Designing a Sustainable Supply Chain Management Model in the Circular Economy of the Petrochemical Industry Using the Fuzzy Cognitive Map Approach

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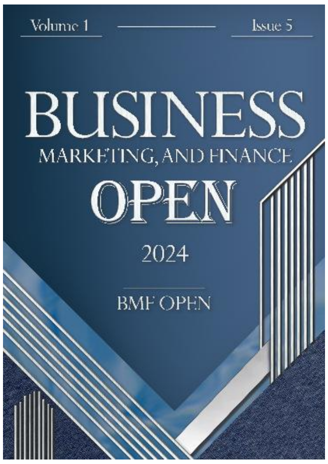

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Abstract: Given the pollutant nature of the petrochemical industry, sustainable supply chain management within a circular economy framework is of great importance. It aims to reduce resource consumption through recycling, recovery, and reuse of materials and products in order to achieve economic, environmental, and social performance, as well as to gain competitive advantage. Therefore, the purpose of this study is to design a sustainable supply chain management model in the circular economy of the petrochemical industry using the Fuzzy Cognitive Maps (FCM) approach. The participants included 16 senior and middle managers of the petrochemical industry, selected through a purposive non-probability sampling method. The data of this study were analyzed in both qualitative and quantitative sections. In the qualitative section, the model's indicators were identified using a multi-content analysis approach and categorized through coding. In the quantitative section, the identified indicators were validated using the fuzzy Delphi method, and then causal relationships were analyzed with the Fuzzy Cognitive Map approach. The findings revealed that the indicators of "sales," "green production process planning," and "reverse logistics," due to their highest interconnections with other indicators, hold the greatest importance in the circular economy. This finding indicates that managers, through collaboration and participation across the identified critical sectors, can enhance sustainable supply chain management.

Keywords: Sustainable supply chain management, Circular economy, Petrochemical industry, Fuzzy Cognitive Maps.

1. Introduction

The petrochemical industry, as a backbone of the global economy, plays a pivotal role in providing essential raw materials for numerous sectors, ranging from energy and construction to pharmaceuticals and consumer goods. However, the environmental and social challenges associated with its operations have increasingly brought attention to the importance of sustainable supply chain management (SSCM) and circular economy (CE) practices in this sector [1, 2]. Given the industry's high dependency on finite resources, its considerable carbon footprint, and its contribution to waste generation, the transformation towards sustainable and circular models has become a pressing necessity [3, 4].

Sustainable supply chain management (SSCM) integrates social, environmental, and economic considerations into the management of flows of goods, information, and finances [5]. In parallel, the circular economy (CE) emphasizes extending product lifecycles, promoting reuse, recycling, and resource efficiency, thereby reducing waste and environmental impact [6, 7]. The intersection of these two paradigms—SSCM and CE—has received significant attention in recent years as a viable strategy for industries aiming to balance economic competitiveness with ecological responsibility [8, 9]. This is especially true in the petrochemical sector, which must address both the sustainability expectations of stakeholders and the regulatory pressures emerging globally [10, 11].

Recent scholarly contributions have highlighted that SSCM and CE are no longer optional but necessary frameworks for maintaining long-term competitiveness in resource-intensive industries. For instance, SSCM models encourage organizations to rethink their procurement, production, and distribution processes by adopting green procurement, reverse logistics, and closed-loop systems [12, 13]. Similarly, CE principles drive firms to consider innovative product design, process efficiency, and technological upgrades to reduce waste and maximize resource use [14, 15]. The convergence of these approaches provides organizations with the tools to navigate complex environmental challenges while simultaneously creating value for multiple stakeholders [16, 17].

In the context of the petrochemical industry, multiple studies have drawn attention to the dual challenge of meeting rising global demand while mitigating negative environmental and social impacts. For example, Keawboonchu [2] emphasizes the importance of integrated sustainable management approaches to reduce air pollution in petrochemical operations, while Alsaif [3] identifies sector-specific SSCM practices within Gulf Cooperation Council countries. These insights highlight that adopting SSCM in petrochemicals requires context-sensitive strategies that incorporate both global frameworks and localized implementation mechanisms.

A critical enabler of SSCM and CE in such industries is the adoption of technological innovations and systems thinking approaches. For example, the integration of system dynamics modeling allows researchers and practitioners to simulate complex cause–effect relationships within supply chains, enabling more informed decision-making [18, 19]. Similarly, hybrid decision-support tools, such as fuzzy cognitive mapping and DEMATEL-based approaches, provide structured mechanisms for prioritizing sustainability indicators and identifying critical bottlenecks [20, 21]. The adoption of these analytical methods underscores the need for robust models that can deal with uncertainty and dynamic interactions, which are inherent in supply chain and industrial ecosystems [22, 23].

Furthermore, stakeholder influences play a decisive role in shaping the sustainability trajectory of supply chains. External pressures from governments, shareholders, communities, and customers have been found to directly influence SSCM implementation [11]. At the same time, internal factors such as managerial commitment and organizational culture determine the degree of success in operationalizing CE strategies [24, 25]. For example, in small manufacturing firms, Alamelu [25] reports that CE-driven SSCM practices serve as stimuli for sustainable development, while Tsai [26] provides evidence of the role of multi-criteria decision-making (MCDM) tools in evaluating and enhancing green supply chain performance.

The implementation of CE in the petrochemical industry is particularly challenging due to the complexity of its supply chains, capital-intensive operations, and reliance on fossil-based raw materials [27, 28]. Yet, the potential for innovation is substantial. For instance, Avikal [29] shows how DEMATEL-DANP-based approaches can identify factors for CE adoption in agro-produce supply chains, while Mandal [30] analyzes CE enablers in sustainable manufacturing. Translating such approaches to petrochemicals could provide valuable insights into how circularity can be embedded into large-scale industrial systems.

In addition, literature suggests that the petrochemical sector can leverage reverse logistics and green logistics practices to improve sustainability performance [31, 32]. Jayarathna [33] highlights the viability of sustainable logistics practices in enabling CE through system dynamics modeling, while Xie [34] proposes MCDM frameworks for sustainable supplier selection in the era of CE and Industry 4.0. Such findings demonstrate the growing consensus that effective supply chain practices, particularly those rooted in collaboration and innovation, are fundamental to achieving CE objectives [5, 35].

The nexus between CE and SSCM has also been examined from a broader theoretical perspective. Mugoni [8] provides a systematic review mapping future research agendas, emphasizing the synergies between CE and SSCM as pathways for sustainable industrial transformation. Hazen [17] conceptualizes the integration of CE into supply chain management, offering a framework that highlights closed-loop practices, innovation, and stakeholder alignment. Furthermore, Kalmykova [6] and De Angelis [9] underscore that while theoretical underpinnings of CE are well-established, practical implementation tools and models remain underdeveloped. This gap indicates a pressing need for empirical research that tailors SSCM-CE models to sector-specific contexts, such as petrochemicals.

A particularly interesting perspective emerges from studies that examine SSCM and CE through the lens of profitability and competitiveness. Zimon [36] argues that sustainable supply chains can improve competitiveness in industries like textiles, while Chaudhary [13] demonstrates how CE models of resource recovery contribute to economic sustainability. Similarly, Debnath [37] confirms that CE adoption contributes to waste nullification and cost savings, aligning environmental and economic performance. These insights highlight the potential for petrochemical companies to not only reduce environmental harm but also to derive financial benefits from sustainability transitions.

At the same time, practical challenges cannot be ignored. Developing economies, in particular, face institutional and infrastructural barriers in implementing CE practices. Yadav [21] emphasizes the role of smart waste management in developing countries, where technological and financial limitations impede progress. Likewise, Sharma [15] and Theeraworawit [38] point to the need for enhanced valorization practices and bibliometric insights to better understand CE implementation trajectories. These findings resonate with the petrochemical sector, where substantial investments and policy support are required to achieve meaningful transitions [10].

Moreover, collaboration across the supply chain is essential for embedding circularity. Chen [5] highlights that supply chain collaboration enables firms to jointly pursue sustainability objectives, while Ansari [12] underscores the importance of frameworks that integrate environmental and social dimensions into supply chain strategy. Althaqafi [39], in the context of electric vehicle manufacturing, demonstrates how multi-criteria evaluation methods can assess and improve GSCM performance, offering transferable lessons to petrochemicals.

In sum, the literature indicates that achieving SSCM in the context of CE requires a multidimensional approach encompassing stakeholder engagement, technological innovation, regulatory support, and system-based analytical tools. For the petrochemical industry, this involves addressing environmental challenges such as emissions and waste [1], implementing reverse logistics and recycling initiatives [32], and adopting system dynamics and fuzzy cognitive mapping models to capture the complexities of industrial ecosystems [20, 22]. Additionally, the sector must leverage lessons from other industries and contexts to design robust SSCM-CE frameworks that balance profitability, competitiveness, and sustainability [24, 29].

Therefore, this study aims to design and validate a sustainable supply chain management model for the petrochemical industry within the circular economy framework.

2. Methodology

This study aims to design a Sustainable Supply Chain Management (SSCM) model in the Circular Economy (CE) of the petrochemical industry, specifically in the production of urea and ammonia, using the Fuzzy Cognitive Map (FCM) approach. The research was conducted using a qualitative–quantitative mixed-methods design. In the qualitative section, a multi-content analysis approach was applied to identify and extract the codes of the model. In this approach, specific aspects of induction and deduction are combined. In the deductive stage, some indicators were identified and extracted from the theoretical background of prior studies, while in the inductive stage, indicators were obtained through semi-structured interviews with experts. This combination ensures sufficient theoretical justification to support the interviews.

The coding process was conducted in three stages: open coding for extracting indicators, axial coding for identifying criteria, and selective coding for extracting dimensions. Finally, to reach expert consensus regarding the agreement on the final indicators of the model, the fuzzy Delphi method was used for the revision, addition, integration, and elimination of indicators. The fuzzy set framework was applied to account for uncertainty in expert responses. The fuzzy Delphi method helps eliminate irrelevant indicators to the research subject and also improves the quality of the selected indicators.

The expert community consisted of senior and middle managers of a petrochemical company. The criteria for selecting experts included at least 10 years of management experience in petrochemical production units, possession of postgraduate education, familiarity with the concept of sustainable supply chain management, and motivation and willingness to collaborate. Based on these criteria, 16 experts were selected through purposive non-probability sampling.

The data collection tools included semi-structured interviews with experts in the qualitative section and a questionnaire in the quantitative section. In the interview phase, the researcher prepared a small number of initial interview questions related to the reasons and processes of SSCM in CE based on the theoretical background of the study, and then, based on expert responses, new questions were developed. In the quantitative phase, a pairwise comparison questionnaire was used, in which experts evaluated the degree of influence of each variable on another using a five-point scale: no influence (0), very low influence (1), moderate influence (2), high influence (3), and very high influence (4). The data from this questionnaire were analyzed using the Fuzzy Cognitive Map method.

The Fuzzy Cognitive Map (FCM) approach is regarded as a suitable method for addressing complex and dynamic problems, as it enables the interpretation of systems through the cognition and simulation of their structures. In addition, it represents causal relationships in graph-based structures and allows stakeholders to visualize and understand interactions among system components. Furthermore, FCMs are widely applied in modeling, control, pattern recognition applications, decision-making, and forecasting. The application of FCMs to SSCM in CE helps capture intuitive knowledge regarding the role of sustainable decision-making in the circular economy, thereby contributing to the improvement of SSCM processes.

3. Findings and Results

In the qualitative findings section, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method was applied to identify the managerial codes of Sustainable Supply Chain Management (SSCM) in the Circular Economy (CE) through a Systematic Literature Review (SLR). In this process, databases such as *Scopus* and *Web of Science* as well as search engines such as *Google Scholar* were utilized. Publications from 2010 to

2025 were considered. In this stage, 52 articles were identified, 33 articles were removed during the screening process, and 19 final articles were selected. Subsequently, indicators were extracted through coding. In addition, semi-structured interviews with experts led to the extraction of some new codes. Then, using the coding method, the extracted codes were categorized into three groups of indicators, criteria, and dimensions. Table 1 presents the qualitative findings and the categorization.

Table 1. Dimensions, Criteria, and Indicators of SSCM in the CE of the Petrochemical Industry

Dimension	Criteria	Indicators	Source
Supply Management	Sustainable supply	Environmental collaboration with petrochemical partners – Supplier evaluation – Green supplier capacity – Sustainable planning – Supplier information transparency – Green purchasing	[26, 34, 35, 39] + Experts
	Sustainable configuration and design	Green production process planning – Eco-design – Redesign – Green investment – R&D – Bio-materials	[18, 31, 33] + Experts
Strategy	Stakeholder perspective	Government pressure – Shareholder pressure – Local community pressure – Customer pressure – Managerial commitment	[11, 16, 26] + Experts
Operations	Sustainable production	Green production – Technological innovation – Circular production capacity – Smart workforce – Total quality management – Sustainable production efficiency – Production waste	[13, 18, 19, 35] + Experts
	Sustainable distribution	Green warehousing – Green distribution	[26] + Experts
Circular Economy	Customer and sustainable consumption	Sales – Customer relationship management – Customer advertising and awareness – Customer cooperation – After-sales services – Rapid response – On-time delivery – Customer satisfaction – Customer behavior change – Secondary reuse demand – Reuse pricing	[19, 26, 35, 39] + Experts
	Reverse logistics	Recycling – Recycling budget – Government subsidies and incentives – Recovery process – Recovery budget – Collection capacity – Collection budget – Customer returns – Reverse logistics	[18, 26, 35] + Experts
Sustainability Goals	Society	Social profitability – Employee welfare – Green initiatives – Corporate social responsibility – Corporate image – Employee safety – Job creation	[33, 34] + Experts
	Environment	Environmental systems – Emission reduction – Energy saving – Waste management – Environmental profitability	[13, 26, 39] + Experts
	Economy	Profitability – Operational costs	[18, 33] + Experts

Subsequently, the indicators were screened using the fuzzy Delphi method. First, experts assessed the importance of each indicator based on a five-point Likert scale, and then the mean evaluation of 16 experts was obtained. Finally, according to the 80/20 rule, indicators with a weighted average greater than 0.8 and a difference between the two Delphi rounds less than 0.2 were selected. The findings of the fuzzy Delphi method showed that all indicators were confirmed. In this stage, experts added the indicators "Customer returns," "Secondary demand," and "Bio-materials" to the model.

To solve the data using the Fuzzy Cognitive Map (FCM) method, the pairwise comparison questionnaire data obtained from the opinions of 16 experts were collected. By aggregating the experts' opinions, the initial intensity matrix of the impact of SSCM indicators in CE was determined, which is presented in Table 2. However, given the large size of the initial intensity matrix (60 × 60), Table 2 is presented in a summarized form.

Table 2. Initial Intensity Matrix of the Impact of SSCM Indicators in CE

	Environmental collaboration with petrochemical partners	Supplier evaluation	Green supplier capacity	Sustainable planning	Supplier information transparency	Green purchasing	Green production process planning	Eco-design	Redesign	Green investment	Research and development	…
Environmental collaboration with petrochemical partners		49	35	24	28	33	30	24	21	19	12	…
Supplier evaluation	24		52	27	23	15	35	34	21	29	32	…
Green supplier capacity	40	43		64	33	50	20	30	35	29	24	…
Sustainable planning	44	24	34		55	32	17	25	16	35	32	…
Supplier information transparency	62	27	23	24		42	40	15	17	39	35	…
Green purchasing	34	25	59	34	35		54	45	24	19	24	…
Green production process planning	34	27	25	37	32	62		60	15	17	28	…
Eco-design	40	41	20	24	41	29	60		24	63	23	…
Redesign	28	27	23	25	40	32	56	40		17	15	…
Green investment	42	24	30	35	21	24	14	42	41		49	…
Research and development	41	42	35	15	14	38	35	60	15	24		…
…	…	…	…	…	…	…	…	…	…	…	…	

Given the extensive nature of the data, the initial intensity matrix developed in this study consisted of 60 × 60 indicators, resulting in a very large dataset that could not be presented in its entirety within the article. For publication purposes, only a summarized portion of the matrix is shown.

Then, to determine the strength and causal relationships between indicators, a threshold was defined. The threshold was equal to 48, obtained from the product of the number of experts and the "high influence" level in the questionnaire. To form the final matrix, the power relations matrix was constructed based on Equation 1 and the study of Karatzinis et al. (2025).

$$X_{ij} = (o_i - \min) / (\max - \min)$$

For example, the intensity of the impact of the indicator *Environmental collaboration with petrochemical partners* on *Supplier evaluation* was obtained as:

Xij = (49 – 0) / (48 – 0) = 0.766.

Then, the data of the final matrix were entered into UcinetSetup software, and the causal relationship network map and the direction of the relationships were drawn, as shown in Figure 1. Figure 1 tracked the direction of relationships within clusters. For example, in the *Strategy* cluster, the indicators *Government pressure*, *Stakeholder pressure*, *Local community pressure*, and *Customer pressure* affect *Managerial commitment*, and *Managerial commitment* itself leads to *Eco-design*. In addition, *Green investment* and *Research and development* also affect *Eco-design*, and this cycle forms a loop. Furthermore, the fuzzy cognitive map clearly demonstrates the relationship between the CE cycle and sustainable development performance. At the center of the CE cycle lies *Reverse logistics*, which, after *Waste collection* and *Customer returns*, carries out recovery, recycling, and reuse processes. In this cycle, budget allocation is of importance, as *Recycling budget* affects *Recycling*, and recycling can direct *Supplier capacity* for secondary material inventory. Finally, through *Sales of waste* and usable secondary materials, *Profit* accrues to stakeholders, which can be beneficial in areas such as *Employee social welfare*, *Employee employment*, or support for *Environmental systems*.

In the sustainable production cycle, technological innovations and infrastructures affect the production capacity of the circular production system, which subsequently influences *Smart workforce* and *Total quality management systems*. This cycle demonstrates that employees in the production sector are highly important, and by providing knowledge, they can improve the quality of the system cycle.

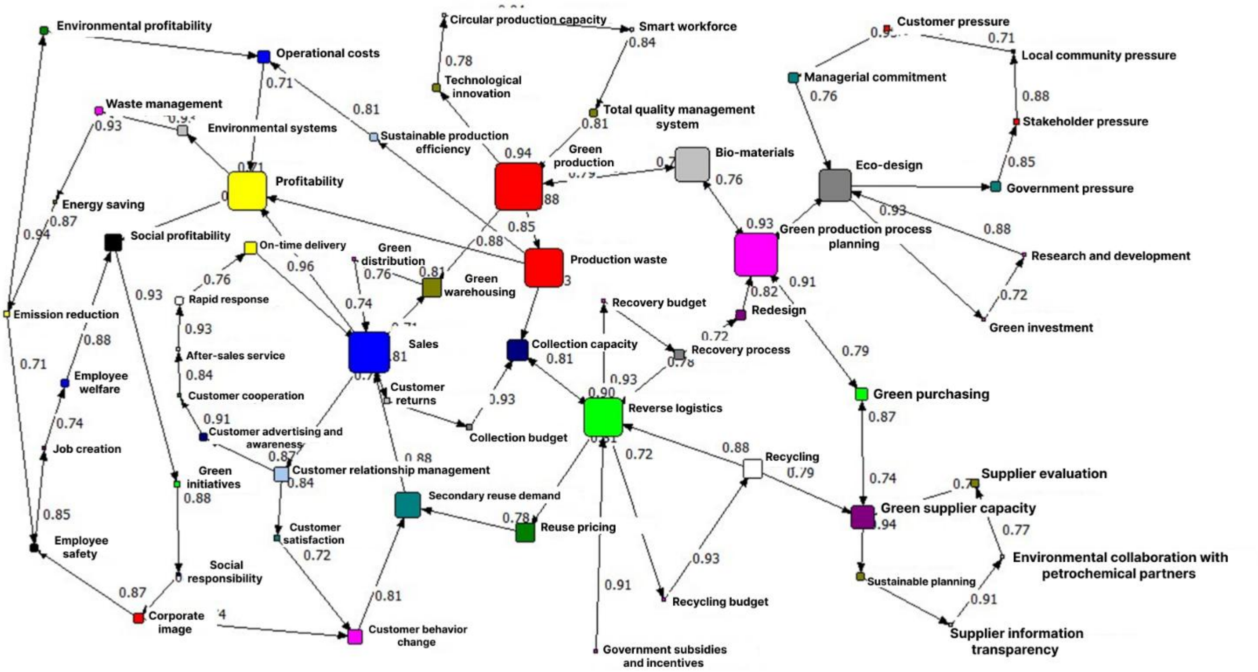

Figure 1. Fuzzy Cognitive Map for SSCM in the CE of the Petrochemical Industry

As Figure 1 shows, in the environmental performance cycle, *Environmental systems* sequentially affect *Waste management*, *Energy saving*, *Emission reduction*, *Environmental profitability*, reduction of *Operational costs*, and ultimately lead to *Profitability*. In this cycle, CO2 from ammonia is separated in the purification section, absorbed and recovered under two pressure levels, and returned to the synthesis section as carbamate solution. Meanwhile, surplus gases from the HRU (reject) section are used as primary reformer fuel gas, which reduces fuel gas consumption and ultimately impacts operational costs.

Finally, centrality indicators were determined and extracted, which are presented in Table 3. Centrality indicators show the importance level of each indicator compared to others.

Table 3. Centrality Indicators of SSCM in the CE of the Petrochemical Industry

Indicators	Outdegree strength	Indegree strength	Outdegree	Indegree	Betweenness	Vector
Environmental collaboration with petrochemical partners	0.766	0.912	1	1	169	0.01
Supplier evaluation	0.765	0.766	1	1	168	0.024
Green supplier capacity	1.676	2.426	2	3*	514	0.071
Sustainable planning	0.809	0.941	1	1	171	0.024
Supplier information transparency	0.912	0.809	1	1	170	0.01
Green purchasing	1.662	1.647	2	2	386	0.041
Green production process planning	2.721	3.265*	3*	4*	1476*	0.068
Eco-design	2.515	2.529	3*	3*	752	0.037
Redesign	0.824	0.721	1	1	625	0.064
Green investment	0.721	0.926	1	1	58	0.016
Research and development	0.882	0.721	1	1	57	0.016
Bio-materials	1.544	1.721	2	2	1036	0.087
Government pressure	0.853	0.706	1	1	226	0.012
Stakeholder pressure	0.882	0.853	1	1	225	0.004
Local community pressure	0.706	0.882	1	1	224	0.003
Customer pressure	0.926	0.706	1	1	223	0.004
Managerial commitment	0.765	0.926	1	1	222	0.012
Green production	3.382*	1.588	4*	2	1171	0.223
Technological innovation	0.779	0.941	1	1	171	0.076
Circular production capacity	0.941	0.779	1	1	170	0.032
Smart workforce	0.838	0.941	1	1	169	0.032
Total quality management system	0.809	0.838	1	1	168	0.076
Sustainable production efficiency	0.809	0.853	1	1	32	0.118
Production waste	2.662	0.882	3*	1	572	0.253
Green warehousing	0.809	1.471	1	2	300	0.256
Green distribution	0.765	0.809	1	1	299	0.205
Sales	2.985*	2.603	4*	3*	1790*	0.432*
Customer relationship management	1.706	0.735	2	1	387	0.17
Customer advertising and awareness	0.912	0.868	1	1	226	0.058
Customer cooperation	0.838	0.912	1	1	225	0.024
After-sales service	0.926	0.838	1	1	224	0.022
Rapid response	0.765	0.926	1	1	223	0.049
On-time delivery	0.956	0.765	1	1	222	0.143
Customer satisfaction	0.721	0.838	1	1	101	0.08
Customer behavior change	0.809	1.456	1	2	824	0.097
Secondary reuse demand	0.882	1.588	1	2	1154	0.202
Recycling	1.676	0.926	2	1	266	0.148
Recycling budget	0.926	0.721	1	1	267	0.131
Government subsidies and incentives	0.912	0	1	0	0	0.087
Recovery process	1.5	0.838	2	1	694	0.145
Recovery budget	0.838	0.926	1	1	695	0.131
Collection capacity	0.809	2.75*	1	3*	1167	0.194
Collection budget	0.926	0.912	1	1	923	0.106
Customer returns	0.912	0.809	1	1	924	0.16
Reverse logistics	3.353*	3.382*	4*	4*	1360*	0.293*
Reuse pricing	0.779	0.809	1	1	273	0.147
Social profitability	0.926	1.721	1	2	763.5	0.119

Employee welfare	0.882	0.735	1	1	217	0.042
Green initiatives	0.882	0.926	1	1	762.5	0.043
Social responsibility	0.912	0.882	1	1	761.5	0.026
Corporate image	1.603	0.912	2	1	760.5	0.045
Employee safety	0.853	1.574	1	2	219	0.029
Job creation	0.735	0.853	1	1	218	0.021
Environmental systems	0.926	0.706	1	1	320.5	0.105
Emission reduction	1.647	0.868	2	1	317.5	0.03
Energy saving	0.868	0.926	1	1	318.5	0.02
Waste management	0.926	0.926	1	1	319.5	0.037
Environmental profitability	0.765	0.941	1	1	133	0.052
Profitability	1.544	2.324	2	3*	869	0.314*
Operational costs	0.706	1.574	1	2	222	0.144

The table of centrality indicator values is presented. In Outdegree strength, the intensity of each indicator's effect on others is shown, with the highest values marked with an asterisk (*). The indicator Green production has the highest influence power with a value of 3.382, followed by the indicators Reverse logistics and Sales. As shown in Figure 1, this indicator affects Bio-materials, Technological innovation, Green warehousing, and Production waste.

Similarly, Indegree strength indicates that Reverse logistics has the highest level of influence received, equal to 3.382, from four indicators: Government subsidies and incentives, Recycling, Collection capacity, and Recovery process. After reverse logistics, the indicators Green production process planning and Collection capacity rank next. Outdegree demonstrates the influence exerted on other indicators, while Indegree reflects the influence received from other indicators.

Furthermore, Betweenness values for the indicators are shown in Table 3, representing how much each indicator mediates the relationships among other indicators within the green supply chain network, forming bottleneck pathways. According to Table 3, the indicator Sales has the highest betweenness value at 1790, indicating its critical role in connecting pathways within the network map. The indicators Green production process planning and Reverse logistics rank second and third, respectively. In Figure 1, the indicators with the highest number of connections across pathways are represented with larger node sizes.

Finally, in Table 3, the Vector indicator represents the potential strength of future connections with other indicators. In this regard, the indicator Sales will remain highly influential in the future of green supply chain management in CE, as it has the highest weight. Following this, the indicator Profitability is ranked next, suggesting that if the system cycle continues effectively, profitability will increase in the future and will influence Reverse logistics.

4. Discussion and Conclusion

The findings of this study provide new insights into the design of a sustainable supply chain management (SSCM) model for the petrochemical industry within the framework of the circular economy (CE). By integrating qualitative and quantitative methodologies, including fuzzy Delphi and fuzzy cognitive mapping approaches, the research identified critical indicators that influence sustainable performance. Among these, *green production*, *reverse logistics*, and *sales* emerged as the most central elements, with high outdegree and indegree values reflecting their influence and interconnectedness with other dimensions of SSCM. These results highlight the importance of production and market-oriented factors in driving circular transitions, as well as the enabling role of reverse logistics in ensuring the effective recovery, recycling, and reuse of materials.

The centrality of *green production* in the results reflects its critical role as both a driver and an outcome of sustainability. Green production encapsulates eco-design, technological innovation, and circular capacity expansion, which were shown to exert strong influence on indicators such as *bio-materials*, *technological innovation*, *green warehousing*, and *production waste*. This aligns with prior research suggesting that production systems represent the linchpin of circular supply chains. For example, Orji [31] emphasizes that dynamic modeling of sustainable operations in green manufacturing environments depends primarily on production innovations. Similarly, Chaudhary [13] highlights that circular economy models of material recovery in India hinge on redesigning production processes to accommodate recycling and reuse. The strong role of green production in this study confirms these insights in the petrochemical context, where production processes are capital-intensive and environmentally sensitive.

Equally significant is the role of *reverse logistics*, which recorded the highest indegree value, demonstrating that it is strongly influenced by other factors such as *government subsidies and incentives*, *recycling*, *collection capacity*, and *recovery processes*. This finding resonates with the work of De Angelis [9], who argued that closed-loop supply chains are essential to operationalizing the circular economy in industrial contexts. Similarly, El-Sheikh [4] showed that closed-loop supply chain structures in the petrochemical industry improve both environmental and economic sustainability by enabling efficient material recirculation. Reverse logistics ensures that waste streams are transformed into valuable inputs, reducing dependence on virgin resources while minimizing environmental impacts. The present study supports these findings and demonstrates that reverse logistics must be positioned at the center of petrochemical SSCM models to fully harness circularity.

Another crucial outcome of the study is the centrality of *sales* in shaping the overall SSCM system. With the highest betweenness and vector values, sales functioned as the key pathway connecting different supply chain components. This suggests that customer-oriented factors such as demand for secondary products, satisfaction, and behavior change are pivotal to sustaining circular loops. Fonseca [35] stressed the importance of organizational alignment with customer needs in promoting circular economy practices, while Zimon [36] argued that sustainable supply chains can enhance competitiveness by better meeting consumer demands. Moreover, Tsai [26] demonstrated that evaluating green supply chain practices through MCDM approaches often places customer collaboration and satisfaction as central dimensions. The present study confirms that sales not only reflect downstream demand but also mediate critical interactions between upstream activities such as production and logistics.

The results also point to the interplay between stakeholder pressures and managerial commitment. Government pressure, shareholder influence, community expectations, and customer demands were found to influence managerial commitment, which in turn guides eco-design and sustainable investment decisions. This outcome is consistent with Rebs [11], who identified stakeholder influences as a major determinant of supply chain sustainability performance, and with Brandenburg [16], who emphasized the role of managerial decisions in modeling sustainable supply chain systems. Moreover, Krimi [10] highlighted how corporate policy responses in the Gulf petrochemical industry are shaped by technological and regulatory pressures, underscoring the necessity of adaptive managerial strategies. Thus, this study supports the notion that stakeholder engagement is not peripheral but rather central to shaping SSCM-CE models in resource-intensive industries.

The importance of financial and market dimensions in the results further reinforces the argument that sustainability and profitability are not mutually exclusive. Indicators such as profitability, operational costs, and reuse pricing were shown to be influential in maintaining circularity. Debnath [37] confirmed that CE-based strategies contribute to waste elimination and cost reduction, while Zimon [24] demonstrated that dynamic SSCM models enhance both sustainability and competitiveness. Likewise, Sharma [15] showed that valorization of end-of-life materials can generate valuable resources, turning environmental liabilities into financial opportunities. The results of this study affirm that profitability must be considered alongside environmental and social performance as a core outcome of SSCM in petrochemicals.

The findings also align with theoretical perspectives on SSCM and CE integration. Hazen [17] provided a conceptual framework emphasizing closed-loop practices and stakeholder alignment, which resonates with the emphasis on reverse logistics and stakeholder pressures in this study. Mugoni [8], in a systematic review, stressed the synergies between CE and SSCM, highlighting the need for models that capture multi-dimensional interactions. The results of this study, by employing fuzzy cognitive mapping, provide empirical validation of these conceptual claims, showing how causal interconnections between production, logistics, sales, and stakeholder pressures form the foundation of sustainable supply chains.

Technological innovation emerged in this study as a secondary but influential factor, with significant ties to green production and circular capacity. This is consistent with the findings of Jayarathna [33], who showed that sustainable logistics practices enabling CE are often contingent on technological and infrastructural innovations. Similarly, Ghavamifar [19] demonstrated that system dynamics modeling of food loss and waste in Norway highlighted technological drivers as crucial for circular transitions. For the petrochemical sector, where innovation in materials, processes, and energy efficiency is critical, these findings underscore the need to embed technology adoption into SSCM strategies.

The study also affirms the importance of resource recovery and recycling practices. Indicators such as recovery budgets, collection capacity, and recycling were tightly linked to reverse logistics, underscoring their importance in closing material loops. This observation echoes the results of Mandal [30], who identified enablers of CE in sustainable manufacturing, and aligns with Avikal [29], who used DEMATEL-DANP methods to highlight the significance of recycling and resource efficiency in agro-produce supply chains. In the petrochemical context, such practices translate into effective reuse of by-products, reduced emissions, and enhanced compliance with environmental regulations [1, 2].

Furthermore, the results highlight the role of environmental indicators such as emission reduction, energy saving, and waste management. These indicators showed strong interdependencies with financial and social outcomes, confirming that environmental performance is integral to overall supply chain sustainability. Kalmykova [6] stressed that CE implementation requires clear tools for measuring environmental outcomes, while Centobelli [14] emphasized that business models in CE must integrate environmental performance into their design. The present study supports these arguments by showing that environmental systems not only reduce emissions but also contribute to profitability and social well-being.

The strong role of customer-oriented indicators, including satisfaction, awareness, cooperation, and after-sales services, demonstrates the centrality of consumer engagement in driving CE transitions. Chen [5] underscored the importance of supply chain collaboration for sustainability, while Althaqafi [39] demonstrated how assessing green supply chain practices can enhance customer relationships. Yadav [21] similarly emphasized that in developing countries, customer engagement in waste management systems is crucial for circularity. The findings of this study show that in petrochemicals, where downstream products reach diverse consumer segments, aligning supply chain sustainability with customer expectations is critical.

Finally, the application of fuzzy cognitive mapping in this study provides methodological contributions by capturing causal relationships and identifying central indicators in a complex industrial system. This approach aligns with the recommendation of Dolatabad [20], who applied hybrid fuzzy cognitive mapping in healthcare supply chains, and with Karatzinis [22], who emphasized the utility of fuzzy cognitive networks for analyzing dynamic systems. By applying this method to petrochemicals, this study demonstrates how advanced analytical tools can illuminate the complexities of SSCM in CE, offering both theoretical and practical contributions.

Despite its contributions, this study has limitations. First, the research was conducted with a relatively small sample of 16 experts from the petrochemical sector, which may limit the generalizability of findings to other contexts or regions. While purposive sampling ensured expertise, the sample size restricts statistical robustness. Second, the study focused specifically on urea and ammonia production within the petrochemical sector. Broader segments of the industry, such as plastics, polymers, and specialty chemicals, may present different dynamics not captured here. Third, the reliance on expert opinions through fuzzy Delphi and cognitive mapping introduces subjectivity, which, although mitigated by methodological rigor, may still influence outcomes. Finally, while the study addressed key dimensions of SSCM and CE, it did not empirically measure performance outcomes, leaving a gap between model design and real-world implementation.

Future studies should expand the scope of analysis by including a larger and more diverse group of experts, as well as cross-country comparisons, to capture regional and cultural differences in SSCM implementation. Longitudinal studies could assess how SSCM-CE indicators evolve over time, providing insights into dynamic changes and long-term impacts. Researchers should also extend the analysis to other segments of the petrochemical industry and related heavy industries, where sustainability challenges and opportunities may differ. Moreover, integrating real-time data, digital technologies, and Industry 4.0 tools into SSCM models could enrich the analysis of complex interactions and enable predictive capabilities. Finally, future research should empirically validate the proposed model by applying it in practice and measuring its impact on environmental, social, and financial performance.

For practitioners, the study highlights the need to prioritize green production processes, reverse logistics, and customer-oriented sales strategies as central levers for achieving circularity in petrochemical supply chains. Managers should focus on aligning stakeholder pressures with organizational commitment to ensure sustainability is embedded at strategic and operational levels. Investment in technological innovation, recycling infrastructure, and reverse logistics systems will be critical for maintaining competitiveness and compliance. Additionally, enhancing customer engagement through awareness campaigns, collaboration initiatives, and service improvements can create demand for secondary products and reinforce circular practices. Ultimately, organizations should adopt a holistic and integrated approach that balances profitability, environmental stewardship, and social responsibility within their supply chain strategies.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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