailored sustainability approaches within specific business sectors.

The article has shown that sustainability performance along supply chains is not only context-sensitive, but also sector-dependent. Manufacturing stands as the most sustainable industry, owing to its regulatory framework maturity, resource-efficient technology investment and broad implementation of circular economy principles. Manufacturing industries can set the best in place for sustainability execution with the ability to integrate waste minimization techniques, optimize material flows, and achieve elevated pieces of compliance level. While retail is improving its sustainability practices, it won't be easy, both upstream supply chain integration and the disposal of packaging have proven difficult to tackle. Even as consumer-oriented sustainability programs have pressured retailers to refine their environmental performance, inefficiencies in resource utilization and waste creation persist. The logistics industry has the biggest gaps, with challenges related to compliance, efficiency, and carbon impact reduction. Factors such as the complexity of logistics networks, reliance on fossil fuels and fragmented regulatory environments underestimate the potential of the transport sector's sustainability performance.

The article contributes significantly by proposing construction Integrated Sustainability Framework by Circular Economy Performance Index (CEP) a multidimensional approach to measuring sectoral sustainability. The index is a comprehensive measure of circular economy adoption, through the inclusion of compliance, efficiency, waste reduction and recycling metrics. The results highlight that manufacturing sectors seem to be more mature for the adoption of circular economy practices while retail and logistics need to evolve towards eco-innovation. It's essential that retail and logistics industries have low resource utilization and minimize negative externalities during road transport, and this research highlights underlying problems that need addressing and contributes to the literature around mechanisms, incentives, and industry collaboration for invigorating sustainability performance.

Technological innovation is key in tackling sustainability challenges in supply chains, it further reveals. Emerging digital solutions like AI, blockchain, and predictive analytics present significant opportunities to enhance resource efficiency, improve compliance tracking, and optimize logistics processes. Supply chains using data to make decisions are more likely to meet sustainability goals and reduce environmental impact. Future research should explore the role of smart technologies in sustainability transitions, particularly in logistics and retail sectors where inefficiencies persist.

Policy interventions and corporate sustainability commitments are essential for achieving long-term improvements in SSCM. Governments and industry regulators must implement standardized sustainability policies that provide clear guidelines for compliance, emissions reduction, and waste management. Incentives such as tax breaks, carbon credits, and grants for green initiatives can accelerate sustainability adoption. Additionally, cross-sector partnerships between governments, businesses, and research institutions can facilitate knowledge sharing, fostering a collaborative approach to sustainable supply chain development.

Although this study provides valuable insights into sector-specific sustainability performance, it also highlights the limitations that must be addressed in future research. The study is based on cross-sectional data, which captures sustainability trends at a single point in time. Longitudinal studies would provide a more dynamic understanding of how sustainability performance evolves over time. Additionally, expanding the scope to include a broader range of industries and geographic regions would enhance the generalizability of the findings. Future research should also consider integrating empirical sustainability data, such as real-time emissions monitoring and third-party audits, to validate self-reported compliance and efficiency metrics.

The article contributes theoretically by bridging two traditionally fragmented domains: legal compliance and environmental sustainability. By integrating them into the CEP framework, it offers a multidimensional approach that enhances decision-making under uncertainty. Practically, the findings provide policymakers with evidence for designing more consistent regulatory frameworks, while guiding managers in manufacturing, retail, and logistics to adopt targeted strategies that improve compliance, resource efficiency, and waste reduction. Managerially, the study highlights the importance of aligning corporate sustainability culture with regulatory requirements to achieve long-term competitiveness. Limitations of the research, particularly the small sample size and reliance on self-reported data, necessitate cautious interpretation of results. Future studies should expand cross-regional datasets, integrate third-party audits, and apply real-time digital monitoring technologies such as blockchain and AI to improve data reliability.

The article advances the understanding of sustainable supply chain management by identifying key sectoral differences, introducing a multidimensional sustainability framework, and emphasizing the role of technology and policy in achieving circular economy objectives. While manufacturing has made significant progress in sustainability implementation, retail and logistics sectors require targeted interventions to bridge sustainability gaps. The transition to a circular economy is a complex but necessary process, requiring continuous innovation, policy reform, and industry commitment. Future research should focus on refining sustainability models, integrating technological advancements, and exploring cross-sector synergies to drive sustainable transformation across global supply chains.

Conflict of interest

The authors declare no conflict of interest

References

1. Theeraworawit M, Suriyankietkaew S, Hallinger P. Sustainable Supply Chain Management in a Circular Economy: A Bibliometric Review. Sustainability [Internet]. 2022; 14(15).
2. Govindan K, Hasanagic M. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. International Journal of Production Research. 2018;56(1-2):278-311.
3. Lima FAd, Seuring S, Sauer PC. A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains. International Journal of Production Research. 2021;60:6013 - 46.
4. Awuah-Gyawu M, Abdul Muntaka S, Owusu-Bio MK, Otchere Fianko A. Assessing the effects of sustainable supply chain management practices on operational performance: the role of business regulatory compliance and corporate sustainability culture. Benchmarking: An International Journal. 2024;ahead-of-print(ahead-of-print).
5. Feng Y, Zhao X, Zhu Q. Sustainable supply chains in a turbulent world: Challenges and opportunities. Australian Journal of Management. 2023;48(2):199-203.
6. Wang J, Lim MK, Wang C, Tseng M-L. Comprehensive analysis of sustainable logistics and supply chain based on bibliometrics: overview, trends, challenges, and opportunities. International Journal of Logistics Research and Applications. 2023;26(10):1285-314.

7. Esan O, Ajayi FA, Olawale O. Supply chain integrating sustainability and ethics: Strategies for modern supply chain management. World Journal of Advanced Research and Reviews. 2024.
8. Sgambaro L, Chiaroni D, Urbinati A. Fostering the transition towards circular economy through collaborations: An open innovation perspective in the building industry. Creativity and Innovation Management. 2025;34(1):30-46.
9. Ada N, Kazançoğlu Y, Sezer MD, Ede-Senturk C, Ozer I, Ram M. Analyzing Barriers of Circular Food Supply Chains and Proposing Industry 4.0 Solutions. Sustainability. 2021.
10. Rajat S. Circular Economy in Supply Chain. Journal of Production, Operations Management and Economics. 2022;2(03):35-45.
11. Jum'a L, Zimon D, Sroufe R, Tyan J. Sustainable supply chain management's impact on triple bottom line performance: Does the firm size matter? Corporate Social Responsibility and Environmental Management. 2024;31(5):4673-93.
12. Groenewald E, Espinosa-Jaramillo M, Garg A, Pipalia K, Umasekar V, Groenewald CA. Circular Economy Strategies in Supply Chain Management: Towards Zero Waste. Power System Technology. 2024;48:460-80.
13. Nugraha B, Hidayat, A., Dania, W., Hatanaka, K., & Ramadhona, S. . Program evaluation and review technique – Data envelopment analysis in benchmarking sustainable supply chain management of the potato chips industry. Advances in Food Science, Sustainable Agriculture and Agroindustrial Engineering. 2023;6(3).
14. Shekarian E, Ijadi B, Zare A, Majava J. Sustainable Supply Chain Management: A Comprehensive Systematic Review of Industrial Practices. Sustainability. 2022;14(13).
15. Genovese A, Acquaye A, Figueroa A, Koh SCL. Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications $. Omega-international Journal of Management Science. 2017;66:344-57.
16. Hemdev O. Supply Chain Management in India: Challenges, Innovations, and the Path to Global Competitiveness in a Dynamic Economic Environment. International Journal of Science and Research (IJSR). 2024;13(9):1426-8.
17. Ramadhan MF, Siroj, R. A., & Afgani, M. W. Validitas and Reliabilitas. Journal on Education. 2024;6(2):10967-75.
18. Kazakova E, Lee J. Sustainable Manufacturing for a Circular Economy. Sustainability [Internet]. 2022; 14(24).
19. Schützenhofer S, Kovacic I, Rechberger H, Mack S. Improvement of Environmental Sustainability and Circular Economy through Construction Waste Management for Material Reuse. Sustainability [Internet]. 2022; 14(17).
20. Kalkha H, Khiat A, Bahnasse A, Ouajji H. The Rising Trends of Smart E-Commerce Logistics. IEEE Access. 2023;11:33839-57.
21. Zhou T, Li W. Efficiency Evaluation and Influencing Factors Analysis of Logistics Industry based on Multiobjective Intelligent Computing. Computational Intelligence and Neuroscience. 2022;2022(1):3098160.
22. Hata S, Nansai K, Nakajima K. Supply Chain Factors Contributing to Improved Material Flow Indicators but Increased Carbon Footprint. Environmental Science & Technology. 2023;57(34):12713-21.
23. Za'im Sahul Hameed M, Nordin R, Ismail A, Zulkifley MA, Sham ASH, Sabudin RZAR, et al. Acceptance of medical drone technology and its determinant factors among public and healthcare personnel in a Malaysian urban environment: knowledge, attitude, and perception. Frontiers in Public Health. 2023;11.
24. Chan CYR, Zailani S. Capabilities to create new value for business sustainability: a retailer case study from Malaysia. Benchmarking: An International Journal. 2024;ahead-of-print(ahead-of-print).
25. Yasir K, Shen J, Lin J. Sustainable Logistics: Synergizing Passive Design and PV–Battery Systems for Carbon Footprint Reduction. Buildings [Internet]. 2024; 14(10).