From Linear to Circular: The Triadic Framework of Reduction, Restoration, and Regeneration as Catalysts in Sustainable Supply Chain Transitions

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ABSTRACT

Overview: This investigation explores the influence of environmentally focused supply chain management on the performance of the circular economy. In addition, it examines how three specific sustainable practices—namely reduction, restoration, and regeneration—serve as intermediaries in this relationship. Methodology: This study focused on Malaysia's manufacturing industry, gathering data from 267 companies through a straightforward random sampling approach. The study's framework was rigorously tested for validity and reliability, and hypothesis testing was performed using Hayes's PROCESS macro within IBM SPSS. Key Findings: The results indicate that sustainable supply chain management exerts a direct, positive impact on circular economy performance. Furthermore, it fosters the adoption of the three sustainable practices, each of which contributes to enhanced CE performance. These practices also mediate the relationship between supply chain management and the circular economy, highlighting their critical role. Conclusion: This study illuminate how sustainable practices bridge the gap between sustainable supply chain management and circular economy outcomes. In summary, this research deepens the insight into how sustainable supply chain management fosters eco-friendly practices and strengthens circular economy outcomes, revealing innovative perspectives on the real-world impact of these vital environmental strategies.

Keywords: Sustainable supply chain management, sustainable reduction, sustainable restoration, sustainable regeneration, circular economy performance, manufacturing sectors, Malaysia.

INTRODUCTION

As environmental concerns and resource limitations intensify, businesses worldwide find themselves at a pivotal juncture. Governments, advocacy groups, and stakeholders are exerting increasing pressure on corporations to rethink their operational strategies, ensuring compliance with environmental standards while mitigating the ecological impact of industrial processes (Latip et al, 2022; Singh et al, 2021; Zhang et al, 2020). This has sparked growing interest among manufacturing firms in embracing circular economy (CE) principles to enhance sustainability. The CE concept, initially recognized by Chinese enterprises, challenges the traditional linear economy by promoting a regenerative approach. Rooted in the "cradle-to-cradle" philosophy, CE aims to optimize resource efficiency through material recovery processes such as reduction, reuse, redistribution, remanufacturing, refurbishment, and recycling (Zhang X et al, 2023; Peralta et al, 2021; Lin et al, 2019) Shifting from a traditional linear economy to a circular one requires a comprehensive overhaul of supply chain structures. Consequently, sustainable supply chain management (SSCM) becomes an essential catalyst in boosting circular economy outcomes. Research suggests that SSCM is not only essential but also one of the key facilitators of a successful CE transformation (Luthra et al, 2022; Le et al, 2022). However, achieving and maintaining CE performance requires companies to adopt innovative production techniques, operational frameworks, and managerial strategies. Sustainable practices, therefore, act as critical enablers of CE by fostering the development of novel products, processes, and technologies.

Although research on the circular economy has expanded recently, the concept remains nascent and calls for deeper exploration from multiple angles—especially within the realm of supply chain management (de Lima et al, 2022; Hina et al, 2023; Kanda et al, 2025). In parallel, investigations into achieving and measuring CE performance are still emerging, with a particular need for studies in developing economies and emerging markets (Ghisellini et al, 2016.; Ella et al, 2017). Notably, the connection between sustainable supply chain management (SSCM) and CE performance has received limited attention. Furthermore, as far as we know, no previous study has assessed how sustainable practices—specifically reduction, restoration, and regeneration—mediate the relationship between SSCM and CE performance. To address these gaps, this study seeks to deepen existing knowledge by examining not only the direct impact of SSCM on CE performance but also its indirect effects mediated by triadic key dimensions of sustainable practices.

From this standpoint, we put forward the following research questions:

RQ1. How does SSCM affect CE performance?

RQ2. In what ways do sustainable practices mediate the relationship between SSCM and CE performance?

This investigation examine the complex interplay between sustainable supply chain management and circular economy outcomes, acknowledging that our current work lays the groundwork for future research. As circular economy studies are still in their infancy, our results serve as an early step toward comprehending the factors that drive CE performance. Notably, our research was carried out in a modestly sized developing nation, where most manufacturing firms are small- to medium-sized enterprises. In Malaysia, manufacturing SMEs are just beginning to embrace and understand CE principles, and many managers have yet to clearly differentiate between these principles and the metrics used to gauge CE success (Kumar et al, 2024; Afif et al, 2021) Given the limited availability of companies within a single industry, our sample encompasses multiple sectors, capturing diverse perspectives on the awareness and implementation of circular economy practices. These industry-specific variations prompted us to use broad, general CE performance indicators that participants could readily comprehend and assess. Additionally, we highlight the need for future research to refine these metrics further, ensuring a clearer distinction between CE performance indicators and the core principles of the circular economy.

The structure of this paper is as follows: Section 2 provides an overview of the relevant literature. Section 3 presents the theoretical framework and the formulation of our hypotheses. Section 4 describes the research methodology employed. Section 5 details the results and hypothesis testing, and Section 6 concludes with a discussion of the findings, their implications, and final conclusions.

LITERATURE REVIEW

Sustainable Supply Chain Management

Sustainable supply chain management (SSCM) has evolved into a pivotal area of research and practice, gaining global prominence over the last two decades. (Ghadimi et al, 2019; Hariharasudan et al, 2021; Tsai et al, 2021). Driven by external pressures—including regulatory mandates, competitive market forces, and heightened stakeholder expectations—sustainability has transcended isolated corporate initiatives to become a cornerstone of strategic supply chain processes. According to Latip et al, (2022) SSCM necessitates a harmonized focus on profitability, ecological preservation, and societal equity. It conceptualize the intentional, strategic integration of an organization's social, environmental, and economic goals into cross-functional supply chain processes, fostering sustained value creation for both the firm and its network. Moreover, aligning environmental and social imperatives with customer needs and economic benchmarks is vital for achieving supply chain resilience and accountability (Brockhaus et al, 2016; Asamoah et al, 2020).

Organizations increasingly adopting strategies such as green procurement, low-impact warehousing, and biodegradable packaging (Tabesh et al., 2024; Ali et al., 2023; Gupta et al., 2022; Bawna et al., 2024). Empirical studies demonstrate that SSCM practices not only reduce waste but also strengthen brand equity, elevate workforce morale, streamline operations, and drive profitability (Kumar et al., 2025; Al-Tarawneha et al., 2025). However, deploying SSCM requires navigating multifaceted challenges, including rapidly evolving stakeholder demands and systemic interdependencies across internal and external networks (Borissov, 2024; Brandao & Godinho, 2024). To unravel these complexities, this study adopts a circular economy lens, offering a theoretical foundation to synthesize insights and guide implementation.

Recent advancements in SSCM have incorporated novel paradigms such as circular economy (CE) principles and Industry 4.0 innovations (Matarneh et al., 2024; Godinho et al., 2024). CE reimagines production-consumption systems by prioritizing the 3Rs—recycling, reuse, and remanufacturing—to create closed-loop supply chains (Zorpas, 2024; Rashid & Malik, 2023). Such systems optimize resource cycles (e.g., energy, materials), enabling firms to achieve holistic sustainability outcomes that align economic growth with ecological preservation and social equity.

CE concept has garnered significant attention from both practitioners and academics, evolving as a critical response to unsustainable economic practices. Practitioners frame CE as a transformative alternative to the linear 'take-make-dispose' model, guided by three foundational principles: eliminating waste and pollution through intentional design, extending the lifecycle of products and materials, and restoring natural ecosystems (Zorpas, 2024). This shift addresses the shortcomings of the dominant linear system, which strains the planet's finite resources and undermines long-term economic sustainability. By prioritizing closed-loop systems—where resources are continually reused and renewables replace finite inputs—CE positions itself as a viable pathway for sustainable production and consumption. Beyond environmental gains like waste reduction, transitioning to CE unlocks socioeconomic advantages, including resource efficiency, cost savings, and employment opportunities in emerging green sectors (Eyo-Udo et al.,2024; Karim et al., 2024). In this research, SSCM is framed within a triadic model, incorporating sustainable reduction, sustainable restoration, and sustainable regeneration as identified in previous studies.

Sustainable reduction in supply chain management

Modern production systems demand a shift beyond merely optimizing conventional resources like labor, materials, and machinery for output and profit. Today's industrial landscape prioritizes a holistic approach that scrutinizes every form of waste generated—whether excess materials, energy inefficiencies, or time delays—and actively seeks strategies to prevent, minimize, repurpose, or recover it (Aiguobarueghian et al., 2024; Wei et al., 2024). Though compliance with environmental laws drives such measures, forward-thinking businesses recognize that innovative waste management not only aligns with regulations but also unlocks cost savings, resource conservation, and ecological stewardship. By integrating waste reduction into their operational DNA, companies transform sustainability into a strategic lever, securing market resilience, operational excellence, and enduring financial success.

Historically, waste management relied on retroactive fixes like end-of-pipe solutions, later evolving into process- and product-integrated environmental innovations. While these approaches addressed waste after its creation, they often operated in silos, targeting symptom reduction within individual companies rather than systemic change (Cairns et a., 2021; Hofstetter et al., 2021) . Despite their intent, such fragmented efforts struggled to curb waste's broader impacts. Now, industries face a paradigm shift: moving away from linear 'take-make-dispose' models—which churn out vast, unsustainable waste—toward circular systems. In this regenerative framework, discarded products, byproducts, and materials are systematically reclaimed, processed, and reintegrated into production cycles. This shift not only boosts resource efficiency but also turns waste streams into revenue streams, aligning profitability with environmental stewardship (Kandpal et al., 2024).

True CE cannot thrive in isolation—no single company possesses the scope or resources to orchestrate a self-sustaining closed-loop system alone. The real power lies in collaborative ecosystems: interconnected supply chains where industries unite to transform waste into wealth. By leveraging supply chain strategies, businesses can bridge gaps between production stages, turning linear 'end-of-life' waste streams into cross-industry inputs. When companies synchronize efforts—sharing byproducts, repurposing materials, and co-designing resource-efficient processes—they unlock dual gains: economic resilience and reduced environmental footprints (Dennisson et al., 2024). To catalyze this shift, industries must reimagine waste not as a liability but as a latent asset, embedding it into restorative regenerative networks where one company's discard becomes another's raw material. Such symbiotic systems don't just close loops—they redefine value creation, proving sustainability and profitability are inseparable partners in tomorrow's economy.

Sustainable restoration in supply chain management

Within circular economy (CE) scholarship, restoration is predominantly framed as the imperative to replenish natural capital—a concept rooted in revitalizing ecosystems and preserving finite environmental assets (Bada-Carbajal et al., 2024; Bertolami, 2024). The concept of natural capital, popularized by Hawken et al. (1999), encompasses both the tangible resources humanity extracts and the broader ecosystems that sustain life (Polasky & Daily, 2021).This paradigm positions nature not as a commodity to exploit but as a finite reserve requiring stewardship (Hails & Ormerod, 2013). Consequently, CE advocates argue that economic systems must transition from extractive models to regenerative ones, where restoration manifests through the active reconstruction of degraded ecosystems and resource bases.

While sustainable supply chain management (SSCM) and the circular economy (CE) have historically been examined as distinct scholarly domains, recent research underscores the value of exploring their intersections to identify mutually reinforcing opportunities (Rada, 2023). SSCM traditionally prioritizes mitigating environmental harm across supply chain activities, such as reducing pollution and resource depletion (Ali et al., 2024). In contrast, CE advocates for a paradigmatic shift toward restorative, self-renewing systems that actively regenerate natural ecosystems while minimizing resource extraction, waste generation, and energy losses through strategies like closed-loop material flows (Ali et al., 2024; Titova & Terentyeva, 2023).

Although SSCM has incorporated certain CE-aligned practices—such as recovery processes and the "3R" (reduce, recycle, reuse) framework (Hazen et al., 2021)—their foundational philosophies diverge. CE operates as an aspirational model, envisioning perpetual resource circulation within closed systems to eliminate reliance on raw inputs (Baker, 2024). While achieving full circularity remains challenging, CE principles offer a robust framework for reconciling economic development with ecological preservation. SSCM conversely, often adopts CE strategies reactively and selectively. For example, SSCM's "3R" approach focuses on curbing environmental impacts through waste mitigation, whereas CE's restorative ethos emphasizes proactive measures, such as replacing harmful materials with bio-based alternatives to remediate ecological damage (Chen et al., 2024)

Sustainable regeneration in supply chain management

Regeneration transcends the ethos of restoration: where the latter seeks to return systems to a prior state of health, the former aspires to enhance them beyond their original condition. This distinction, however, is often obscured by historical and conceptual ambiguities. During the 1990s, proponents of regeneration framed their arguments through a lens of techno-optimism, aligning it with broader narratives of societal progress (Kirby & Mahoney, 2017). Yet, as Mang and Reed (2012, proposed, the term became entangled with—and often conflated with—other sustainability paradigms emerging at the time, diluting its unique intent. The resulting proliferation of interpretations has rendered "regeneration" a fragmented concept, echoing the chaotic evolution of frameworks that sought to define it (Mang & Reed, 2012).

Scholars such as Pauliuk (2024), Pitt and Heinemeyer (2015), and Rhodes (2017) frame ecological regeneration as a process of amplifying ecosystems' capacity to sustain life, aligning with the principle of "ecosystem health." Yet this vision hinges on the nebulous idea of "better conditions," which lacks clarity without defined historical baselines or metrics to gauge progress. Rhodes (2017) specifies tangible outcomes like habitat creation, soil enrichment, water purification, and enhanced biogeochemical cycles (e.g., carbon sequestration), proposing that scaling smaller regenerative units can build systemic resilience. While parallels exist with restoration—notably in repairing ecological harm—regeneration adopts a forward-looking stance, aiming to forge symbiotic human-nature relationships. This proactive ethos aligns with concepts like ecological design which integrates human systems with natural processes; ecological engineering that focused on bio-based infrastructures (Toner et al., 2023) and "positive development," advocating net ecological gains (Birkeland, 2022)

Circular Economy Performance (CEP)

The Circular Economy (CE) model aspires to break the link between economic growth and finite resource depletion—particularly carbon-intensive energy systems—by systematically eliminating waste streams, perpetually cycling materials, and revitalizing ecological integrity. This paradigm, as conceptualized by the Ellen MacArthur Foundation (2015), positions economic activity as a catalyst for societal well-being, prioritizing systems that generate holistic value over extractive consumption. Operationalizing CE demands radical innovation across industries. Producers must rethink manufacturing through durable, modular designs and adopt processes enabling repair, remanufacturing, and material recovery (de Lima et al., 2024). Yet transitioning to such models confronts entrenched barriers: innovation gaps in recycling technologies, funding constraints for circular infrastructure, and institutional inertia favoring linear practices (Bonetti & Villa, 2023; Kastelli et al., 2023).

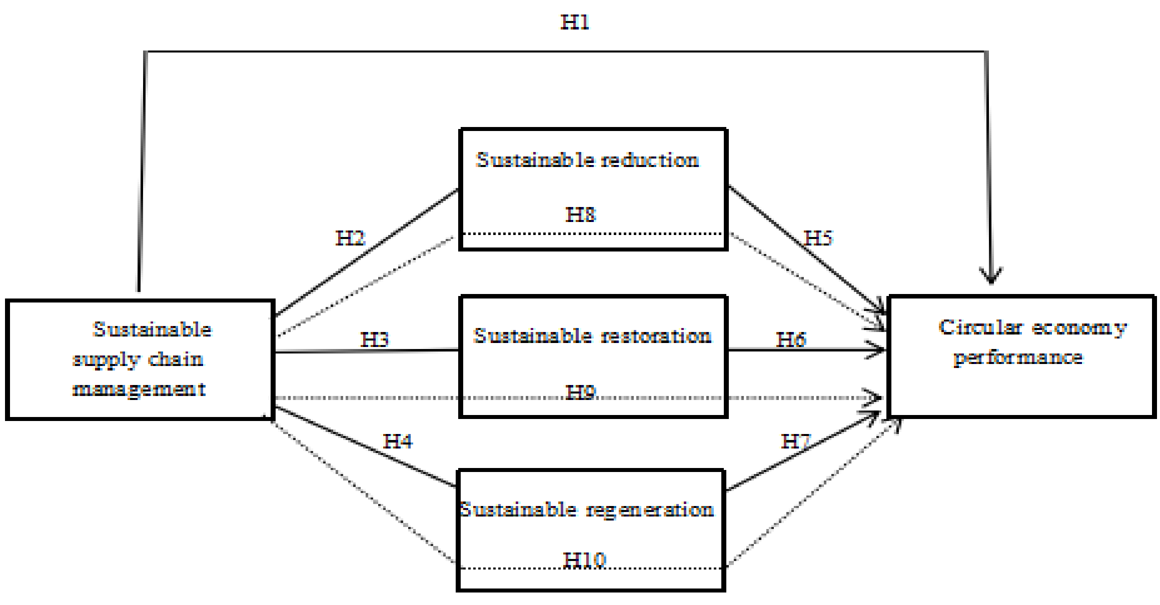
While supply chain proponents routinely address these challenges—whether through waste reduction or resource optimization—their efforts often lack the systemic coherence and intentionality required to fully align with CE's regenerative ambition. Although a proliferation of circular economy (CE) assessment frameworks has emerged in recent research, significant discrepancies persist across studies in defining their objectives, operational boundaries, and implementation methodologies, compounded by divergent approaches to evaluating performance across micro-, meso-, and macro-level systems (Kuzoma & Dovgal, 2023). This investigation focuses specifically on organizational-scale CE measurement, prioritizing indicators with robust empirical validation and scholarly consensus. Key metrics integrated into the analysis encompass strategies for resource efficiency optimization, emission reduction, material loss mitigation, increased utilization of renewable/recyclable inputs, and product longevity enhancement – criteria widely recognized in foundational CE literature (Vranjanac et al., 2022; Elshaer et al., 2024).

Theoretical Framework and Hypotheses Development

RESEARCH FRAMEWORK

This research employs the conceptual framework depicted in Figure 1 to analyze how Sustainable Supply Chain Management (SSCM) influences strategies for minimizing waste (reduction), renewing resources (restoration), revitalizing systems (regeneration), and enhancing Circular Economy (CE) outcomes. It further examines the direct contributions of reduction, restoration, and regeneration to CE performance, as well as their role as mediators in linking SSCM practices to improved CE results

Figure 1. Research model.



SSCM and Circular Economy Performance

Shifting from linear economic models to circular systems requires businesses to fundamentally reconfiguring their supply networks. Ricardo and Sandoval (2024) highlighted that adopting SSCM optimizes resource use, safeguards ecosystems, and elevates CE outcomes. Consequently, SSCM is positioned as a strategic approach to balancing profitability, mitigating ecological harm, and boosting resource efficiency to strengthen CE performance (Malhotra, 2023). Zhang et al., (2024) reinforced this, arguing that SSCM acts as a catalyst for CE adoption, while other researchers have explored synergistic links between SSCM and CE frameworks (Galanton, 2024; Patel et al., 2021). SSCM encompasses all stages of a product's lifecycle—design, sourcing, manufacturing, distribution, consumption, and recycling—ensuring closed-loop systems that drive CE progress (Galanton, 2024). To maximize CE outcomes, SSCM implementation must align with core 3R principles (reduce waste, renewing resource, revitalising system). Empirical studies, such as Li et al. (2023) demonstrated that sustainable supply chain practices directly enhance CE capabilities in China's eco-industrial sectors. Bai et al. (2023) similarly identified SSCM practices as critical precursors for advancing CE initiatives in China. Conversely, Wang et al. (2024) revealed disparities in CE implementation and performance among firms with varying levels of SSCM adoption. This leads to the proposed hypothesis:

Hypothesis 1: The implementation of SSCM directly and positively influence CE performance..

SSCM and sustainable reduction, restoration and regeneration practice

Growing global consumer preference for sustainable goods is prompting manufacturers to overhaul supply chain operations, not merely to curb toxic byproducts but to revitalize ecological balance in production systems while securing returns on green investments (Iannuzzi, 2024). Iannuzzi (2024) also highlights that aligning supply chain strategies with eco-conscious buyer expectations is a pivotal motivator for adopting SSCM. For an example, gasoline-powered vehicles contribute heavily to atmospheric contamination, driving the rise of electric cars as a cleaner alternative. This shift underscores the need for eco-design strategies that merge user-centric performance with planetary well-being. Forward-thinking firms now recognize SSCM as a gateway to untapped markets rooted in sustainable innovation. Supporting this, studies by Zankl & Grimes (2024) underscore that cross-supply-chain partnerships amplify corporate commitment to reducing pollutants, spurring collaborative efforts in waste reduction and eco-efficient practices. Such alliances often catalyze transformative environmental initiatives led by industry leaders.

Strategic execution of SSCM can also drives measurable advantages, including superior product standards, minimized operational expenses, punctual distribution, and optimized resource use. Lean manufacturing frameworks further prioritize employee accountability in refining workflows, fostering productivity gains through shortened cycle times and systematic waste reduction (Trotta & Fernandez, 2022; Basiru et al., 2023) Enhanced logistical coordination—spanning procurement to delivery—enables firms to source premium materials from select partners, mitigate production inefficiencies, and curb defects, thereby elevating output consistency while slashing avoidable losses (Basiru et al., 2023) Integrating these practices across the supply network not only safeguards material integrity but also fortifies compliance, positioning businesses to achieve both economic and operational excellence.

Additionally, regenerative and restorative approaches within SSCM emphasise sustainability beyond traditional practices (Bag, 2025; Howard et al., 2019) For instance, the meticulous disassembly and assessment of used devices or materials allows components to be refurbished, remanufactured, or recycled, effectively minimising waste. This not only reduces environmental harm but also restores ecosystems and resources. These practices align with industrial ecology principles, focusing on closed-loop systems and enabling natural cycles in industrial processes. Therefore, the following hypotheses are proposed:

Hypothesis 2: The implementation of SSCM is expected to enhance the positive influence of sustainable reduction practice.

Hypothesis 3: The implementation of SSCM is expected to enhance the positive influence of sustainable restoration practice.

Hypothesis 4: The implementation of SSCM is expected to enhance the positive influence of sustainable regeneration practice.

Sustainable reduction, restoration regeneration practice and CE Performance

Firms worldwide seek to transform their manufacturing processes and consumption behaviors to minimize material waste and produce environmentally friendly products and embedding the principles of a circular economy into traditional supply chain frameworks, fostering resource efficiency and sustainability (Batista et al., 2019; Ashby et al., 2019). Rooted in minimizing resource depletion, extending material lifespans, and regenerating value, the circular economy model prioritizes sustainable outcomes by closing resource loops. Vegter et al. (2021)further emphasize by focusing on the orchestration of interconnected organizations and consumers to advance economic, ecological, and social goals through restorative systems that emphasize resource conservation, reuse, and regeneration.

The CE performance prioritizes minimizing resource consumption, sustaining ecosystems, and revitalizing materials, emphasizing closed-loop systems that mirror natural renewal processes (Roy et al., 2022; Vegter et al., 2021). Guided by interconnected performance goals, this model outlines a material's journey: resources are harvested from the environment, manufactured into goods, utilized across phases of repair and repurposing, and finally returned via disposal methods like landfills or incineration (Roy et al., 2022). The lifespan of these cycles—termed service lifetime—spans from a material's initial extraction to its ultimate reintroduction into the environment as waste.

Hypothesis 5. The implementation of sustainable reduction practice is expected to enhance the positive influence on CE performance.

Hypothesis 6. The implementation of sustainable restoration practice is expected to enhance the positive influence on CE performance.

Hypothesis 7. The implementation of sustainable regeneration practice is expected to enhance the positive influence on CE performance.

Sustainable reduction, restoration and regeneration practices mediating the effects on the SSCM–CE Performance Relationship

Existing research suggests SSCM directly strengthens CE outcomes (e.g., resource efficiency, waste mitigation). However, its indirect effects—mediated through variables like sustainable reduction, restoration, and regeneration practices—warrant deeper analysis to fully unravel this dynamic . By embedding SSCM frameworks, firms can institutionalize eco-conscious collaboration with suppliers, refine production processes, and foster employee engagement in sustainability initiatives, all of which amplify CE performance. For instance, SSCM operationalizes measures such as energy optimization, material recycling, and pollution control, thereby curbing resource exploitation and aligning operations with CE principles (Batista et al., 2019).

Critically, SSCM acts as a catalyst: it establishes the infrastructure for reduction-restoration-regeneration cycles (e.g., reusing materials, repairing products), which subsequently elevate CE metrics. As Del Giudice et al. (2021) emphasize, advancing CE through SSCM demands cross-functional alignment—training teams, incentivizing sustainable behaviors, and partnering with external stakeholders to design supply chains that prioritize circularity. Thus, SSCM's value lies not only in its immediate environmental gains but also in its capacity to systemicize circular practices across organizational and industrial boundaries.

Hypothesis 8. The implementation of sustainable reduction practices is expected to enhance the positive influence of SSCM on CE performance.

Hypothesis 10. The implementation of restoration practice is expected to enhance the positive influence of SSCM on CE performance.

Hypothesis 11. The implementation of regeneration practice is expected to enhnace the positive influence of SSCM on CE performance.

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METHODOLOGY

Sample

The research focused on manufacturing enterprises in Malaysia, encompassing 1,783 registered firms as the target population. A representative sample of 316 companies was selected for analysis, with individual firms serving as the primary unit of investigation. To ensure diversity, the study incorporated businesses across multiple industries, as individual sectors in Jordan host relatively few firms. A random sampling approach was employed, though this method—common in supply chain studies—posed challenges, including the labor-intensive process of compiling company databases and logistical efforts to engage participants. To mitigate low response rates typical of digital or mailed surveys in Malaysia, The research sample was carefully curated by Embrain, a company renowned for its employee database and rigorous sample selection protocols to ensure the integrity and quality of the data collected.

At each firm, a single manager with adequate understanding of operational or supply chain dynamics (e.g., SC, plant, operations, or executive managers) was invited to complete the questionnaire. Data collection spanned January to March 2024, beginning with coordination through human resource departments. These teams assisted in identifying qualified respondents, particularly in smaller firms lacking dedicated SC roles, where operations managers often handled such responsibilities. Participants were assured confidentiality, with data reserved solely for academic purposes. Of the 316 distributed questionnaires, 267 were returned fully completed, achieving an 87.6% response rate attributed to the direct, in-person distribution strategy. Demographic and organizational profiles of respondents and firms are detailed in Table 1.

Table 1: Profiles of respondents and surveyed companies.

Category	**Frequency**	**Percentage (100%)**
Gender		
Male	208	78
Female	59	22
Total	267	100.0
Job Position		
Supply chain manager	99	37
Operations manager	82	30
Plant manager	37	13.8
Executive manager	31	11.6
Others	18	6.7
Total	267	100.0
Company age		
Less than 5 years	19	7.1
5–less than 10 years	28	10.4
10–less than 15 years	105	39.3
15 years and above	115	43
Total	267	100.0
Respondent’s experience		
Less than 5 years	73	27.3

5–less than 10 years	88	33
10–less than 15 years	52	19.4
15–less than 20 years	30	11.2
20 years and above	24	9
Total	267	100.0
Industry Type		
Machinery and hardware	43	16.1
Electrical and electronics	40	15
Chemical	39	14.6
Food	39	14.6
Textiles and garments	35	13
Rubber and plastic	23	8.6
Pharmaceutical	15	5.6
Paper and packaging	14	5.2
Others	19	7.1
Total	267	100.0

Questionnaire and Measures

To accomplish the research objectives, a structured survey was designed by synthesizing insights from existing scholarly works. The framework and measurement items were adapted from well-established, peer-reviewed studies in English [11,63,70,83–86], chosen for their robust validation and frequent application in prior research. For example, Chiou et al. [70] documented reliability scores of 0.77 (product innovation), 0.96 (process innovation), and 0.92 (management innovation), while Zeng et al. [11] reported a Cronbach's alpha of 0.897 for circular economy performance. The questionnaire was initially drafted in English and subsequently translated into Arabic by the research team. To ensure conceptual accuracy and linguistic equivalence, academics specializing in operations and supply chain management evaluated both language versions, refining the wording and structure based on their feedback. Further clarity checks were conducted by distributing the survey to seven industry managers, leading to additional adjustments. Respondents rated their agreement with each statement using a five-point Likert scale (1 = "strongly disagree," 5 = "strongly agree"). A comprehensive list of constructs, their corresponding measurement items, and original sources is provided in Table 2.

Table 2. Measurement items.

Item Number	**Item Descriptions (Reference)**
Green Procurement Practices (Tabesh et al., 2024)	
GPP1	Our organization prioritizes suppliers with certified environmental management systems (e.g., ISO 14001)
GPP2	We select suppliers based on their use of recycled or renewable materials.
GPP3	Our procurement policies explicitly include environmental performance metrics.

GPP4	We collaborate with suppliers to reduce packaging waste (e.g., reusable containers).
GPP5	We conduct regular audits to ensure suppliers comply with sustainability standards.
Sustainable Production Processes (Ali et al., 2023; Kumar et al., 2025)	
SPP1	Our production processes are designed to minimize waste generation.
SPP2	We utilize renewable energy sources in manufacturing.
SPP3	We employ closed-loop water systems to reduce consumption.
SPP4	Our facility uses energy-efficient machinery (e.g., IoT-enabled equipment).
SPP5	We actively monitor and reduce greenhouse gas emissions during production.
Resource Efficiency and Optimization (Zorpas, 2024)	
REO1	We systematically measure and optimize material usage (e.g., material flow analysis)
REO2*	We recycle or reuse >80% of production by-products (e.g., metal scraps).
REO3	Lean manufacturing techniques are applied to reduce resource waste.
REO4	We invest in AI/ML technologies to enhance resource productivity
REO5	Annual targets are set to reduce raw material consumption by 10%
Collaboration and Stakeholder Engagement (Borissov, 2024; Brandao & Godinho, 2024)	
CSE1	We collaborate with suppliers on joint sustainability initiatives (e.g., waste reduction).
CSE2	We partner with customers for product take-back programs (e.g., e-waste recycling).
CSE3*	We work with NGOs to advance circular economy goals (e.g., plastic neutrality).
CSE4	Sustainability performance is communicated quarterly to stakeholders
CSE5	Local communities are involved in our circularity efforts (e.g., upskilling programs)
Sustainable Reduction Practice (Aiguobarueghian et al., 2024; Wei et al., 2024)	
SRDP1	Our production processes are designed to reduce material waste
SRDP2	We actively optimize logistics to lower energy consumption.
SRDP3	Our company prioritizes lightweight/eco-friendly packaging.
SRDP4	We set measurable targets for reducing greenhouse gas emissions.
SRDP5	Resource efficiency is a key performance indicator in our operations.
Sustainable Restoration Practice (Bada-Carbajal et al., 2024; Bertolami, 2024)	
SRTP1	We have systems in place to recover used products for refurbishment.
SRTP2	Our company partners with recycling firms to reprocess waste materials.

SRTP3	We design products for easy disassembly and component reuse.
SRTP4	Customers are incentivized to return end-of-life products to us.
SRTP5	We use recycled materials in at least 30% of our production inputs.
Sustainable Regeneration Practice(Toner et al., 2023;Birkeland,2022)	
SRGP1	Our company invests in renewable energy for supply chain operations.
SRGP2	We engage in biodiversity restoration projects (e.g., reforestation).
SRGP3	Our agricultural suppliers adopt regenerative farming practices.
SRGP4	We prioritize materials that restore soil/water health during production.
SRGP5	Our waste management systems aim to regenerate natural resources.
Circular Economy Performance(de Lima et al., 2024;Vranjanac et al., 2022; Elshaer et al., 2024)	
CEP1	Our company has significantly reduced virgin material use in the past 3 years.
CEP2	Our Product lifecycles are extended through repair/refurbishment programs.
CEP3	We achieve cost savings by reusing/recycling materials.
CEP4	Our environmental footprint has decreased due to circular practices.
CEP5	Energy used in production is primarily from renewable sources.
CEP6	Our Customer perception of our brand aligns with circular economy values.
CEP7	Circular supply chains have enhanced our brand reputation with customers.
CEP8	Circular practices (reduction/restoration/regeneration) have improved our supply chain resilience
CEP9	We share circular economy best practices with our supply chain partners.
CEP10	Our company invests in technologies (e.g., IoT, blockchain) to enhance supply chain transparency.

Note: *: deleted items.

Data Analysis and Results

Assessment of the Measurement Model

The investigation conducted a thorough examination of the research model and its components by applying strict validity and reliability tests. Central to this analysis were criteria such as unidimensionality, convergent validity, and composite reliability . Confirmatory factor analysis (CFA) using Amos 24.0 was employed to assess both the unidimensionality and overall adequacy of the model, thereby confirming the integrity of the entire measurement framework. Eight first-order constructs were scrutinized, with each indicator systematically paired with its corresponding variable. Those indicators that registered factor loadings below 0.50 were removed—resulting in the exclusion of two items—while the remaining indicators provided strong evidence of convergent validity and unidimensionality for these constructs. Additionally, every average variance extracted (AVE) score

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exceeded the 0.50 threshold, further reinforcing convergent validity. The model's fit indices (χ^2 = 740.865; df = 466; χ^2/df = 1.592; CFI = 0.959; IFI = 0.957; TLI = 0.948; RMSEA = 0.057; RMR = 0.043) supported its acceptable validity, and the composite reliability for all first-order variables surpassed the 0.70 benchmark [89]. For the second-order SSCM construct used in hypothesis testing, additional tests for validity and reliability were conducted. This model displayed satisfactory fit indices (χ^2 = 814.577; df = 479; χ^2/df = 1.703; CFI = 0.923; IFI = 0.928; TLI = 0.925; RMSEA = 0.064; RMR = 0.050). All factor loadings for the second-order construct were above 0.50, and both its AVE (0.675) and CR values exceeded the established thresholds of 0.50 and 0.70, respectively, thereby confirming convergent validity. A detailed summary of these assessments is presented in Table 3.

Table 3. Reliability and validity of the constructs.

Construct	**Item number**	**Mean**	**Standard Deviation**	**Loading CFA**	**Composite reliability**
GPP	GPP1	4.35	0.756	0.647	0.867
	GPP2			0.698	
	GPP3			0.791	
	GPP4			0.853	
	GPP5			0.741	
SPP	SPP1	3.77	0.738	0.766	0.822
	SPP2			0.625	
	SPP4			0.786	
	SPP5			0.737	
REO	REO1	3.95	0.864	0.831	0.865
	REO2			0.826	
	REO3			0.746	
	REO4			0.738	
CSE	CSE1	4.14	0.765	0.720	0.844
	CSE2			0.787	
	CSE3			0.808	
	CSE4			0.644	
	CSE5			0.637	
GSCM [a]	CSE [b]	4.04	0.640	0.812	0.889
	SPP [b]			0.941	
	REO [b]			0.866	
	GPP [b]			0.630	
SRDP	GPRD1	3.38	0.863	0.843	0.897
	GPRD2			0.769	
	GPRD3			0.754	
	GPRD4			0.817	

	GPRD5			0.795	
SRTP	GPRC1	3.77	0.695	0.785	0.838
	GPRC2			0.691	
	GPRC3			0.846	
	GPRC4			0.674	
SRGP	GMGT1	3.96	0.715	0.724	0.806
	GMGT2			0.747	
	GMGT3			0.683	
	GMGT4			0.698	
CEP	CEP1	3.64	0.873	0.717	0.915
	CEP2			0.685	
	CEP3			0.686	
	CEP4			0.722	
	CEP5			0.742	
	CEP6			0.672	
	CEP7			0.725	
	CEP8			0.707	
	CEP9			0.744	
	CEP10			0.810	

Note: a second-order construct; b second-order indicators.

To verify the distinctiveness of the first-order constructs within the research model, discriminant validity was rigorously examined. This evaluation involved calculating the square root of the average variance extracted (AVE) for each construct and comparing it against the correlation coefficients between that construct and all others in the study. As displayed in Table 4, the analysis confirmed that all constructs met this criterion, with the square roots of their AVE values surpassing their inter-construct correlations. These findings confirm that the constructs are statistically distinct, thereby establishing robust discriminant validity in the study's framework.

Table 4. Assessment of discriminant validity.

Construct	**AVE**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1. GPP	0.561	**0.748**							
2. SPP	0.536	0.524	**0.732**						
3. REO	0.620	0.512	0.570	**0.787**					
4. CSE	0.520	0.475	0.547	0.566	**0.720**				
5. SRDP	0.631	0.717	0.466	0.422	0.471	**0.793**			
6. SRTP	0.569	0.569	0.409	0.487	0.437	0.619	**0.754**		
7. SRGP	0.507	0.436	0.481	0.538	0.585	0.672	0.741	**0.711**	
8. CEP	0.524	0.648	0.429	0.476	0.539	0.398	0.424	0.466	**0.724**

Results

The study hypotheses were tested using the PROCESS macro (Model 4) in SPSS to analyze parallel mediation effects, following Hayes's recommendations (Hayes, 2012). This approach employed 5000 bootstrapped samples and 95% confidence intervals (CIs) to examine direct, indirect, and total effects. Statistical significance was determined when CIs excluded zero between their lower (LL) and upper (UL) bounds (Hayes, 2012; Hayes et al., 2017). The analysis revealed a significant positive direct effect of sustainable supply chain management (SSCM) on circular economy (CE) performance ($\beta = 0.421$, $p = 0.01$), supporting Hypothesis 1. SSCM also demonstrated strong positive associations with sustainable reduction, restoration, and regeneration practices, significantly influencing SRDP ($\beta = 0.405$, $p = 0.01$), SRTP ($\beta = 0.678$, $p = 0.01$), and SRGP ($\beta = 0.695$, $p = 0.01$), thereby validating Hypotheses 2, 3, and 4.

Furthermore, each sustainable practice independently contributed to CE performance: SRDP ($\beta = 0.245$, $p = 0.01$), SRTP ($\beta = 0.172$, $p = 0.01$), and SRGP ($\beta = 0.188$, $p = 0.01$), confirming Hypotheses 5–7. Mediation analysis indicated that SRDP ($\beta = 0.098$, 95% CI [0.055, 0.151]), SRTP ($\beta = 0.115$, 95% CI [0.022, 0.214]), and SRGP ($\beta = 0.130$, 95% CI [0.041, 0.223]) each partially mediated the relationship between SSCM and CE performance, supporting Hypotheses 8–10. The persistence of a significant direct SSCM–CE effect ($\beta = 0.421$, $p = 0.01$) alongside these indirect pathways confirmed partial mediation [93]. The total impact of SSCM on CE performance, calculated as the sum of direct and indirect effects (0.421 + 0.098 + 0.115 + 0.130), yielded a combined effect size of 0.764. A detailed summary of these findings is presented in Table 5

T**able 5.** Summary of results.

Hypothesis	Path	Mediated Model	95% Confidence	Interval	Result
			Lower	Upper	
H1	SSCM → CEP	0.421 **	0.293	0.487	Supported
H2	SSCM → SRDP	0.405 **	0.259	0.469	Supported
H3	SSCM → SRTP	0.678 **	0.524	0.693	Supported
H4	SSCM → SRGP	0.695 **	0.615	0.803	Supported
H5	SRDP → CEP	0.244 **	0.172	0.330	Supported
H6	SRTP → CEP	0.172 **	0.063	0.291	Supported
H7	SRGP → CEP	0.188**	0.071	0.275	Supported
H8	SSCM → SRDP → CEP	0.098 (indirect effect)	0.055	0.151	Supported
H9	SSCM → SRTP → CEP	0.115 (indirect effect)	0.022	0.214	Supported
H10	SSCM → SRGP → CEP	0.130 (indirect effect)	0.041	0.223	Supported

Note: ** $p < 0.01$.

DISCUSSION, CONCLUSIONS, AND IMPLICATIONS

Discussion

The study demonstrated that sustainable supply chain management (SSCM) serves as a significant driver of circular economy (CE) outcomes, with empirical data reinforcing its direct, positive influence. While these findings align with broader literature, nuanced distinctions emerged. For example, prior work by Zeng et al. (2017) linked supply chain relationship management (SCRM) and sustainable supply chain design (SSCD) to enhanced CE capabilities in China's eco-industrial parks, whereas this research shifts focus to SSCM's role in a developing nation's industrial landscape. Similarly, while Kazancoglu et al. (2021) proposed a theoretical model for SSCM-CE integration, this analysis advances the discourse by grounding the relationship in tangible evidence. Critically, the results challenge the assumption that internal sustainability initiatives alone suffice for achieving robust CE performance. Instead, they underscore the necessity of external collaboration: partnering with suppliers to source low-impact materials and engaging customers in product return systems, recycling programs, and reuse protocols. Such coordinated efforts create closed-loop synergies, enabling manufacturers to align with core CE principles—reduction, reuse, and recycling. By prioritizing SSCM, firms optimize resource efficiency, curb energy consumption, and mitigate pollution, thereby elevating both environmental outcomes and operational circularity.

The findings of this study confirm that SSCM has a positive influence on all three aspects of 3R's sustainable practices: reduction, restoration, and regeneration. These results align with previous research (Tseng et al., 2019; Abu Seman et al., 2022). However, unlike earlier studies that primarily examined SSCM's impact on green practices as a whole, our research takes a more granular approach by analyzing its effect on each specific 3R's sustainable practices individually. Several distinctions set our study apart from previous work. For instance, Tseng et al. (2019) conducted a literature review, whereas our research provides empirical evidence of this relationship. Similarly, Abu Seman et al. (2022) explored the influence of SSCM on green practices as a unified concept in Malaysia, while our study breaks it down further, considering its impact across different functional areas—procurement, production, resource management, and stakeholder engagement—on 3R's practices. Additionally, Chiou et al. (2011) found that sustainable supplier practices positively affected product, process, and managerial innovations in Taiwan. In contrast, our study specifically examines how SSCM influences three distinct sustainable practices. Notably, our results indicate that SSCM's influence on restoration and regeneration practices is more pronounced than on reduction practices. This discrepancy may stem from the fact that SRDP primarily focuses on minimizing production waste, often requiring advanced technologies and substantial financial investment. Conversely, SRTP and SRGP emphasize process enhancements and investment returns through operational efficiency, sourcing strategies, and logistics improvements that lower resource consumption and emissions. As a result, SRDP tends to be more costly, while SRTP and SRGP provide companies with more opportunities for cost reduction, environmental sustainability, and an enhanced green reputation.

Our study confirms that 3R's sustainable practices have a strong and positive impact on CE performance. While these findings generally align with prior research [13,14,76], some key differences emerge. For instance, de Jesus et al. (2021) conducted a literature-based analysis, whereas our study provides empirical evidence on CE performance outcomes. Similarly, Maldonado-Guzmán et al. (2021) identified a positive relationship between sustainable practices and CE performance within Mexico's automotive and auto parts sector, but our research differs by focusing on SMEs in a developing economy rather than large corporations. Additionally, Bag et al. (2020) examined the influence of a broad green practice framework on CE capability in South Africa. In contrast, our study takes a more detailed approach, assessing how specific sustainable practices contribute to CE performance. The results indicate that SRDP, SRGP, and SRTP were the most impactful 3R's practices, in that order. Interestingly, while SRDP was the least influenced by SSCM, it played the most significant role in enhancing CE performance. This may be due to the high costs, technical complexity, and advanced expertise required for SRDP innovation. However, once companies successfully implement SRDP, its benefits for CE performance appear to be the most substantial.

Ultimately, the different types of 3R's practices played a significant mediating role in the relationship between SSCM and CE performance. These findings highlight that implementing 3R's practices can be an effective approach for improving CE performance in manufacturing firms. Our study underscores SSCM as a key driver of both sustainable practices and CE performance. By fostering sustainability initiatives, SSCM is likely to amplify CE performance through the adoption of reduction, restoration, and regeneration strategies. Although these environmental concepts are still emerging in Malaysia, their presence may indicate growing environmental awareness among manufacturing firms. Companies that strategically align their SSCM initiatives with sustainable practices are expected to achieve superior CE performance. To our knowledge, this study is the first to provide empirical evidence on how reduction, restoration, and regeneration practices mediate the SSCM–CE performance link. However, our findings partially align with Abu Seman et al. (2022), who identified the mediating role of green practices—considered as a broad construct—between SSCM and environmental performance in Malaysia.

Conclusions

This research explored how SSCM influences the adoption of sustainable practices (Reduction, Restoration, and Regeneration) and CE performance within Malaysia's manufacturing sector. It also examined the direct link between 3R's practices and CE performance, along with the indirect role of SSCM in enhancing CE performance through 3R's implementation. The findings revealed that SSCM plays a crucial role in driving sustainability-focused innovations in products, processes, and management. Additionally, the study demonstrated that SSCM significantly contributes to improved CE performance. Moreover, the research emphasized the essential role of 3R practices in strengthening CE performance outcomes. The results further indicated that reduction, restoration, and regeneration practices positively mediate the relationship between SSCM and CE performance. Ultimately, this study enhances the understanding of SSCM's influence on sustainable practices and CE performance, offering fresh perspectives on the practical implications of these key environmental strategies.

Theoretical Contribution

This study makes several theoretical contributions. Firstly, it enriches existing research by presenting empirical evidence on how SSCM influences both sustainable practices and CE performance. Furthermore, it builds on previous studies by analyzing the effect of 3R practices on CE performance and investigating their mediating role in the SSCM–CE performance link. Secondly, this research is among the first to explore how SSCM affects three distinct categories of sustainable practices. Additionally, it highlights the broader role of sustainability efforts by emphasizing not just waste reduction but also restoration and regeneration practice as key components of sustainable resource management in manufacturing industry. By adopting a circular economy perspective, this study deepens the understanding of the interconnectedness between various sustainable practices within the manufacturing sector.

Managerial Implications

This research provides valuable insights and recommendations for leaders in the manufacturing sector. It underscores the vital role of Sustainable Supply Chain Management (SSCM) in driving sustainable practices and fostering innovation, ultimately enhancing Circular Economy (CE) performance. By integrating SSCM strategies with 3R sustainable practices initiatives, managers can not only meet environmental regulations but also achieve higher levels of CE efficiency. While many manufacturers primarily focus on minimizing waste, this study highlights the broader necessity of restoring ecological balance while simultaneously generating economic benefits. SSCM's impact extends beyond CE performance, as prior research suggests it plays a pivotal role in advancing sustainable production methods and process innovations. Though implementing these environmental strategies may seem financially and logistically challenging, especially in developing economies, they are essential for long-term business viability and regulatory compliance at both local and global levels. Moreover, adhering to stringent environmental standards enables manufacturers to access international markets with strict import regulations. Despite the upfront investment, the long-term gains—such as business sustainability, enhanced brand reputation, and increased export potential—justify the costs associated with these green initiatives.

Limitations and Future Research Directions

This investigation acknowledges several limitations that open avenues for future exploration. To begin with, while it evaluated the collective influence of Sustainable Supply Chain Management (SSCM) on sustainable practices and Circular Economy (CE) outcomes, it did not dissect the effects of specific SSCM initiatives. Future research could benefit from analyzing these individual components to offer more nuanced insights. Moreover, the study's sample spanned multiple industries due to the limited representation within any single sector in Malaysia, yet the degree to which environmental strategies are executed can vary widely based on industry-specific factors such as technological sophistication, supply chain configurations, product features, and ecological impacts. Conducting research within a single industry might therefore provide more detailed understanding of these relationships. Additionally, the reliance on a single managerial viewpoint from each company, although common in research, may constrain the broader applicability of the findings; incorporating feedback from multiple informants could enhance the robustness of future conclusions. Finally, because the current assessment of CE performance captured only early-stage implementation efforts rather than long-term, comprehensive outcomes, future studies should refine these indicators. It would also be worthwhile to examine the reverse influence—exploring how mature CE practices might, in turn, drive sustainable innovations and shape SSCM.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data Availability Statement

Not Applicable

Authors's Contributions

The authors confirm their contribution to the paper as follows: Study conception and design:Mohammad Ammalluddin Ramli; Data collection: Mohammad Ammalluddin Ramli; Analysis and interpretation of results: Mohammad Ammalluddin Ramli; Draft manuscript preparation; Mohammad; Ammalluddin Ramli.

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