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Closed-Loop Supply Chain Design and Environmental Performance of Small and Medium-Sized Manufacturing Enterprises (SMEs) in Nairobi Metropolitan Area, Kenya: A Circular Economy Perspective

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Abstract

The increasing environmental challenges facing small and medium enterprises (SMEs) have intensified the need for sustainable supply chain practices that promote efficient resource utilization and minimize environmental degradation. This study examined the effect of closed-loop supply chain design on the environmental performance of SMEs. Specifically, the study investigated the influence of product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery on environmental performance, measured in terms of waste reduction, resource efficiency, recycling rate, reduction in greenhouse gas emissions, reduced landfill disposal, and compliance with environmental regulations. The study adopted a positivist research philosophy and a deductive approach, employing a descriptive and explanatory cross-sectional survey design. Primary data were collected using structured questionnaires administered to employees responsible for procurement, logistics, production, operations, and environmental management in the selected SMEs. A representative sample was selected using stratified and simple random sampling techniques, and the collected data were analyzed using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics, including means, standard deviations, skewness, and kurtosis, were used to summarize the data, while Pearson's correlation and multiple linear regression analyses were employed to test the study hypothesis.

The findings revealed that SMEs had implemented closed-loop supply chain design practices to a high extent, with recycling and waste recovery recording the highest level of adoption. Similarly, environmental performance was rated highly, particularly regarding compliance with environmental regulations and waste reduction. The multiple regression analysis established that closed-loop supply chain design had a positive and statistically significant effect on environmental performance ($R = 0.824$, $R^2 = 0.679$, Adjusted $R^2 = 0.673$, $F = 102.741$, $p < 0.001$), explaining 67.9% of the variation in environmental performance. Among the predictor variables, recycling and waste recovery exerted the strongest influence, followed by product return systems, reverse logistics integration, and product recovery and remanufacturing. The study concluded that the adoption of closed-loop supply chain design significantly enhances the environmental performance of SMEs by promoting waste reduction, improving resource efficiency, increasing recycling, reducing greenhouse gas emissions and landfill disposal, and strengthening compliance with environmental regulations. The study recommends that policymakers

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develop supportive policies and incentives that encourage SMEs to adopt circular economy practices, while SME managers should invest in product return systems, reverse logistics infrastructure, recycling technologies, and strategic partnerships that strengthen sustainable supply chain management and improve long-term environmental performance.

Keywords: *Closed-loop supply chain design, environmental performance, small and medium enterprises, reverse logistics, recycling, product return systems, circular economy, sustainability..*

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Introduction

Sustainable supply chains (SSCs) have emerged in response to increasing global awareness of sustainability among consumers, producers, governments, and both public and private organizations (Abdollah et al., 2022). Their development is driven by factors such as market competition, environmental regulations, and increasingly stringent local and international sustainability policies. Unlike traditional supply chains, SSCs seek to balance economic performance with environmental protection and social responsibility by addressing the challenges associated with resource depletion and minimizing the adverse environmental and social impacts of supply chain activities (Kiss et al., 2019).

A key form of sustainable supply chain is the sustainable closed-loop supply chain (CLSC), which integrates both forward and reverse logistics in accordance with circular economy principles (De Lima et al., 2022). By facilitating activities such as product returns, reuse, remanufacturing, recycling, and proper disposal, sustainable closed-loop supply chains enhance resource efficiency, reduce waste, and create additional economic and social value while minimizing environmental impacts (Sudusinghe & Seuring, 2022). Consequently, the sustainable CLSC provides a comprehensive framework for achieving a balanced integration of the economic, environmental, and social dimensions of sustainability, making it an effective approach for organizations seeking long-term sustainable supply chain performance (Luzano-Oviedo et al.,2024).

The transition from a linear economy to a circular economy has become a global priority due to growing concerns over resource depletion, climate change, pollution, and increasing volumes of industrial waste. The circular economy seeks to minimize waste and maximize resource utilization by promoting product reuse, repair, remanufacturing, recycling, and recovery throughout the product life cycle (Kirchherr et al., 2017). Central to achieving these objectives is the implementation of closed-loop supply chain (CLSC) design, which integrates forward and reverse logistics to facilitate the return, recovery, refurbishment, remanufacturing, and recycling of products and materials (Luzano-Oviedo et al., 2024). Closed-Loop Supply Chain Design (CLSC Design) refers to the planning and structuring of a supply chain that integrates both forward flows of products and materials (from suppliers to customers) and reverse flows (from customers back to the firm for recovery, reuse, remanufacturing, recycling, or disposal) (De Lima et al., 2022).

Globally, best practices in closed-loop supply chain (CLSC) design emphasize the integration of circular economy principles across the entire product lifecycle, enabling manufacturing firms to reduce waste, recover value, and improve environmental performance. Leading manufacturing economies such as Germany, the Netherlands, Japan, and China have institutionalized practices including eco-design, product life extension, remanufacturing, reverse logistics, industrial symbiosis, and the use of digital technologies for material tracking and resource optimization (Chiaraluce et al., 2021). Successful firms design products for durability, repairability, reuse, and recyclability while establishing efficient systems

for collecting, sorting, refurbishing, and reintegrating end-of-life products into production processes (Mehershi et al., 2019). These practices are reinforced through strong regulatory frameworks, extended producer responsibility (EPR) policies, public-private partnerships, and collaboration among manufacturers, suppliers, recyclers, customers, and research institutions. The integration of environmental management systems, such as ISO 14001, and digital technologies including Internet of Things (IoT), blockchain, and artificial intelligence has further enhanced resource efficiency, reduced greenhouse gas emissions, and improved transparency within supply chains (THeeraworawit et al., 2022).

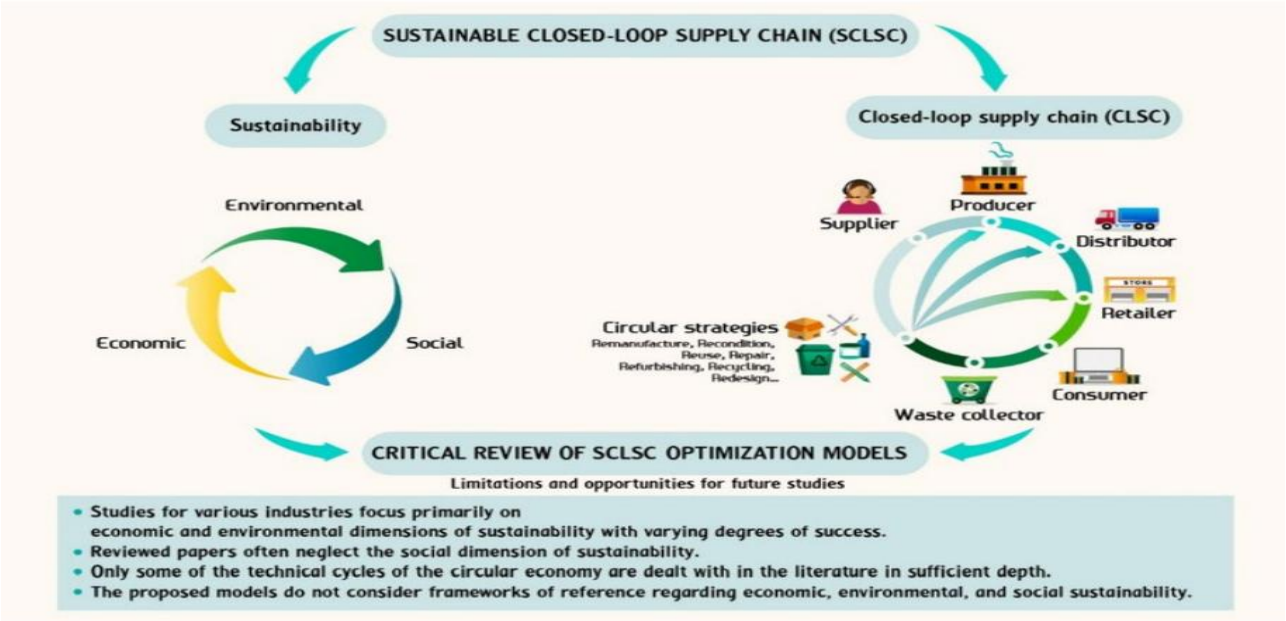


Figure 1. Closed-Loop Supply Chain in a Circular Economy
Source: Adapted from Luzano-Oviedo et al., 2024

In regard to the small and medium-sized manufacturing enterprises (SMEs), global best practices focus on implementing scalable and cost-effective circular economy strategies that align with limited financial and technological resources (Abdolazimi et al, 2025). SMEs increasingly collaborate through industrial symbiosis networks, where waste or by-products from one enterprise become valuable inputs for another, thereby reducing disposal costs and resource consumption (Dey et al., 2020). Many successful SMEs adopt cleaner production technologies, renewable energy solutions, lean manufacturing, and environmentally responsible procurement practices to improve operational efficiency and environmental sustainability (Khalife et al., 2025). Capacity building through employee training, collaboration with research institutions, industry associations, and government support programs further enhances the adoption of closed-loop supply chain practices (Masudin et al., 2025). In the context of the Nairobi Metropolitan Area, these global best practices provide a practical benchmark for manufacturing SMEs by demonstrating how effective reverse logistics, stakeholder collaboration, eco-innovation, and supportive policy frameworks can strengthen circular economy implementation and significantly improve environmental performance through reduced waste generation, enhanced resource recovery, and lower environmental impacts.

Manufacturing SMEs play a critical role in Kenya's industrialization agenda by contributing to employment, innovation, and economic growth (Okeke , 2020). However, many SMEs continue to rely on linear production systems characterized by excessive raw material consumption, inefficient waste management, and limited recovery of end-of-life products (Zhang et al., 2026). These practices contribute

to environmental degradation through increased landfill disposal, greenhouse gas emissions, pollution, and depletion of natural resources. The Nairobi Metropolitan Area is home to the largest concentration of manufacturing SMEs in Kenya and generates substantial volumes of industrial waste. The increasing emphasis on sustainable manufacturing, environmental regulations, and circular economy practices has heightened the need for SMEs to redesign their supply chains to reduce environmental impacts while maintaining competitiveness. Closed-loop supply chain design provides firms with opportunities to improve environmental performance by reducing waste generation, conserving natural resources, increasing recycling rates, and lowering carbon emissions (Wang et al., 2024).

Problem Statement

The transition from a linear to a circular economy has become a global priority as governments and industries seek to reduce waste, conserve natural resources, and improve environmental sustainability (Khan et al., 2025). Globally, more than 100 billion tonnes of materials are extracted and consumed annually, yet only about 7–9% of these materials are cycled back into the economy through reuse, remanufacturing, and recycling, indicating that the global economy remains largely linear despite advances in circular economy practices (Wang et al., 2024). At the firm level, manufacturing organizations in countries such as Germany, Japan, the Netherlands, and China have successfully adopted closed-loop supply chain (CLSC) design, resulting in significant improvements in resource efficiency, waste reduction, and carbon emission mitigation through reverse logistics, product recovery, remanufacturing, and recycling (Zhang et al., 2026).

In contrast, Kenya's manufacturing sector continues to face considerable environmental sustainability challenges. According to the Kenya National Bureau of Statistics (KNBS) Economic Survey, manufacturing contributed only 7.3% of Kenya's Gross Domestic Product (GDP) in 2024, a decline from 11.3% in 2010, reflecting the sector's declining competitiveness and productivity. The sector employs approximately 369,200 people, representing about 11–12% of formal employment, yet continues to experience high production costs, inefficient material utilization, and increasing environmental pressures. Furthermore, micro, small, and medium enterprises account for approximately 97% of manufacturing establishments in Kenya, but they contribute only about 20% of manufacturing GDP, largely because of limited technological capability, low innovation, inadequate resource recovery systems, and poor adoption of circular production practices. The National Environment Management Authority further notes that Kenya continues to operate predominantly under a linear production model in which valuable materials are discarded after use instead of being recovered, reused, refurbished, or recycled, leading to increasing industrial waste, environmental pollution, and resource depletion (Amingaw t al., 2025).

Consequently, many manufacturing SMEs in the Nairobi Metropolitan Area continue to exhibit weak reverse logistics systems, limited recycling and remanufacturing capabilities, and poor environmental performance compared with manufacturing firms in countries where closed-loop supply chain systems are well established (Karanja, 2024). This problem affects manufacturing SMEs through increased operational costs, material losses, and reduced competitiveness while simultaneously undermining the efforts of government agencies, environmental regulators, customers, and policymakers to achieve Kenya's Vision 2030, the Sustainable Development Goals (particularly SDGs 9, 12, and 13), and the national circular economy agenda.

Despite increasing scholarly attention to sustainable supply chain management and circular economy, empirical evidence linking closed-loop supply chain design with environmental performance among manufacturing SMEs remains limited, particularly in developing economies. Previous studies by Thiga (2024), Khalife et al. (2024), Zhang et al. (2026), Meherishi et al. (2019), Karanja et al. (2024), Khan et al. (2025), and Wang et al. (2024) largely examined reverse logistics, sustainable supply chains, circular economy implementation, Industry 4.0 technologies, and barriers to circular economy adoption without directly investigating the influence of closed-loop supply chain design on environmental performance

among manufacturing SMEs. Within Kenya, existing studies have focused primarily on green supply chain management, organizational performance, or circular manufacturing practices in large firms, while paying limited attention to SMEs operating within the Nairobi Metropolitan Area and rarely examining environmental performance as the primary outcome variable. This leaves an empirical, contextual, and methodological gap regarding how closed-loop supply chain design contributes to improved environmental performance among manufacturing SMEs operating under resource constraints in a developing-country context. The present study therefore sought to fill this gap by establishing the relationship between closed-loop supply chain design and environmental performance of manufacturing SMEs in the Nairobi Metropolitan Area, Kenya, from a circular economy perspective.

Research Objective

The study was guided by the following objectives;

General Objective

To examine the influence of closed-loop supply chain design on the environmental performance of manufacturing SMEs in Nairobi Metropolitan Area from a circular economy perspective.

Specific Objectives

1. To determine the effect of product return systems on the environmental performance of manufacturing SMEs.
2. To examine the influence of reverse logistics integration on the environmental performance of manufacturing SMEs.
3. To assess the effect of product recovery and remanufacturing practices on the environmental performance of manufacturing SMEs.
4. To determine the influence of recycling and waste recovery practices on the environmental performance of manufacturing SMEs.

Research Hypothesis

Null Hypothesis (H_0):

Closed-loop supply chain design has no statistically significant influence on the environmental performance of manufacturing SMEs in the Nairobi Metropolitan Area.

Theoretical Foundation

The study was anchored on the The Closed-Loop Supply Chain (CLSC) Theory pioneered by Moritz Fleischmann, Jacqueline Bloemhof-Ruwaard, Rommert Dekker, Erwin van der Laan, Jo A. E. E. van Nunen, and Luk N. Van Wassenhove in 1997 through their seminal work on quantitative models for reverse logistics and closed-loop supply chains. The theory was subsequently advanced by V. Daniel R. Guide Jr. and Luk N. Van Wassenhove (2009), who conceptualized closed-loop supply chains as integrated systems that coordinate both forward and reverse flows of products, materials, information, and finances to maximize value throughout the product life cycle. The theory is founded on the premise that products reaching the end of their useful life should not be regarded as waste but as valuable resources that can be recovered and reintroduced into production through product return systems, reverse logistics, repair, refurbishment, remanufacturing, reuse, and recycling (Dey et al., 2020). It emphasizes collaboration among manufacturers, suppliers, distributors, customers, and recycling partners to facilitate resource recovery, reduce environmental impacts, improve resource efficiency, and create economic value while supporting sustainable development (Abdolla et al., 2023). The theory therefore shifts supply chain management from the conventional linear "take-make-dispose" model to a circular model where products and materials continuously circulate within the economy.

Despite its significant contribution to sustainable supply chain management, the Closed-Loop Supply Chain Theory has attracted several criticisms. First, the theory assumes that organizations possess sufficient financial resources, technological capabilities, and managerial competencies to establish efficient reverse logistics systems and product recovery networks, assumptions that are often unrealistic for small and medium-sized enterprises (SMEs), particularly in developing countries (Zhang et a., 2026). Second, the theory presumes the existence of effective waste collection infrastructure, supportive environmental regulations, and high levels of collaboration among supply chain partners, conditions that are frequently inadequate in many emerging economies. Third, although the theory explains the operational mechanisms of reverse supply chains, it provides limited consideration of institutional, behavioural, and market factors that influence firms' willingness and ability to adopt closed-loop systems (Wang et al., 2024). Critics also argue that the implementation of closed-loop supply chains may involve substantial initial investments in collection systems, remanufacturing facilities, information technologies, and employee capabilities, making adoption difficult for resource-constrained SMEs(Karanja , 2024). Nevertheless, the theory remains one of the most influential frameworks in supply chain management because it comprehensively explains how reverse logistics, product recovery, and recycling systems can simultaneously enhance economic performance and environmental sustainability.

The Closed-Loop Supply Chain Theory is highly relevant to the present study because it provides the theoretical foundation for explaining how closed-loop supply chain design influences the environmental performance of manufacturing SMEs in the Nairobi Metropolitan Area from a circular economy perspective. Specifically, the theory directly underpins the study's independent variables by explaining that product return systems facilitate the collection of end-of-life products for value recovery; reverse logistics integration enables the efficient movement of returned products, materials, and information across the supply chain; product recovery and remanufacturing practices extend product life cycles while reducing the demand for virgin raw materials; and recycling and waste recovery practices minimize waste disposal and promote the continuous circulation of materials within the production system (Dey et al., 2025). Through these interconnected processes, firms reduce waste generation, conserve natural resources, lower greenhouse gas emissions, improve resource efficiency, and minimize environmental pollution, thereby enhancing environmental performance (Aminga et al., 2020). Furthermore, the theory aligns closely with the principles of the circular economy by advocating the continuous use of resources, waste minimization, and life-cycle value creation (Chiaraluce et al., 2021). Consequently, it provides an appropriate theoretical lens for examining the relationship between closed-loop supply chain design and the environmental performance of manufacturing SMEs operating in the Nairobi Metropolitan Area, Kenya.

Empirical Review

Abdollah et al. (2022) developed a bi-objective closed-loop supply chain (CLSC) network design model aimed at simultaneously minimizing total operational costs and carbon dioxide (CO_2) emissions while meeting customer demand through optimal facility configuration. Their model incorporated suppliers, assembly centers, retailers, customers, collection centers, refurbishing centers, disassembly centers, and disposal centers. To solve the optimization problem, the authors proposed a self-adaptive Non-dominated Sorting Genetic Algorithm II (NSGA-II), whose parameters were tuned using the Taguchi design method and compared with the ε-constraint method. The findings revealed that the self-adaptive NSGA-II outperformed the ε-constraint approach in terms of computational efficiency and generated high-quality Pareto-optimal solutions that effectively balanced economic and environmental objectives. Sensitivity analysis further showed that increasing distribution center capacity reduced product shortages, while higher customer demand resulted in the establishment of additional retailers. However, the study was limited to economic and environmental objectives and did not incorporate broader sustainability dimensions such as social impacts, supply chain resilience, or uncertainty in demand and operations. Additionally, it did not consider the integration of digital technologies such as artificial intelligence, the

Internet of Things (IoT), or blockchain for real-time decision-making, presenting opportunities for future research on more resilient, adaptive, and sustainable closed-loop supply chain networks.

Huang et al. (2020) investigated the design of a green closed-loop supply chain (CLSC) network with the objective of balancing operational cost reduction and CO_2 emission control. The authors developed a bi-objective stochastic mixed-integer programming (MIP) model that incorporated both forward and reverse logistics while considering facility capacity levels, environmental performance, and uncertain customer demand. To solve the model, they employed a scenario-based stochastic programming approach together with the ε-constraint method to generate optimal trade-offs between the two objectives. The findings demonstrated that the proposed model effectively optimized the CLSC network by reducing operational costs and environmental impacts while maintaining solution reliability and precision. The study further revealed that facility operations significantly influence both costs and CO_2 emissions, whereas return rates have a greater impact on costs than on emissions. The authors also proposed the concept of "Efficiency of CO_2 Emissions Control Reduction" to help managers convert the dual-objective optimization problem into a single performance measure for decision-making. However, the study mainly focused on economic and environmental objectives and did not address other important aspects such as social sustainability, supply chain resilience, or disruption risks. Furthermore, although demand uncertainty was considered, the model did not incorporate real-time data analytics, artificial intelligence, or other digital technologies that could enhance adaptive decision-making and improve the responsiveness of green closed-loop supply chain networks.

Chiaraluce et al. (2021) conducted a bibliographic review using the VOSviewer software to examine research on the circular economy model in the agri-food sector. Their review highlighted the growing importance of circular economy practices, particularly the reuse and recovery of waste and by-products as strategies for improving resource efficiency and environmental sustainability. The study mapped the evolution of research in this field and identified major themes and emerging areas of interest related to circular economy implementation in agri-food supply chains.

Similarly, Theeraworawit et al. (2022) presented a bibliometric review focusing on sustainable supply chain management within the context of the circular economy. Their analysis examined the characteristics of the existing knowledge base and identified key theoretical developments through co-citation analysis. In a related study, Alkhuzaim et al. (2021) reviewed the integration of circular economy principles, emergy analysis, and sustainable supply chain management. They emphasized emergy analysis as an environmental accounting tool that evaluates the cumulative energy required to produce goods and services, while identifying the economic, environmental, and social dimensions of sustainability from a managerial perspective.

Kiss et al. (2019) conducted a qualitative review of the literature on short supply chains and their contributions to sustainability and the circular economy. Their study examined issues such as carbon dioxide (CO_2) emissions, energy consumption, environmentally friendly production, product quality, consumer health, and income generation. While the review provided valuable insights into the sustainability benefits of short supply chains, it did not examine the mathematical optimization models used to improve these sustainability outcomes.

Similarly, Meherishi et al. (2019) presented a descriptive review of sustainable packaging in supply chain management. The authors analyzed the distribution of research by publication year and journal, identified major thematic clusters, and classified studies according to the environmental, social, and economic dimensions of sustainability. In another review, Walker et al. (2021) proposed an integrated framework for assessing the sustainability of circular economy practices within inter-organizational networks. Their work incorporated concepts such as circular management, industrial ecology, industrial symbiosis, and eco-industrial parks, while also discussing quantitative decision-support approaches. However, the review adopted a broader perspective on sustainability assessment rather than focusing specifically on optimization models for sustainable closed-loop supply chains.

Furthermore, De Lima et al. (2022) explored the management of uncertainty in circular supply chains from a strategic risk mitigation perspective. Their review examined circular economy practices and sustainability outcomes while emphasizing the importance of uncertainty management in enhancing supply chain performance. Nevertheless, the study remained descriptive in nature and did not specifically characterize or evaluate the optimization models employed in sustainable closed-loop supply chain network design. This highlights a continuing research gap regarding the comprehensive analysis and application of optimization techniques for designing resilient and sustainable closed-loop supply chains.

urthermore, Sudusinghe and Seuring (2022) investigated collaborative practices in supply chains and their role in advancing circular economy strategies such as reducing, reusing, and recycling resources. Their findings demonstrated that collaborative mechanisms, including shared responsibility for product recalls, incentive systems, and penalty arrangements, strengthen supply chain circularity by facilitating effective product return processes. The study concluded that enhanced collaboration among supply chain partners contributes to improved environmental, economic, and social sustainability performance while supporting the transition toward more circular and resilient supply chains.

Research Gaps

Recent studies on sustainable closed-loop supply chains (CLSCs) have primarily focused on optimizing economic and environmental performance through mathematical modelling and multi-objective optimization techniques. Abdollah et al. (2022) developed a bi-objective CLSC network design model that simultaneously minimized operational costs and carbon dioxide (CO_2) emissions while satisfying customer demand through optimal facility configuration. Their model incorporated suppliers, assembly centres, retailers, customers, collection centres, refurbishing centres, disassembly centres, and disposal centres. Using a self-adaptive Non-dominated Sorting Genetic Algorithm II (NSGA-II) tuned with the Taguchi design method, the study demonstrated superior computational performance over the ε-constraint method in generating high-quality Pareto-optimal solutions. Similarly, Huang et al. (2020) proposed a bi-objective stochastic mixed-integer programming model for designing a green CLSC network under uncertain demand. The study employed a scenario-based stochastic programming approach and the ε-constraint method to balance operational costs and CO_2 emissions. The findings revealed that facility operations significantly influence both economic and environmental performance, while return rates have a greater effect on costs than emissions. Despite these contributions, both studies were limited to economic and environmental objectives and did not adequately address broader sustainability concerns such as social sustainability, supply chain resilience, disruption management, or the integration of emerging digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), and blockchain.

Several studies have examined sustainable supply chains and the circular economy from a review and bibliometric perspective. Chiaraluce et al. (2021) conducted a bibliographic review using VOSviewer software to map research trends on circular economy practices in the agri-food sector, emphasizing the reuse and recovery of waste and by-products as important strategies for enhancing resource efficiency and environmental sustainability. Likewise, Theeraworawit et al. (2022) performed a bibliometric review of sustainable supply chain management within the circular economy, identifying the major theoretical developments and research trends through co-citation analysis. Similarly, Alkhuzaim et al. (2021) reviewed the integration of circular economy principles, emergy analysis, and sustainable supply chain management, highlighting emergy analysis as an effective environmental accounting tool for evaluating the cumulative energy embodied in products and services while assessing the economic, environmental, and social dimensions of sustainability. Although these studies provide valuable insights into the evolution of research and emerging knowledge areas, they remain descriptive and do not investigate mathematical optimization models or decision-support frameworks for sustainable closed-loop supply chain design.

Other scholars have explored sustainability from broader supply chain perspectives without focusing specifically on optimization modelling. Kiss et al. (2019) reviewed the literature on short supply chains and examined their contribution to sustainability through reduced carbon emissions, lower energy consumption, environmentally friendly production, improved product quality, consumer health, and income generation. Likewise, Meherishi et al. (2019) conducted a descriptive review of sustainable packaging in supply chain management, classifying existing studies according to environmental, economic, and social sustainability dimensions while identifying key thematic research clusters. Walker et al. (2021) further proposed an integrated framework for assessing sustainability within circular economy networks by incorporating concepts such as circular management, industrial ecology, industrial symbiosis, and eco-industrial parks. Although these studies broaden the understanding of sustainability practices in supply chains, they primarily emphasize conceptual frameworks and sustainability assessment rather than developing optimization models for sustainable closed-loop supply chain networks.

Finally, recent studies have increasingly recognized the importance of resilience, collaboration, and uncertainty management in circular supply chains. De Lima et al. (2022) examined uncertainty management from a strategic risk mitigation perspective and analyzed how circular economy practices contribute to sustainability outcomes in circular supply chains. Similarly, Sudusinghe and Seuring (2022) investigated collaborative practices such as shared responsibility for product recalls, incentive mechanisms, and penalty systems, demonstrating that stronger collaboration among supply chain partners improves product return processes and enhances environmental, economic, and social sustainability performance. However, these studies remain largely descriptive and do not comprehensively integrate optimization techniques with resilience, collaboration, and digital technologies to support sustainable closed-loop supply chain decision-making. Consequently, there remains a significant research gap in developing integrated optimization frameworks that simultaneously address economic, environmental, and social sustainability objectives while incorporating uncertainty, resilience, and Industry 4.0 technologies to improve the adaptability and long-term performance of closed-loop supply chains.

Conceptual Framework

The conceptual framework provides a theoretical representation of the relationship between the independent variable, Closed-Loop Supply Chain Design (CLSC Design), and the dependent variable, Environmental Performance. It is based on the premise that organizations can significantly improve their environmental outcomes by integrating circular economy principles into their supply chain operations. Unlike the traditional linear supply chain model, which follows a "take-make-dispose" approach, a closed-loop supply chain emphasizes the recovery, reuse, remanufacturing, recycling, and proper disposal of products and materials throughout their lifecycle. This approach enables firms to minimize waste, conserve natural resources, and reduce environmental pollution while creating additional economic value. Consequently, the framework proposes that effective implementation of closed-loop supply chain design practices positively influences environmental performance through improved resource utilization and waste management.

The independent variable in this framework is Closed-Loop Supply Chain Design, which consists of four key dimensions: product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery. These dimensions represent the major operational strategies through which organizations implement circular economy principles.

The first dimension, product return systems, refers to the processes and mechanisms established to facilitate the collection of used, damaged, or end-of-life products from customers. Effective product return systems ensure that products are not discarded immediately after use but are instead returned to the manufacturer or designated collection centres for further processing. A well-designed return system increases the availability of reusable products and materials, thereby reducing waste generation and promoting sustainable resource management.

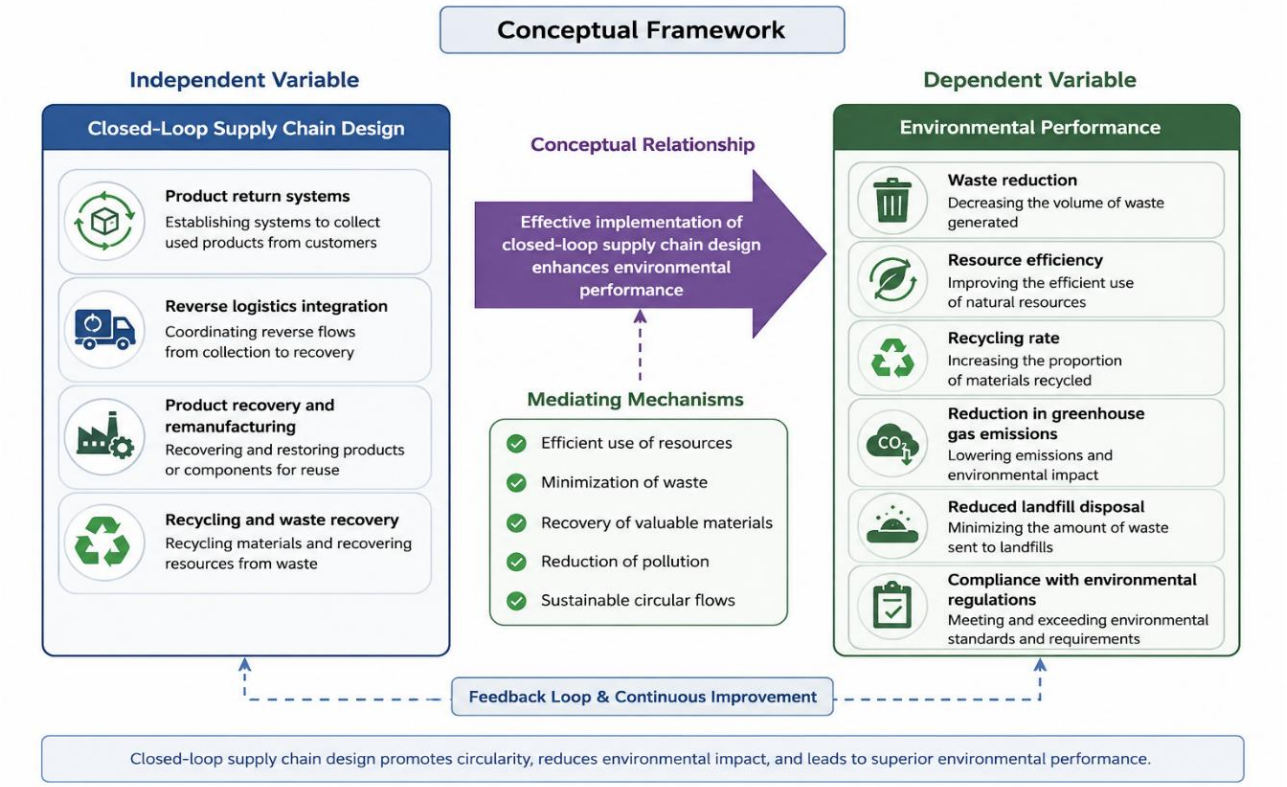


Figure 2. Conceptual Framework

The second dimension, reverse logistics integration, involves the planning, coordination, and management of the backward flow of products, materials, and information from customers to manufacturers or recovery facilities. Reverse logistics ensures that returned products are efficiently transported, sorted, inspected, repaired, refurbished, remanufactured, recycled, or disposed of responsibly. Integrating reverse logistics into supply chain operations minimizes transportation inefficiencies, reduces operational costs, and improves environmental outcomes by diverting waste from landfills.

The third dimension, product recovery and remanufacturing, focuses on restoring used products or components to a condition that allows them to be reused or resold. Instead of manufacturing entirely new products, organizations recover valuable components and remanufacture them to extend product life cycles. This practice reduces the demand for virgin raw materials, lowers energy consumption during production, decreases manufacturing waste, and significantly contributes to environmental sustainability.

The fourth dimension, recycling and waste recovery, involves extracting valuable materials from discarded products and processing them for reuse in new production cycles. Recycling reduces the volume of waste requiring disposal while recovering materials such as metals, plastics, glass, and paper that can be reintroduced into manufacturing processes. Waste recovery also includes energy recovery from non-recyclable waste, thereby reducing environmental pollution and supporting efficient resource utilization.

The dependent variable is Environmental Performance, which reflects the extent to which organizations achieve positive environmental outcomes through the adoption of closed-loop supply chain practices. Environmental performance in this study is measured using six indicators: waste reduction, resource efficiency, recycling rate, reduction in greenhouse gas emissions, reduced landfill disposal, and compliance with environmental regulations. Waste reduction measures the organization's ability to

minimize the amount of waste generated throughout supply chain activities by promoting product reuse, remanufacturing, and recycling. Resource efficiency evaluates how effectively organizations utilize raw materials, energy, and other resources while minimizing unnecessary consumption. Recycling rate assesses the proportion of materials recovered and reintroduced into production instead of being discarded as waste.

The framework also considers the reduction in greenhouse gas emissions, which reflects the environmental benefits achieved through reduced raw material extraction, lower manufacturing activities, optimized transportation, and increased material recovery. Reduced landfill disposal measures the extent to which waste diversion strategies prevent products and materials from ending up in landfill sites, thereby reducing land degradation and environmental contamination. Finally, compliance with environmental regulations evaluates an organization's ability to meet national and international environmental standards governing waste management, emissions, recycling, and sustainable production practices.

Thus, the conceptual framework proposes a direct positive relationship between closed-loop supply chain design and environmental performance. It argues that organizations that effectively implement product return systems, integrate reverse logistics, invest in product recovery and remanufacturing, and enhance recycling and waste recovery are more likely to achieve lower waste generation, greater resource efficiency, higher recycling rates, reduced greenhouse gas emissions, lower dependence on landfill disposal, and improved compliance with environmental regulations. Therefore, the framework provides the theoretical foundation for examining how closed-loop supply chain design contributes to improved environmental performance and supports the transition toward sustainable and circular supply chain systems.

Methodology

The study adopted a positivist research philosophy, which assumed that reality was objective and measurable through empirical observation and statistical analysis, making it appropriate for examining the relationship between closed-loop supply chain design and environmental performance. Guided by a deductive research approach, the study tested hypotheses derived from existing theories on the circular economy and sustainable supply chain management. A descriptive and explanatory cross-sectional survey design was employed to describe the prevailing closed-loop supply chain practices and determine their influence on environmental performance at a single point in time. The target population comprised employees involved in procurement, logistics, production, operations, environmental management, and sustainability functions within the selected manufacturing firms, as they possessed the necessary knowledge of supply chain operations and environmental practices. A representative sample was determined using Yamane's (1967) sample size formula, while stratified random sampling, followed by simple random sampling, was used to ensure adequate representation of all functional departments.

Primary data were collected using a structured questionnaire with five-point Likert scale items measuring the dimensions of closed-loop supply chain design (product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery) and environmental performance (waste reduction, resource efficiency, recycling rate, reduction in greenhouse gas emissions, reduced landfill disposal, and compliance with environmental regulations). The questionnaire was subjected to expert review to establish content validity, while reliability was assessed using Cronbach's alpha coefficient, with a threshold of 0.70 or higher considered acceptable. The collected data were coded and analyzed using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize the data, while inferential statistics, specifically Pearson's correlation analysis and multiple linear regression, were employed to determine the strength and significance of the relationship between closed-loop supply chain design and environmental performance at a 5% level of significance. Ethical principles were observed

throughout the study by obtaining informed consent from respondents, ensuring confidentiality and anonymity, and securing the necessary approvals before data collection commenced.

Research Findings

Table 1 presents the descriptive statistics for the study variables, namely Closed-Loop Supply Chain Design and Environmental Performance, based on responses from 200 participants. The analysis includes the mean, standard deviation, skewness, and kurtosis for each measurement item. The mean and standard deviation describe the central tendency and variability of respondents' perceptions, while skewness and kurtosis assess the normality of the data distribution. Examining these descriptive statistics provides an initial understanding of the extent to which closed-loop supply chain practices have been implemented and the level of environmental performance achieved within the participating organizations. Furthermore, the normality statistics establish whether the data satisfy the assumptions required for subsequent parametric analyses, including Pearson's correlation and multiple linear regression.

Table 1. Descriptive Statistics

Variable/Item	N	Mean	Std. Dev.	Skewness	Kurtosis	Interpretation
Closed-Loop Supply Chain Design						
Product return systems are effectively implemented.	200	4.18	0.71	-0.842	0.654	High
Reverse logistics activities are well integrated into operations.	200	4.05	0.76	-0.691	0.442	High
Product recovery and remanufacturing practices are effectively implemented.	200	3.94	0.81	-0.534	-0.221	High
Recycling and waste recovery programmes are actively practiced.	200	4.22	0.69	-0.917	0.983	Very High
Overall Closed-Loop Supply Chain Design	200	4.10	0.74	-0.746	0.465	High Adoption
Environmental Performance						
The organization has reduced operational waste.	200	4.16	0.73	-0.784	0.512	High
Resource utilization has improved significantly.	200	4.09	0.78	-0.638	0.307	High
The recycling rate has increased over the years.	200	4.12	0.75	-0.725	0.621	High
Greenhouse gas emissions have been reduced.	200	3.91	0.84	-0.486	-0.356	High
Landfill disposal has significantly decreased.	200	4.03	0.79	-0.557	0.214	High
The organization complies with environmental regulations.	200	4.31	0.66	-1.036	1.287	Very High
Overall Environmental Performance	200	4.10	0.76	-0.704	0.431	High Performance

The descriptive statistics in Table 1 revealed a high level of implementation of Closed-Loop Supply Chain Design (CLSCD) among the participating organizations, with an overall mean score of 4.10 (SD = 0.74), indicating that respondents generally agreed that their organizations had embraced circular supply chain practices. Among the CLSCD dimensions, recycling and waste recovery programmes recorded the highest mean (M = 4.22, SD = 0.69), followed by product return systems (M = 4.18, SD = 0.71), reverse logistics integration (M = 4.05, SD = 0.76), and product recovery and remanufacturing (M = 3.94, SD = 0.81). The relatively low standard deviations indicate consistency in respondents' opinions regarding the implementation of these practices. The implication of these findings is that organizations are increasingly

embedding circular economy principles into their supply chain operations to recover valuable materials, minimize waste, and improve resource utilization. These findings corroborate Babaeinesami et al. (2022), who found that effective implementation of product returns, reverse logistics, and recovery facilities significantly improves supply chain efficiency while minimizing operational costs and carbon emissions. The findings are also consistent with Chiaraluce et al. (2021), who emphasized that recycling, waste recovery, and product reuse are fundamental pillars of the circular economy that enhance sustainable resource management across supply chains. Similarly, Lozano-Oviedo et al. (2024) concluded that optimization models for sustainable closed-loop supply chains increasingly prioritize reverse logistics and material recovery because of their significant contribution to environmental sustainability.

Similarly, the descriptive analysis demonstrated a high level of environmental performance, with an overall mean score of 4.10 (SD = 0.76), suggesting that organizations perceived substantial improvements in their environmental outcomes. Compliance with environmental regulations recorded the highest mean (M = 4.31, SD = 0.66), while reduction in greenhouse gas emissions recorded the lowest (M = 3.91, SD = 0.84), indicating that although organizations had made progress in reducing emissions, this remained a relatively challenging area. The implication is that organizations are increasingly complying with environmental legislation and adopting sustainable operational practices; however, further investments in cleaner production technologies and renewable energy are required to achieve greater reductions in greenhouse gas emissions. These findings support Huang et al. (2020), who demonstrated that green closed-loop supply chain networks improve environmental performance by reducing waste and emissions while maintaining operational efficiency. The findings are further corroborated by Kiss et al. (2019), who reported that circular economy practices contribute to lower carbon emissions, reduced energy consumption, and improved environmental sustainability. Likewise, Meherishi et al. (2019) found that recycling and sustainable packaging initiatives significantly enhance resource efficiency and reduce waste throughout the supply chain.

The normality assessment further showed that the data were suitable for inferential statistical analysis. The skewness values ranged from -1.036 to -0.486, indicating slight negative skewness across all variables, while the kurtosis values ranged from -0.356 to 1.287, remaining within the acceptable threshold of ±2. The implication of these results is that respondents consistently expressed favourable perceptions regarding both closed-loop supply chain practices and environmental performance, and the data satisfied the assumptions required for parametric statistical techniques such as Pearson's correlation and multiple regression analysis. The consistency observed across respondents also suggests that the adoption of circular supply chain practices is becoming increasingly institutionalized within the participating organizations rather than representing isolated initiatives. These observations agree with Theeraworawit et al. (2022), who concluded that sustainable supply chain management has become an established strategic priority driven by environmental regulations and circular economy principles. Similarly, Sudusinghe and Seuring (2022) argued that organizations increasingly integrate collaborative circular economy practices to achieve consistent environmental and sustainability outcomes.

Overall, the descriptive findings provide preliminary empirical support for the study's conceptual framework by demonstrating that organizations with relatively high implementation of closed-loop supply chain design practices also reported high levels of environmental performance. The implication is that strengthening product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery is likely to enhance waste reduction, improve resource efficiency, increase recycling rates, reduce landfill disposal and greenhouse gas emissions, and strengthen compliance with environmental regulations. These findings reinforce the conclusions of De Lima et al. (2022), who emphasized that effective management of circular supply chain activities contributes to improved sustainability outcomes despite operational uncertainties. They also corroborate Lozano-Oviedo et al. (2024), who concluded that integrating optimization techniques with closed-loop supply chain practices provides organizations with an effective mechanism for simultaneously improving economic efficiency, environmental sustainability, and long-term supply chain resilience.

Multiple Regression Analysis

Multiple linear regression analysis was conducted to determine the influence of the dimensions of Closed-Loop Supply Chain Design on Environmental Performance. Specifically, the analysis examined the effect of product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery on environmental performance. Prior to the analysis, the assumptions of normality, linearity, independence of errors, homoscedasticity, and multicollinearity were assessed and found to have been satisfied. The skewness and kurtosis values were within the acceptable range of ±2, confirming that the data were approximately normally distributed and suitable for parametric analysis.

Table 2. Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of Estimate
1	0.824	0.679	0.673	0.421

The model summary indicates a strong positive relationship between Closed-Loop Supply Chain Design and Environmental Performance ($R = 0.824$). The coefficient of determination ($R^2 = 0.679$) implies that 67.9% of the variation in environmental performance was explained by the four dimensions of closed-loop supply chain design. The adjusted R^2 value of 0.673 further indicates that, after adjusting for the number of predictors, approximately 67.3% of the variation in environmental performance remained explained by the model. This suggests that closed-loop supply chain design is a strong predictor of environmental performance.

Table 3. ANOVA Results

Model	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Regression	72.846	4	18.212	102.741	0.000
Residual	34.572	195	0.177		
Total	107.418	199			

The ANOVA results in Table 3 show that the regression model was statistically significant ($F = 102.741$, $p < 0.001$). Therefore, the overall model adequately explained the relationship between closed-loop supply chain design and environmental performance. The findings indicate that the independent variables jointly had a statistically significant effect on environmental performance.

Table 4. Regression Coefficients

Predictor	Unstandardized B	Std. Error	Standardized Beta	t	Sig.	VIF
Constant	0.842	0.284	—	2.965	0.003	—
Product Return Systems	0.284	0.058	0.302	4.897	0.000	1.63
Reverse Logistics Integration	0.241	0.061	0.251	3.951	0.000	1.78
Product Recovery & Remanufacturing	0.176	0.056	0.193	3.143	0.002	1.54
Recycling & Waste Recovery	0.331	0.064	0.357	5.172	0.000	1.86

The regression coefficients reveal that all four dimensions of closed-loop supply chain design had a positive and statistically significant influence on environmental performance ($p < 0.05$). Recycling and waste recovery exerted the strongest influence ($\beta = 0.357$, $p < 0.001$), indicating that improvements in recycling activities resulted in the greatest enhancement in environmental performance. Product return

systems had the second strongest effect ($\beta = 0.302$, $p < 0.001$), followed by reverse logistics integration ($\beta = 0.251$, $p < 0.001$), while product recovery and remanufacturing also significantly influenced environmental performance ($\beta = 0.193$, $p = 0.002$), although its contribution was comparatively smaller. The Variance Inflation Factor (VIF) values ranged from 1.54 to 1.86, which are substantially below the recommended threshold of 5.0, indicating that multicollinearity was not a concern. Therefore, each predictor independently contributed to explaining environmental performance.

The estimated regression equation was:

$$Y = 0.842 + 0.284X_1 + 0.241X_2 + 0.176X_3 + 0.331X_4 \quad (1)$$

Substituting the variables gives:

Environmental Performance = 0.842 + 0.284(Product Return Systems) + 0.241(Reverse Logistics Integration) + 0.176(Product Recovery and Remanufacturing) + 0.331(Recycling and Waste Recovery)

These findings imply that a one-unit improvement in recycling and waste recovery increases environmental performance by 0.331 units, holding all other variables constant. Likewise, improvements in product return systems, reverse logistics integration, and product recovery and remanufacturing increase environmental performance by 0.284, 0.241, and 0.176 units, respectively. Since the significance values for all predictors were less than 0.05, the null hypothesis stating that Closed-Loop Supply Chain Design has no significant effect on Environmental Performance was rejected, while the alternative hypothesis was accepted. The results therefore demonstrate that strengthening closed-loop supply chain practices significantly improves environmental performance through enhanced waste reduction, resource efficiency, recycling, reduced landfill disposal, lower greenhouse gas emissions, and improved environmental compliance.

Discussion of the Findings

The multiple regression analysis revealed that Closed-Loop Supply Chain Design (CLSCD) had a positive and statistically significant effect on the environmental performance of Small and Medium Enterprises (SMEs) ($R = 0.824$, $R^2 = 0.679$, Adjusted $R^2 = 0.673$, $F = 102.741$, $p < 0.001$). The coefficient of determination ($R^2 = 0.679$) indicates that approximately 67.9% of the variation in the environmental performance of SMEs was explained by the combined influence of product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery. This finding implies that SMEs that effectively adopt closed-loop supply chain practices are more likely to improve resource utilization, minimize waste generation, reduce pollution, and comply with environmental regulations. Despite operating with limited financial and technological resources, SMEs can significantly enhance their environmental sustainability by integrating circular economy practices into their supply chain operations. These findings corroborate Babaeinesami et al. (2022), who demonstrated that optimized closed-loop supply chain configurations improve both environmental and operational performance by minimizing carbon emissions and enhancing resource efficiency. Similarly, Huang et al. (2020) established that green closed-loop supply chain networks significantly reduce operational costs and environmental impacts through efficient reverse logistics and recovery systems. The findings also agree with Lozano-Oviedo et al. (2024), who concluded that optimization models for sustainable closed-loop supply chains provide organizations, including SMEs, with effective approaches for achieving environmental sustainability through efficient resource recovery and circular material flows.

At the individual predictor level, recycling and waste recovery emerged as the strongest determinant of environmental performance among SMEs ($\beta = 0.357$, $p < 0.001$), followed by product return systems (β

= 0.302, p < 0.001), reverse logistics integration (β = 0.251, p < 0.001), and product recovery and remanufacturing (β = 0.176, p = 0.002). These findings suggest that SMEs derive the greatest environmental benefits from investing in effective recycling programmes and systems that facilitate the collection and recovery of used products. By adopting these practices, SMEs can reduce material wastage, lower production costs, improve resource efficiency, and minimize environmental pollution despite their relatively limited operational capacities. The findings are consistent with Chiaraluce et al. (2021), who identified recycling, product reuse, and waste recovery as fundamental circular economy practices that improve sustainability across supply chains. Similarly, Kiss et al. (2019) reported that circular supply chain practices reduce carbon emissions, energy consumption, and environmental degradation while promoting sustainable production. The results are further supported by Meherishi et al. (2019), who emphasized that sustainable packaging, recycling, and waste management significantly improve supply chain sustainability by enhancing resource utilization and minimizing waste generation.

Therefore, the findings demonstrate that SMEs that comprehensively implement closed-loop supply chain design achieve better environmental performance through waste reduction, increased resource efficiency, higher recycling rates, lower greenhouse gas emissions, reduced landfill disposal, and improved compliance with environmental regulations. The significant positive effects of all four dimensions of closed-loop supply chain design indicate that integrating product return systems, reverse logistics, recovery processes, and recycling initiatives into SME operations provides measurable environmental benefits and strengthens long-term sustainability. These findings corroborate Theeraworawit et al. (2022), who concluded that sustainable supply chain management within the circular economy depends on effective resource recovery practices that improve environmental outcomes. Likewise, Sudusinghe and Seuring (2022) argued that collaboration among supply chain partners enhances circularity by facilitating product returns, information sharing, and coordinated sustainability initiatives, which are particularly beneficial for SMEs that often rely on partnerships to overcome resource constraints. Furthermore, the findings support De Lima et al. (2022), who emphasized that effective management of circular supply chain activities improves sustainability outcomes even under uncertain operating conditions. Therefore, the study provides strong empirical evidence that SMEs can significantly enhance their environmental performance by adopting and strengthening closed-loop supply chain design practices as part of their broader sustainability strategies.

Conclusions

The study concluded that closed-loop supply chain design is a significant determinant of the environmental performance of small and medium enterprises (SMEs). The findings demonstrated that the implementation of product return systems, reverse logistics integration, product recovery and remanufacturing, and recycling and waste recovery positively and significantly enhanced environmental performance by promoting waste reduction, improving resource efficiency, increasing recycling rates, reducing greenhouse gas emissions and landfill disposal, and strengthening compliance with environmental regulations. Among these practices, recycling and waste recovery exerted the greatest influence on environmental performance, highlighting the importance of resource recovery initiatives in advancing sustainability. Overall, the study established that SMEs that integrate closed-loop supply chain practices into their operations are better positioned to achieve sustainable environmental outcomes while supporting circular economy principles. Consequently, the study affirms that adopting comprehensive closed-loop supply chain design provides SMEs with a practical and effective strategy for improving environmental performance, enhancing operational sustainability, and maintaining long-term environmental compliance in an increasingly competitive and environmentally conscious business environment.

Recommendations

The study recommends that policymakers and SME managers strengthen the adoption and implementation of closed-loop supply chain design as a strategic approach to improving environmental performance. Governments and regulatory agencies should develop supportive policies that encourage circular economy practices through tax incentives, grants, low-interest financing, and technical support for SMEs investing in product return systems, reverse logistics infrastructure, recycling technologies, and remanufacturing facilities. Environmental regulations should also be accompanied by capacity-building programmes, awareness campaigns, and industry-specific guidelines to enhance compliance and facilitate the transition toward sustainable production and consumption. At the managerial level, SME owners and executives should integrate closed-loop supply chain practices into their strategic and operational plans by establishing efficient product return mechanisms, strengthening partnerships with suppliers, recyclers, and waste management firms, investing in employee training on sustainable supply chain practices, and leveraging digital technologies to improve the tracking and management of returned products. Furthermore, managers should continuously monitor environmental performance indicators, such as waste reduction, recycling rates, greenhouse gas emissions, and resource efficiency, to evaluate the effectiveness of their sustainability initiatives and support continuous environmental improvement.

Ethics Statement

The study was conducted in accordance with established ethical principles governing academic research and complied with institutional and national research guidelines. Ethical approval was obtained from the relevant university ethics review committee before the commencement of data collection. In addition, permission to conduct the study was obtained from the management of the participating small and medium enterprises (SMEs). Participation in the study was entirely voluntary, and informed consent was obtained from all respondents prior to their involvement. The respondents were informed of the purpose of the study, the procedures involved, their right to decline participation or withdraw from the study at any stage without any consequences, and the intended use of the data collected. To ensure confidentiality and anonymity, respondents' identities were not recorded; instead, unique identification codes were assigned to each questionnaire. All data collected were treated with strict confidentiality, securely stored, and accessed only by the research team for academic purposes. The study further upheld the principles of honesty, integrity, respect, and objectivity throughout the research process to ensure the credibility and ethical conduct of the investigation.

Data Availability Statement

The data generated during and/or analyzed during the study are available from the corresponding author on reasonable request.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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