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Identification and Quantitative Analysis of Key Sustainability Indicators for Developing a Sustainable Closed-Loop Supply Chain Network for Nylon Yarn Product Using a Fuzzy Approach

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A B S T R A C T

This study aimed to identify and validate the key economic, environmental, and social sustainability indicators relevant to the nylon yarn supply chain in the rubber and plastics industry using expert consensus and the fuzzy Delphi technique. This applied study employed a quantitative expert-based design using the fuzzy Delphi method. An initial pool of sustainability indicators was developed through an extensive review of the theoretical literature, previous empirical studies, and preliminary expert screening. Twenty-three experts with postgraduate education and substantial academic or managerial experience in industrial management, industrial engineering, supply chain management, production planning, procurement, distribution, and related areas were selected purposively. The preliminary indicators were classified into economic, environmental, and social dimensions and evaluated during successive Delphi rounds. Expert linguistic judgments were converted into triangular fuzzy numbers, aggregated using the geometric mean, and defuzzified to obtain crisp scores. Indicators with crisp values of at least 7.00 were retained. Stability of expert judgments between rounds was assessed using the absolute difference between defuzzified values, with values of 0.20 or less indicating sufficient consensus. Of the 26 initial sustainability indicators, 23 were retained after the first fuzzy Delphi round and three were excluded. In the second round, four additional indicators were removed, resulting in a final framework of 19 validated indicators comprising 10 economic, three environmental, and six social indicators. The highest second-round score was obtained for occupational accidents and work-related diseases (8.38), followed by variable water-consumption cost and number of rewarded employees (8.23 each). All retained indicators showed an absolute inter-round difference below 0.20, indicating stable expert consensus and eliminating the need for a third Delphi round. The study produced a concise, expert-validated, and context-specific sustainability indicator framework for the nylon yarn supply chain, demonstrating that sustainable performance in this industry requires simultaneous attention to economic efficiency, environmental resource use, occupational health and safety, employment, and human resource development.

Keywords: *Sustainable Closed-Loop Supply Chain; Fuzzy Delphi; Sustainability Indicators; Nylon Yarn; Economic Sustainability; Environmental Sustainability; Social Sustainability*

1. Introduction

Supply chains have increasingly evolved from linear systems centered primarily on cost, speed, and operational efficiency into complex socio-technical networks expected to simultaneously respond to economic, environmental, and social requirements. Global competition, resource scarcity, environmental degradation, climate-related pressures, increasing stakeholder scrutiny, and growing concern regarding the social consequences of industrial activities have collectively transformed sustainability from an optional corporate initiative into a central dimension of supply chain decision-making. Sustainable supply chain management therefore requires organizations to extend their perspective beyond conventional operational performance and consider how sourcing, production, transportation, distribution, recovery, and other interorganizational activities affect financial viability, natural resources, emissions, employees, communities, and long-term industrial resilience. The literature has consequently moved toward integrated conceptualizations in which sustainability performance is assessed through economic, environmental, and social dimensions rather than through isolated operational measures. Bastas and Liyanage emphasized that sustainability must be embedded in supply chain quality and management systems rather than treated as an independent organizational program, highlighting the need for integrated indicators capable of linking operational quality with broader sustainability objectives (Bastas & Liyanage, 2018). This multidimensional perspective creates an important methodological challenge because sustainability cannot be adequately evaluated through a single criterion; instead, it requires a carefully selected set of indicators that captures the different forms of value creation, resource consumption, environmental burden, and social impact generated across supply chain activities.

The increasing complexity of contemporary supply networks has further strengthened the importance of identifying reliable sustainability indicators before any attempt is made to evaluate supply chain performance. Network configurations now frequently include geographically dispersed suppliers, production sites, distribution channels, recovery processes, changing demand conditions, and considerable uncertainty. These conditions make the selection of sustainability criteria particularly consequential because the quality of subsequent managerial assessments depends directly on whether the selected indicators represent the actual economic, environmental, and social concerns of the focal industry. Madani et al., in their systematic review of sustainable supply chain network design, demonstrated the substantial expansion of sustainability-oriented research and showed that economic, environmental, and social criteria have become increasingly incorporated into supply chain studies, although their representation remains uneven across industries and methodological approaches (Madani et al., 2024). The development of more sophisticated sustainable supply chain systems therefore depends not merely on increasing the number of criteria considered, but on distinguishing indicators that are theoretically defensible, operationally meaningful, contextually appropriate, and sufficiently measurable. In this respect, the identification and screening of sustainability indicators represents a foundational research task, particularly in sectors in which resource consumption, industrial emissions, workforce conditions, and complex cost structures coexist.

Economic sustainability remains an essential dimension because no supply chain can maintain long-term environmental or social commitments without economic viability. Traditional supply chain management has generally emphasized procurement, production, inventory, facility, transportation, and distribution costs; however, sustainability-oriented approaches broaden the economic perspective by incorporating costs associated with resource consumption, employee development, reverse flows, waste handling, and other consequences of responsible operations. Mahapatra et al. demonstrated that changing demand patterns, integration of different distribution channels, and smart supply chain configurations can substantially influence operational and economic outcomes, indicating that economic sustainability indicators must reflect the actual structure and behavior of the supply system under study (Mahapatra et al., 2025). Similarly, Rostamzadeh et al. addressed multi-product and multi-period supply chain conditions under uncertainty, demonstrating how contemporary sustainable supply chains require economic assessments capable of accommodating dynamic operational environments rather than relying only on static cost concepts (Rostamzadeh et al., 2025). In industrial supply chains such as those associated with rubber and plastic products, the economic dimension may encompass not only conventional production and transportation costs but also raw-material procurement, collection, recycling, employee-related expenditure, training, and water-related costs. The relevance of these indicators should nevertheless be established

empirically rather than assumed from generic models, because cost structures and managerial priorities vary significantly across industries.

Environmental sustainability is equally central to contemporary supply chain management because industrial production and logistics can create substantial ecological pressures through energy use, water consumption, emissions, material extraction, waste generation, and transportation activities. Green supply chain research has consistently shown that environmental outcomes are shaped by interactions among firms, regulators, consumers, and supply chain partners. Zhang and Yousaf showed that government intervention, green investment, and customer environmental preferences can influence coordination and sustainability decisions within industrial supply chains, demonstrating that environmental performance is embedded in a wider institutional and market context (Zhang & Yousaf, 2020). Governmental mechanisms may also directly influence closed-loop supply chain sustainability, as Gu et al. found that subsidy decisions can alter firm behavior and affect sustainable development outcomes across supply chain structures (Gu et al., 2023). At the operational level, environmental sustainability indicators commonly include carbon emissions, energy consumption, resource use, recycling, and waste-related variables. However, not all environmental indicators have equal relevance across industries. For water-intensive or resource-sensitive production systems, for example, water consumption may represent a particularly critical sustainability measure, while in transport-intensive systems carbon emissions may dominate environmental concerns. Consequently, the environmental component of sustainability assessment should be adapted to the operational characteristics of the specific industrial context rather than transferred uncritically from other sectors.

The social dimension has historically received less attention than economic and environmental dimensions, yet it has become increasingly recognized as indispensable to sustainable supply chain management. Social sustainability concerns the human consequences of industrial activities, including employment creation, occupational safety, worker health, gender participation, training, employee advancement, equitable opportunities, and broader community effects. The challenge is that social indicators are frequently more difficult to quantify and standardize than economic costs or environmental emissions. Organizational relationships and coordination also affect social and sustainability outcomes. Li et al., for example, illustrated the importance of organizational coordination in sustainable humanitarian supply chains, demonstrating that sustainability depends on interactions and behavioral alignment among actors rather than solely on physical resource flows (Li et al., 2019). In conventional manufacturing environments, the social dimension likewise requires attention to indicators that reflect both the quantity and quality of employment and the organization's capacity to protect and develop its workforce. Indicators such as total employment, employment opportunities for women, occupational accidents and work-related diseases, training, incentives, and promotion can therefore provide important information regarding the human dimension of sustainable supply chain activities. Their appropriateness, however, must be examined within the cultural, industrial, and organizational setting in which the supply chain operates.

Closed-loop supply chain thinking has further intensified the need for multidimensional sustainability indicators. Unlike conventional forward supply chains, closed-loop structures incorporate reverse flows involving collection, reuse, recycling, recovery, or other forms of product return. These additional activities can simultaneously generate economic opportunities, environmental benefits, and new operational and social requirements. Gholizadeh et al. demonstrated the relevance of sustainability considerations within a closed-loop dairy supply chain and showed that uncertainty and reverse flows substantially complicate supply chain decision-making (Gholizadeh et al., 2021). Abir et al. similarly considered sustainable closed-loop supply chains under demand uncertainty, underscoring the importance of simultaneously considering multiple sustainability-related performance criteria in complex network settings (Abir et al., 2020). Ravansh also emphasized multi-objective considerations in sustainable closed-loop supply chain network design under flexible conditions, further illustrating the multidimensional nature of decisions within closed-loop structures (Ravansh, 2021). Although these studies demonstrate the growing maturity of closed-loop supply chain research, they also indicate that the usefulness of any sustainability assessment depends fundamentally on the indicators chosen to represent sustainability dimensions in the specific industrial system being examined.

Uncertainty constitutes another important reason for carefully identifying sustainability indicators. Supply chains operate under fluctuating demand, changing costs, uncertain supply availability, regulatory change, technological disruption, and unexpected crises. Research following the

COVID-19 pandemic particularly highlighted the relationship between sustainability and resilience. Liu et al. examined resilience strategies for sustainable supply chains under budget constraints, demonstrating that sustainability decisions increasingly need to account for disruptions and resource limitations simultaneously (Liu et al., 2023). Bamakan et al. addressed the bullwhip effect in the COVID-19 vaccine supply chain and showed how disruptions and information distortions can affect supply chain stability and sustainability-related operations (Bamakan et al., 2021). He et al. likewise developed an integrated approach for identifying and prioritizing resilience solutions within sustainable supply chains, emphasizing that risk, sustainability, and decision criteria are interconnected (He et al., 2021). These findings suggest that selecting robust sustainability indicators is not merely an exercise in descriptive measurement; it provides a basis for identifying which aspects of supply chain performance should remain visible when organizations confront uncertainty and disruption.

The growing emphasis on resilience has also encouraged researchers to incorporate regional, structural, and risk-related considerations into sustainable supply chain assessments. Hasani et al. proposed an approach to sustainable and resilient supply chain design incorporating regional considerations, demonstrating that sustainability criteria can vary according to geographical, institutional, and infrastructural characteristics (Hasani et al., 2021). Jafari Eskandari and Emami Salout similarly integrated risk assessment into a sustainable closed-loop supply chain context under parameter uncertainty, emphasizing that supply chain sustainability is closely linked to the treatment of uncertain and adverse conditions (Jafari Eskandari & Emami Salout, 2022). Sadeghi Goughari et al. further examined risk management, modeling, and optimization issues in sustainable agricultural supply chains, illustrating that different sectors face distinct combinations of sustainability challenges and operational risk (Sadeghi Goughari et al., 2024). Taken together, these studies reinforce the importance of context-specific indicator selection. An indicator framework developed for healthcare, agriculture, steel, or food products cannot necessarily be transferred directly to rubber and plastics because the relative importance of emissions, water, recycling, labor, logistics, and economic costs differs across industrial systems.

Sector-specific evidence further demonstrates this need for contextualization. Yousefi-Babadi et al. addressed the sustainable redesign of the wheat-flour-bread supply chain under uncertainty and showed that sustainability-oriented network decisions must be formulated according to the characteristics of a specific production and distribution chain (Yousefi-Babadi et al., 2023). Shafiei et al. examined sustainable supply chains for perishable dairy products, where perishability and operational constraints create a different sustainability structure from that encountered in durable industrial manufacturing (Shafiei et al., 2020). Azadi et al. considered healthcare supply chain sustainability using data-driven techniques, again demonstrating that sustainability assessment frameworks evolve in accordance with sector-specific performance requirements (Azadi et al., 2023). Ala et al. also examined sustainable healthcare supply chain network design under fuzzy conditions, illustrating the importance of accounting for uncertainty when several sustainability criteria coexist (Ala et al., 2024). These studies are valuable because they demonstrate the breadth of sustainable supply chain research, but they simultaneously reveal that indicator relevance is conditional on the characteristics of the focal sector. The rubber and plastics industry, and particularly the nylon yarn supply chain, possesses specific patterns of raw-material consumption, manufacturing activities, transportation requirements, resource consumption, employment, and environmental burden that warrant independent investigation.

The circular economy has created an additional conceptual bridge between sustainable supply chains and closed-loop systems by emphasizing resource retention, recovery, recycling, and reduced dependence on virgin inputs. In industries characterized by material-intensive production, circularity can affect both environmental and economic performance. Khalili-Fard et al. developed a robust sustainable steel supply chain network oriented toward circular-economy principles and demonstrated the importance of incorporating uncertainty and circularity into supply chain decisions (Khalili-Fard et al., 2024). Such research indicates that sustainability indicators should capture not only direct production consequences but also resource use and recovery-related activities occurring across the supply chain. In the rubber and plastics sector, where material flows and recovery processes can have substantial environmental consequences, the identification of relevant sustainability indicators becomes particularly important. Moreover, indicators related to recycling costs, reverse collection, water use, emissions, training, and occupational safety may provide a more comprehensive representation of

sustainability than conventional measures based exclusively on production cost or environmental emissions.

Recent sustainable supply chain research has increasingly adopted data-driven, robust, fuzzy, and other advanced analytical approaches, but sophisticated analysis cannot compensate for poorly selected criteria. Gu, Ala, Azadi, Khalili-Fard, and other recent studies collectively demonstrate a movement toward increasingly complex analytical environments in which sustainability criteria must be explicitly defined before they can be incorporated into decision processes (Ala et al., 2024; Azadi et al., 2023; Gu et al., 2023; Khalili-Fard et al., 2024). This point is particularly important because the validity of any subsequent quantitative representation of sustainability ultimately rests on the conceptual validity of the indicators being measured. If relevant social, environmental, or economic variables are omitted, the resulting representation of sustainability becomes incomplete regardless of the sophistication of subsequent analysis. Conversely, retaining too many redundant or weakly relevant indicators can reduce interpretability and complicate decision-making. A systematic screening process is therefore needed to reduce a broad initial list to a parsimonious set of indicators supported both by the literature and by knowledgeable experts.

Expert-based approaches are especially useful when the phenomenon under investigation includes context-dependent, qualitative, or difficult-to-observe dimensions. The Delphi technique provides a structured mechanism for eliciting expert knowledge, progressively refining judgments, and developing consensus. Its fuzzy extension is particularly suitable when experts express their evaluations through linguistic judgments that contain ambiguity and gradation. Sustainable supply chain indicators often involve precisely this type of uncertainty because experts may agree that an indicator is important while differing in the intensity of that importance. Fuzzy representation enables such linguistic assessments to be converted into numerical ranges without imposing artificial precision on expert judgments. This is especially valuable in sustainability research, where social relevance, environmental significance, and long-term economic importance cannot always be represented adequately by binary inclusion or exclusion decisions at the initial evaluation stage. Through iterative fuzzy Delphi assessment, an initially comprehensive indicator pool can therefore be screened according to both expert support and stability of judgment.

The need for such an approach is particularly evident in the nylon yarn supply chain within the rubber and plastics industry. This supply chain combines several sustainability-sensitive characteristics, including substantial production and procurement costs, transportation and distribution activities, resource consumption, potential carbon emissions, water use, reverse-flow considerations, occupational health and safety concerns, and human-resource development requirements. Nevertheless, the existing literature offers limited evidence regarding a specifically validated sustainability indicator framework for this industrial context. Recent work has advanced sustainable supply chain assessment across steel, healthcare, agriculture, dairy, humanitarian logistics, petroleum, food, and other sectors (Li et al., 2019; Sadeghi Goughari et al., 2024; Zhang & Yousaf, 2020), but differences in production technologies, workforce structures, resource intensity, environmental exposure, and reverse logistics mean that direct adoption of indicator sets from these industries may lead to inappropriate prioritization. Furthermore, as the review by Madani et al. indicates, sustainable supply chain research continues to exhibit variation in the dimensions and criteria selected across applications (Madani et al., 2024). This creates a clear need for empirically grounded, industry-specific indicator identification before sustainability concepts can be meaningfully operationalized in the nylon yarn supply chain.

Another important gap concerns the balance among the three dimensions of sustainability. Many supply chain studies continue to emphasize economic and environmental dimensions more extensively than social sustainability. Economic costs and carbon emissions are comparatively easier to quantify, whereas indicators such as occupational safety, employee training, advancement, gender-related employment, and workforce development require stronger contextual interpretation. Yet neglecting such indicators can produce an incomplete representation of sustainable industrial performance. The sustainable and resilient supply chain literature increasingly recognizes that organizational viability depends on human as well as material and financial resources (He et al., 2021; Liu et al., 2023). Likewise, sectoral analyses have demonstrated that sustainability frameworks need to encompass operational, environmental, and organizational realities rather than applying a narrow environmental definition of sustainability (Hasani et al., 2021). For the nylon yarn supply chain, it is therefore important to establish whether indicators representing employee development, occupational health, employment generation, women's employment, water consumption, carbon emissions, and different economic costs are

perceived by industry and academic experts as sufficiently important to be retained in a consolidated sustainability framework.

Accordingly, developing a credible set of indicators requires combining evidence from prior research with knowledge derived from experts familiar with the focal industry. Literature-based identification provides theoretical breadth and prevents potentially important indicators from being overlooked, while expert screening improves contextual validity by distinguishing indicators that are genuinely relevant to industrial practice. The use of multiple Delphi rounds additionally makes it possible to assess not only the level of support for each indicator but also the stability of expert judgments. Indicators that retain sufficiently high evaluations across rounds can consequently be distinguished from those that initially appear relevant but fail to maintain expert endorsement. Such a procedure responds directly to the broader methodological requirement in sustainable supply chain research for transparent, reproducible, and context-sensitive selection of sustainability criteria.

The present study therefore aims to identify, evaluate, and validate the key economic, environmental, and social sustainability indicators relevant to the nylon yarn supply chain in the rubber and plastics industry through a fuzzy Delphi process based on expert consensus.

2. Methods and Materials

The present study employed a quantitative research design based on the Delphi approach to identify, refine, and validate key sustainability indicators applicable to supply chain management in the rubber and plastics industry, with a particular focus on the nylon yarn supply chain. The study was applied in purpose because it sought to generate a contextually relevant and expert-validated set of sustainability indicators that could support assessment and decision-making within the industry. The research process was conducted through two interconnected stages. In the first stage, an extensive review of the theoretical literature and previous empirical studies on sustainable supply chains, closed-loop supply chains, sustainability assessment, and industrial sustainability indicators was undertaken. The purpose of this stage was to develop an initial pool of indicators representing the principal dimensions of sustainability in supply chain systems. Particular attention was devoted to indicators reflecting economic, environmental, and social sustainability and to those that could be meaningfully interpreted within the operational conditions of the rubber and plastics industry and the nylon yarn sector. In the second stage, the preliminary indicators identified from the literature were subjected to systematic expert review through a Delphi process. This stage enabled the researchers to assess the relevance, importance, applicability, and contextual appropriateness of each proposed indicator and to progressively eliminate indicators that lacked adequate expert support.

Because the subject matter required specialized knowledge of industrial supply chains and sustainability management, the participants were selected through purposive and availability-based expert sampling. The expert panel consisted of 23 individuals drawn from both industry and academia who possessed relevant education, managerial experience, and professional knowledge in industrial management, industrial engineering, supply chain management, production planning, procurement and supply, distribution, business development, or sustainability-related industrial decision-making. All participants had postgraduate academic qualifications in industrial management, industrial engineering, or closely related fields. The panel included three senior business development or industrial managers holding doctoral degrees and having at least 10 years of relevant professional experience, two senior distribution managers holding master's degrees and having at least 20 years of professional experience, seven senior supply chain managers holding doctoral degrees and having at least 15 years of relevant experience, four senior procurement and supply managers holding master's degrees and having at least 15 years of experience, five senior production planning managers holding master's degrees and having at least 20 years of professional experience, and two university professors or industrial consultants holding doctoral degrees and having at least 15 years of relevant academic or industrial experience. Accordingly, the panel incorporated complementary managerial, operational, and academic perspectives and was considered sufficiently knowledgeable to evaluate sustainability indicators within the specific industrial setting investigated.

Eligibility for participation was based on demonstrated familiarity with supply chain operations, industrial management, production or distribution systems, and sustainability-related issues, together with substantial practical or academic experience. Preference was given to experts who were directly familiar with the rubber and plastics industry or with supply chain structures comparable to those involved in nylon yarn production and distribution.

Participation was voluntary and depended on the expert's willingness and availability to contribute to successive Delphi rounds. The size of the panel was considered appropriate for a Delphi-based expert study because the objective was not statistical representation of a general population, but rather the systematic elicitation of informed judgments from a specialized group possessing substantial domain knowledge. The iterative structure of the Delphi procedure also made it possible to reconsider judgments across successive rounds and to move progressively toward greater convergence of expert opinion regarding the most important sustainability indicators.

Data were collected using two principal sources: documentary and literature-based evidence and structured expert elicitation through Delphi questionnaires and evaluation checklists. Initially, a comprehensive review of books, peer-reviewed articles, previous empirical studies, and relevant conceptual frameworks was conducted to identify sustainability indicators previously applied to supply chain systems. The literature review was used to create the initial indicator pool rather than to impose a predetermined framework on the expert panel. Indicators appearing conceptually similar were compared, consolidated where necessary, and organized according to their underlying sustainability meaning. The resulting preliminary set subsequently formed the basis of the expert evaluation instrument. The content of the instrument focused on whether each proposed indicator was sufficiently important, conceptually relevant, practically meaningful, and applicable to sustainability assessment in the nylon yarn supply chain within the rubber and plastics industry.

The primary data collection instrument was an expert questionnaire developed specifically for the Delphi rounds. Each indicator was presented to the experts for assessment using linguistic judgments reflecting different degrees of perceived importance. The response categories ranged from extremely low to extremely high importance. To accommodate the uncertainty and imprecision inherent in linguistic expert judgments, these verbal assessments were represented using triangular fuzzy numbers. The linguistic categories consisted of “extremely low,” “very low,” “low,” “moderate,” “high,” “very high,” and “extremely high.” These categories were associated respectively with triangular fuzzy values of (1, 2, 3), (2, 3, 4), (3, 4, 5), (4, 5, 6), (5, 6, 7), (6, 7, 8), and (7, 8, 9). This approach allowed experts to express judgments in intuitive verbal terms while permitting systematic comparison of the collective evaluations across the panel.

The Delphi process was conducted iteratively rather than through a single round of consultation. In the first round, the experts reviewed the sustainability indicators extracted from the literature and assessed their importance and applicability. They were also able to provide quantitative observations regarding the wording, conceptual overlap, relevance, or practical interpretation of the proposed indicators. These comments were reviewed by the research team and were used to refine the indicator descriptions where necessary. Indicators that clearly failed to satisfy the predefined acceptance criterion were removed, while those receiving sufficient expert support were retained for subsequent evaluation. In the next round, the refined set of indicators was redistributed to the panel so that experts could reconsider their assessments in light of the collective tendency observed in the preceding round. The iterative process was intended to reduce dispersion in expert judgments and facilitate convergence toward a stable expert consensus.

The expert questionnaire and associated checklists were designed to ensure that judgments were obtained in a structured and comparable manner while maintaining the essential characteristics of the Delphi technique, particularly iteration, controlled feedback, and the gradual development of consensus. The assessment focused specifically on identifying the indicators regarded by the expert panel as sufficiently important to represent sustainability within the investigated industrial supply chain. Consequently, the instrument was not intended to measure organizational performance or individual attitudes, but rather to elicit expert judgments concerning the conceptual and practical significance of candidate sustainability indicators.

The expert judgments obtained through the Delphi rounds were analyzed using the fuzzy Delphi technique. This method was selected because conventional Delphi procedures may be affected by ambiguity in verbal judgments and by difficulties in distinguishing between closely related degrees of expert agreement. The fuzzy Delphi approach retains the iterative and consensus-oriented logic of the conventional Delphi technique while translating linguistic evaluations into fuzzy numerical values, thereby enabling a more structured interpretation of uncertain or imprecise expert judgments. For each sustainability indicator, the linguistic assessment provided by every expert was first transformed into its corresponding triangular fuzzy number, expressed as:

$\tilde{a}_{ij} = (L_{ij} , M_{ij} , U_{ij})$

where L_{ij}, M_{ij}, and U_{ij} represent the lower, modal, and upper values of the judgment of expert i regarding indicator j, respectively. The index i represents the individual expert, where i = 1, 2, ..., n, and the index j represents the sustainability indicator, where j = 1, 2, ..., m.

The collective fuzzy evaluation of each indicator was subsequently obtained by aggregating the judgments of the 23 experts. The geometric mean was used separately for the lower, middle, and upper components of the triangular fuzzy numbers because this aggregation procedure provides an appropriate representation of collective expert judgments while reducing the disproportionate influence of individual extreme assessments. Accordingly, for each indicator j, the aggregate fuzzy values were calculated as:

$L_j = (\prod_{i=1-n} (L_{ij}))^{1/n}$

$M_j = (\prod_{i=1-n} (M_{ij}))^{1/n}$

$U_j = (\prod_{i=1-n} (U_{ij}))^{1/n}$

Accordingly, the aggregated triangular fuzzy number for indicator j was expressed as:

$\tilde{a}_j = (L_j, M_j, U_j)$

where n represents the total number of participating experts. In the present study:

n = 23

After aggregation, the fuzzy value of each indicator was converted into a single crisp score through defuzzification. The defuzzified value for each indicator was calculated as:

$A_j = (U_j + 4M_j + L_j) / 6$

The decision rule for retaining or rejecting each indicator was defined as:

$A_j \geq 7 \rightarrow$ Accepted

$A_j < 7 \rightarrow$ Rejected

Thus, only indicators with a defuzzified value equal to or greater than 7 were retained as key sustainability indicators.

Consensus and stability across successive Delphi rounds were also examined. For each indicator retained after the first round, the absolute difference between the defuzzified values obtained in the first and second rounds was calculated as:

$D_j = |A_j^{(2)} - A_j^{(1)}|$

where:

$A_j^{(1)}$ = defuzzified value of indicator j in Round 1

$A_j^{(2)}$ = defuzzified value of indicator j in Round 2

D_j = absolute difference between the two rounds

The stopping rule for the fuzzy Delphi process was defined as:

$D_j \leq 0.20 \rightarrow$ Consensus achieved

$D_j > 0.20 \rightarrow$ Consensus not achieved

Accordingly, when the absolute difference between the first- and second-round defuzzified values was equal to or less than 0.20 for the retained indicators, expert judgments were considered sufficiently stable and no additional Delphi round was required. If D_j exceeded 0.20, the corresponding indicator would have required reassessment in a subsequent round.

Therefore, the complete analytical procedure can be summarized mathematically as follows:

$\tilde{a}_{ij} = (L_{ij}, M_{ij}, U_{ij})$

$L_j = (\prod_{i=1-n} (L_{ij}))^{1/n}$

$M_j = (\prod_{i=1-n} (M_{ij}))^{1/n}$

$U_j = (\prod_{i=1-n} (U_{ij}))^{1/n}$

$\tilde{a}_j = (L_j, M_j, U_j)$

$A_j = (U_j + 4M_j + L_j) / 6$

$A_j \geq 7 \rightarrow$ Accepted

$A_j < 7 \rightarrow$ Rejected

$D_j = |A_j^{(2)} - A_j^{(1)}|$

$D_j \leq 0.20 \rightarrow$ Consensus achieved

$D_j > 0.20 \rightarrow$ Additional Delphi round required

The final output of the analysis was a refined and expert-validated set of key sustainability indicators considered relevant to the nylon yarn supply chain in the rubber and plastics industry. All fuzzy calculations, aggregation of expert judgments, defuzzification procedures, comparisons between successive Delphi rounds, and final screening of the sustainability indicators were performed using Microsoft Excel 2022.

3. Findings and Results

The initial identification of sustainability indicators was performed through a combination of expert interviews, screening of frequently reported indicators in the relevant literature, and examination of previous studies on sustainable and closed-loop supply chains. This preliminary process resulted in the identification of 26 indicators distributed across the three principal dimensions of sustainability: economic, environmental, and social. The economic dimension contained 12 indicators related primarily to different categories of costs associated with supply chain activities. The environmental dimension comprised six indicators addressing carbon emissions, environmental initiatives, energy consumption, and water consumption, while the social dimension included eight indicators reflecting employment, occupational health and safety, human resource development, advancement, incentives, and gender-related employment characteristics.

These 26 indicators constituted the preliminary sustainability framework subsequently submitted to the expert panel for fuzzy Delphi assessment, as presented in Table 1.

Table 1

Preliminary Framework of Sustainability Indicators for the Nylon Yarn Supply Chain

Main Dimension	Indicator	Indicator Code
Economic (EC)	Fixed or facility establishment cost	EC1
Economic (EC)	Holding cost	EC2
Economic (EC)	Variable transportation cost	EC3
Economic (EC)	Variable production cost	EC4
Economic (EC)	Variable raw-material procurement cost	EC5
Economic (EC)	Variable recycling cost of returned products	EC6
Economic (EC)	Variable distribution cost	EC7
Economic (EC)	Variable collection cost of returned products	EC8
Economic (EC)	Social and environmental costs	EC9
Economic (EC)	Training cost	EC10
Economic (EC)	Personnel cost, including salary, insurance, and rewards	EC11
Economic (EC)	Variable water-consumption cost	EC12
Environmental (EN)	Fixed carbon dioxide emissions resulting from facility establishment	EN1
Environmental (EN)	Carbon dioxide emissions resulting from operational activities	EN2
Environmental (EN)	Carbon dioxide emissions resulting from transportation	EN3
Environmental (EN)	Support for green and humanitarian projects	EN4
Environmental (EN)	Energy consumption	EN5
Environmental (EN)	Water consumption	EN6
Social (SO)	Total number of jobs	SO1
Social (SO)	Number of working days lost due to accidents	SO2
Social (SO)	Number of jobs for women	SO3
Social (SO)	Number of occupational accidents and work-related diseases	SO4
Social (SO)	Number of trained employees	SO5
Social (SO)	Number of rewarded employees	SO6
Social (SO)	Number of promoted employees	SO7
Social (SO)	Number of female managers	SO8

As shown in Table 1, the initial framework included a relatively broad range of indicators in order to prevent premature exclusion of potentially relevant sustainability criteria. The economic dimension was the most extensive, accounting for 12 of the 26 indicators, reflecting the diversity of cost-related considerations in industrial supply chains. Six indicators represented environmental sustainability, with particular emphasis on carbon emissions, energy use, and water consumption. Eight indicators reflected the social dimension and encompassed employment generation, occupational safety, employee training and advancement, and women's participation in employment and management. This initial framework was not considered final; rather, it served as the candidate indicator set for structured evaluation by the 23-member expert panel through the fuzzy Delphi procedure.

The 26 preliminary indicators were subsequently evaluated by the 23 experts using the first round of the fuzzy Delphi technique. The qualitative judgments provided by the experts were transformed into triangular fuzzy numbers, and the aggregated fuzzy mean was calculated for each indicator. The corresponding crisp value was then obtained through defuzzification. Consistent with the predefined decision rule, indicators with a defuzzified value of 7.00 or higher were retained, whereas indicators with a value below 7.00 were rejected. The first-round results are reported in Table 2.

Table 2

First-Round Fuzzy Delphi Results for Sustainability Indicator Evaluation

Main Dimension	Indicator	Code	Fuzzy Mean (L, M, U)	Crisp Value	Decision
Economic	Fixed or facility establishment cost	EC1	(6.10, 7.20, 9.30)	7.37	Accepted
Economic	Holding cost	EC2	(5.56, 7.13, 9.01)	7.18	Accepted
Economic	Variable transportation cost	EC3	(5.60, 8.09, 9.40)	7.89	Accepted
Economic	Variable production cost	EC4	(5.50, 8.00, 9.50)	7.83	Accepted
Economic	Variable raw-material procurement cost	EC5	(5.60, 8.10, 9.40)	7.90	Accepted
Economic	Variable recycling cost of returned products	EC6	(5.50, 7.23, 9.50)	7.32	Accepted
Economic	Variable distribution cost	EC7	(6.30, 7.98, 9.20)	7.90	Accepted
Economic	Variable collection cost of returned products	EC8	(6.10, 6.80, 8.98)	7.05	Accepted
Economic	Social and environmental costs	EC9	(4.30, 5.81, 7.98)	5.92	Rejected
Economic	Training cost	EC10	(6.89, 7.08, 9.12)	7.39	Accepted
Economic	Personnel cost, including salary, insurance, and rewards	EC11	(5.60, 8.09, 9.40)	7.89	Accepted
Economic	Variable water-consumption cost	EC12	(5.30, 8.30, 9.80)	8.05	Accepted
Environmental	Fixed carbon dioxide emissions resulting from facility establishment	EN1	(4.88, 5.69, 7.48)	5.85	Rejected
Environmental	Carbon dioxide emissions resulting from operational activities	EN2	(6.30, 8.80, 9.70)	8.53	Accepted
Environmental	Carbon dioxide emissions resulting from transportation	EN3	(5.40, 7.80, 9.10)	7.62	Accepted
Environmental	Support for green and humanitarian projects	EN4	(5.18, 7.09, 9.11)	7.11	Accepted
Environmental	Energy consumption	EN5	(5.10, 7.05, 9.50)	7.13	Accepted
Environmental	Water consumption	EN6	(6.30, 7.60, 9.30)	7.67	Accepted
Social	Total number of jobs	SO1	(5.00, 7.50, 9.40)	7.40	Accepted
Social	Number of working days lost due to accidents	SO2	(5.40, 7.00, 8.80)	7.03	Accepted
Social	Number of jobs for women	SO3	(5.20, 7.09, 9.10)	7.11	Accepted
Social	Number of occupational accidents and work-related diseases	SO4	(5.60, 7.30, 9.10)	7.32	Accepted
Social	Number of trained employees	SO5	(5.30, 7.10, 9.50)	7.20	Accepted
Social	Number of rewarded employees	SO6	(5.80, 8.30, 9.70)	8.12	Accepted
Social	Number of promoted employees	SO7	(5.30, 7.80, 9.50)	7.67	Accepted
Social	Number of female managers	SO8	(4.99, 5.91, 7.93)	6.09	Rejected

The first-round fuzzy Delphi results indicated that 23 of the 26 preliminary sustainability indicators satisfied the acceptance criterion, whereas three indicators obtained defuzzified scores below 7.00 and were therefore excluded. The rejected indicators were social and environmental costs (EC9), with a crisp value of 5.92; fixed carbon dioxide emissions resulting from facility establishment (EN1), with a value of 5.85; and number of female managers (SO8), with a value of 6.09. Among the retained indicators, carbon dioxide emissions resulting from operational activities (EN2) received the highest first-round score at 8.53, followed by number of rewarded employees (SO6) at 8.12 and variable water-consumption cost (EC12) at 8.05. Several other economic indicators, including variable raw-material procurement cost, variable distribution cost, transportation cost, and personnel cost, also received relatively high levels of expert support. Overall, the first round reduced the preliminary framework from 26 to 23 indicators.

The 23 indicators retained after the first round were subjected to a second fuzzy Delphi evaluation by the same expert panel. The purpose of the second round was both to reassess the perceived importance of the surviving indicators and to examine whether expert judgments would converge toward a stable consensus. The same procedures for fuzzy aggregation, defuzzification, and application of the 7.00 acceptance threshold were employed. Indicators excluded in the first round were not reassessed. The results of the second Delphi round are presented in Table 3.

Table 3

Second-Round Fuzzy Delphi Results for Sustainability Indicator Evaluation

Main Dimension	Indicator	Code	Fuzzy Mean (L, M, U)	Crisp Value	Decision
Economic	Fixed or facility establishment cost	EC1	(6.60, 7.01, 8.78)	7.24	Accepted
Economic	Holding cost	EC2	(5.76, 6.78, 7.64)	6.75	Rejected
Economic	Variable transportation cost	EC3	(4.90, 8.04, 9.60)	7.78	Accepted
Economic	Variable production cost	EC4	(5.40, 8.16, 9.30)	7.89	Accepted

Economic	Variable raw-material procurement cost	EC5	(5.40, 7.90, 9.30)	7.72	Accepted
Economic	Variable recycling cost of returned products	EC6	(5.30, 7.10, 9.10)	7.13	Accepted
Economic	Variable distribution cost	EC7	(6.30, 8.09, 9.12)	7.96	Accepted
Economic	Variable collection cost of returned products	EC8	(5.14, 7.01, 8.90)	7.01	Accepted
Economic	Social and environmental costs	EC9	–	–	–
Economic	Training cost	EC10	(5.90, 7.43, 9.71)	7.56	Accepted
Economic	Personnel cost, including salary, insurance, and rewards	EC11	(5.90, 7.81, 9.80)	7.82	Accepted
Economic	Variable water-consumption cost	EC12	(6.10, 8.40, 9.70)	8.23	Accepted
Environmental	Fixed carbon dioxide emissions resulting from facility establishment	EN1	–	–	–
Environmental	Carbon dioxide emissions resulting from operational activities	EN2	(5.08, 7.40, 9.30)	7.45	Accepted
Environmental	Carbon dioxide emissions resulting from transportation	EN3	(6.90, 7.60, 8.20)	7.58	Accepted
Environmental	Support for green and humanitarian projects	EN4	(5.18, 6.89, 8.12)	6.81	Rejected
Environmental	Energy consumption	EN5	(5.14, 6.97, 7.98)	6.83	Rejected
Environmental	Water consumption	EN6	(5.98, 7.74, 8.61)	7.59	Accepted
Social	Total number of jobs	SO1	(6.01, 7.01, 9.30)	7.23	Accepted
Social	Number of working days lost due to accidents	SO2	(5.12, 6.86, 8.19)	6.79	Rejected
Social	Number of jobs for women	SO3	(6.17, 7.01, 8.98)	7.20	Accepted
Social	Number of occupational accidents and work-related diseases	SO4	(6.20, 8.60, 9.70)	8.38	Accepted
Social	Number of trained employees	SO5	(5.10, 7.30, 9.20)	7.25	Accepted
Social	Number of rewarded employees	SO6	(6.10, 8.40, 9.70)	8.23	Accepted
Social	Number of promoted employees	SO7	(5.10, 8.15, 9.10)	7.80	Accepted
Social	Number of female managers	SO8	–	–	–

The second-round results further refined the sustainability indicator framework. Of the 23 indicators reassessed, four received crisp values below the 7.00 threshold and were consequently removed. These included holding cost (EC2), with a score of 6.75; support for green and humanitarian projects (EN4), with a score of 6.81; energy consumption (EN5), with a score of 6.83; and number of working days lost due to accidents (SO2), with a score of 6.79. Following these exclusions, 19 sustainability indicators remained. The highest second-round score was observed for the number of occupational accidents and work-related diseases (SO4), with a crisp value of 8.38, followed by variable water-consumption cost (EC12) and number of rewarded employees (SO6), both with values of 8.23. Other strongly supported indicators included variable distribution cost (EC7), variable production cost (EC4), personnel cost (EC11), number of promoted employees (SO7), and variable transportation cost (EC3). These results indicated that the expert panel placed substantial emphasis on economic efficiency, water-related sustainability, occupational health and safety, and employee development and recognition.

Following completion of the second Delphi round, the stability of expert judgments was assessed by calculating the absolute difference between the defuzzified values obtained in the first and second rounds for each of the 19 indicators that remained accepted. According to the predefined stopping criterion, an absolute difference of 0.20 or less was interpreted as evidence of sufficient stability and consensus, allowing termination of the fuzzy Delphi process without conducting a third round. Table 4 presents the comparison of first- and second-round crisp values and the corresponding absolute deviations.

Table 4

Assessment of Consensus and Stability Across the Two Fuzzy Delphi Rounds

Main Dimension	Indicator	Code	Round 1 Crisp Value	Round 2 Crisp Value	Absolute Difference
Economic	Fixed or facility establishment cost	EC1	7.37	7.24	0.13
Economic	Holding cost	EC2	7.18	6.75	–
Economic	Variable transportation cost	EC3	7.89	7.78	0.11
Economic	Variable production cost	EC4	7.83	7.89	0.06
Economic	Variable raw-material procurement cost	EC5	7.90	7.72	0.18
Economic	Variable recycling cost of returned products	EC6	7.32	7.13	0.19
Economic	Variable distribution cost	EC7	7.90	7.96	0.06
Economic	Variable collection cost of returned products	EC8	7.05	7.01	0.04

Economic	Social and environmental costs	EC9	5.92	–	–
Economic	Training cost	EC10	7.39	7.56	0.17
Economic	Personnel cost, including salary, insurance, and rewards	EC11	7.89	7.82	0.07
Economic	Variable water-consumption cost	EC12	8.05	8.23	0.18
Environmental	Fixed carbon dioxide emissions resulting from facility establishment	EN1	5.85	–	–
Environmental	Carbon dioxide emissions resulting from operational activities	EN2	8.53	7.45	0.08
Environmental	Carbon dioxide emissions resulting from transportation	EN3	7.62	7.58	0.04
Environmental	Support for green and humanitarian projects	EN4	7.11	6.81	–
Environmental	Energy consumption	EN5	7.13	6.83	–
Environmental	Water consumption	EN6	7.67	7.59	0.08
Social	Total number of jobs	SO1	7.40	7.23	0.17
Social	Number of working days lost due to accidents	SO2	7.03	6.79	–
Social	Number of jobs for women	SO3	7.11	7.20	0.09
Social	Number of occupational accidents and work-related diseases	SO4	7.32	8.38	0.06
Social	Number of trained employees	SO5	7.20	7.25	0.05
Social	Number of rewarded employees	SO6	8.12	8.23	0.11
Social	Number of promoted employees	SO7	7.67	7.80	0.13
Social	Number of female managers	SO8	6.09	–	–

The comparison of the two Delphi rounds demonstrated that the absolute difference between the first- and second-round defuzzified values for all 19 retained indicators was below the predetermined threshold of 0.20. The observed deviations ranged from 0.04 to 0.19, indicating a high degree of stability in expert judgments. The smallest differences were observed for variable collection cost of returned products (EC8) and carbon dioxide emissions resulting from transportation (EN3), both at 0.04, while the largest acceptable difference was observed for variable recycling cost of returned products (EC6), at 0.19. Because all retained indicators satisfied the consensus criterion, a third Delphi round was considered unnecessary and the expert consultation process was terminated after the second round. Overall, seven of the 26 initial indicators were eliminated through the two-stage fuzzy Delphi screening process, leaving a final set of 19 sustainability indicators across the economic, environmental, and social dimensions.

The final framework therefore consisted of 10 economic, three environmental, and six social sustainability indicators. The retained economic indicators were fixed or facility establishment cost, variable transportation cost, variable production cost, variable raw-material procurement cost, variable recycling cost of returned products, variable distribution cost, variable collection cost of returned products, training cost, personnel cost, and variable water-consumption cost. The retained environmental indicators were carbon dioxide emissions resulting from operational activities, carbon dioxide emissions resulting from transportation, and water consumption. The retained social indicators were total employment, employment of women, occupational accidents and work-related diseases, number of trained employees, number of rewarded employees, and number of promoted employees. Accordingly, the fuzzy Delphi findings produced a concise and expert-validated sustainability indicator framework specifically adapted to the nylon yarn supply chain within the rubber and plastics industry.

4. Discussion and Conclusion

The present study sought to identify and validate the key sustainability indicators relevant to the nylon yarn Closed-Loop Supply Chain in the rubber and plastics industry through a fuzzy Delphi process based on expert judgment. The findings showed that, from an initial pool of 26 sustainability indicators distributed across economic, environmental, and social dimensions, 19 indicators were ultimately retained after two rounds of expert evaluation. Seven indicators were removed because they did not satisfy the predefined acceptance threshold or failed to maintain sufficient expert support across the Delphi process. The final framework comprised 10 economic indicators, three environmental indicators, and six social indicators, indicating that experts perceived sustainability in this industrial context as a multidimensional construct in which economic viability remained highly important but was complemented by environmental resource concerns and human-centered social considerations. This finding is consistent with the broad conceptualization of sustainable supply chain management described by Bastas and

Liyanage, who emphasized that sustainability should be embedded across economic, environmental, and social components of supply chain quality management rather than treated as an isolated environmental initiative (Bastas & Liyanage, 2018). Similarly, the systematic review conducted by Madani et al. showed that contemporary sustainable supply chain network research increasingly integrates multiple sustainability dimensions, although their degree of representation varies across industries and analytical contexts (Madani et al., 2024). The retention of indicators from all three dimensions in the present study therefore reinforces the argument that sustainability assessment in industrial supply chains requires a balanced and context-sensitive set of criteria rather than a purely cost-based or environmentally focused perspective.

The economic dimension was the largest component of the final framework, with 10 indicators surviving the fuzzy Delphi screening. These included fixed or facility establishment cost, variable transportation cost, variable production cost, variable raw-material procurement cost, recycling cost of returned products, distribution cost, collection cost of returned products, training cost, personnel cost, and variable water-consumption cost. This broad economic structure indicates that experts did not interpret economic sustainability simply as minimization of production expenditure but instead viewed it as a combination of operational, resource-related, reverse-flow, and workforce-related costs. The result is compatible with the increasing complexity observed in sustainable supply chain research, where economic performance is affected by several interdependent components rather than by a single cost criterion. Rostamzadeh et al. demonstrated that sustainable supply chain performance under uncertain, multi-product, and multi-period conditions requires consideration of several interacting operational costs and resource constraints (Rostamzadeh et al., 2025). Mahapatra et al. likewise showed that demand patterns and integrated channel structures can considerably influence cost and supply chain performance, illustrating the need to capture several economic components when assessing modern supply systems (Mahapatra et al., 2025). The present findings therefore support the view that economic sustainability in the nylon yarn supply chain is multifaceted and must incorporate the costs associated with forward operations, reverse logistics, human resources, and resource consumption.

Among the economic indicators, variable water-consumption cost achieved one of the highest scores in both rounds, reaching a crisp value of 8.23 in the second round. This high level of expert agreement suggests that water is viewed not only as an environmental resource but also as an economically important production input within the investigated industry. Such dual significance is particularly relevant in resource-intensive industries where water scarcity, water tariffs, process consumption, and environmental regulation may simultaneously affect production continuity and cost structures. Khalili-Fard et al. showed that sustainable supply chain configurations within resource-intensive industries such as steel increasingly require integration of resource efficiency and circular-economy considerations into economic decision structures (Khalili-Fard et al., 2024). Similarly, sustainable production-oriented research has increasingly incorporated resource-use constraints into supply chain assessment rather than limiting economic sustainability to conventional facility and transportation costs (Madani et al., 2024). The high importance attributed to water-related cost in the present study therefore reflects an expanded understanding of economic sustainability in which resource efficiency becomes directly connected to industrial competitiveness and long-term operational viability.

Transportation, production, raw-material procurement, and distribution costs also received strong expert support. This pattern is logical because these cost categories are among the main determinants of supply chain performance and are closely affected by network configuration, demand variation, supplier relationships, and market conditions. Research on sustainable supply chain design has repeatedly demonstrated that transportation, procurement, production, and distribution decisions remain central economic drivers even when environmental and social objectives are incorporated. Yousefi-Babadi et al., for instance, showed that redesigning the wheat-flour-bread supply chain under uncertainty required simultaneous attention to economic and sustainability-related network considerations (Yousefi-Babadi et al., 2023). Gholizadeh et al. similarly integrated cost-related and sustainability dimensions into a closed-loop dairy supply chain under uncertain conditions (Gholizadeh et al., 2021). Abir et al. further illustrated that sustainable closed-loop supply chain structures require simultaneous consideration of multiple objectives and cost components under demand uncertainty (Abir et al., 2020). The current findings therefore align with prior evidence showing that economic sustainability remains inseparable from operational configuration and logistics efficiency.

Another notable finding was the retention of recycling and collection costs associated with returned products. Their acceptance indicates that experts considered reverse-flow activities relevant to the economic sustainability of the nylon yarn supply chain. This result is consistent with the growing emphasis on closed-loop supply chain structures and circular economy principles, where value recovery from returned materials and products is viewed as a significant component of sustainable operations. Gholizadeh et al. demonstrated that incorporating recovery and reverse logistics processes into supply chain design can simultaneously influence sustainability performance and operational cost structures (Gholizadeh et al., 2021). Ravansh likewise emphasized the importance of flexible closed-loop supply chain structures in multi-objective sustainability contexts (Ravansh, 2021). Khalili-Fard et al. also highlighted the importance of circular flows and resource recovery in the sustainable redesign of industrial supply chains (Khalili-Fard et al., 2024). The confirmation of reverse-logistics cost indicators in the present study therefore suggests that the experts perceived sustainability not as a linear production-distribution issue but as one that includes recovery-oriented and circular supply chain activities.

The removal of holding cost from the final indicator set is also noteworthy. Although holding cost was accepted in the first round with a crisp value of 7.18, its second-round score declined to 6.75, leading to its exclusion. This finding may indicate that experts considered inventory holding cost comparatively less critical than transportation, production, procurement, and reverse-flow costs within the specific structure of the nylon yarn supply chain. The result does not imply that inventory costs are generally unimportant; rather, it shows that expert prioritization is industry dependent. In some supply chains, particularly those involving perishability or highly volatile demand, inventory costs may be central. Shafiei et al., for example, demonstrated the importance of inventory-related and operational considerations in sustainable perishable dairy supply chains (Shafiei et al., 2020). Mahapatra et al. also showed that demand patterns and channel integration can substantially alter inventory-related decisions in smart retail supply chains (Mahapatra et al., 2025). Thus, the exclusion of holding cost in the present study should be interpreted as a context-specific judgment reflecting the relative importance of different economic sustainability dimensions within the nylon yarn sector.

The environmental dimension was refined considerably during the Delphi process. Of the six initial indicators, only three were retained: carbon dioxide emissions resulting from operational activities, carbon dioxide emissions resulting from transportation, and water consumption. These findings indicate that experts prioritized direct and measurable environmental pressures associated with industrial activity and logistics. Carbon emissions from operations received particularly strong support in the first round, while transportation-related emissions remained consistently above the acceptance threshold in both rounds. This result corresponds closely with previous sustainable supply chain research, where carbon emissions are among the most frequently used environmental indicators. Zhang and Yousaf demonstrated the importance of environmental performance, green investment, and regulatory mechanisms in petroleum supply chains, particularly where emissions and green preferences shape coordination decisions (Zhang & Yousaf, 2020). Gu et al. similarly showed that policy instruments can alter the environmental behavior and sustainable development performance of closed-loop supply chains (Gu et al., 2023). Ala et al. incorporated environmental objectives within a fuzzy sustainable healthcare supply chain framework, further illustrating the widespread use of emissions-related criteria in sustainability assessment (Ala et al., 2024). The confirmation of operational and transportation emissions in the present study is therefore strongly consistent with existing sustainable supply chain literature.

Water consumption was also retained as a key environmental indicator and achieved a second-round crisp score of 7.59. This result is particularly important because environmental sustainability studies frequently emphasize carbon and energy, whereas water-related indicators may receive less systematic attention. For the nylon yarn supply chain, however, experts clearly regarded water use as a significant environmental consideration. This reflects the broader movement toward incorporating resource efficiency into sustainable supply chain assessments. Khalili-Fard et al. emphasized the importance of circularity and resource-sensitive supply chain design in industrial systems (Khalili-Fard et al., 2024), while Madani et al. identified environmental resource consumption as an important emerging theme in sustainable supply chain network research (Madani et al., 2024). The present result therefore contributes to this trend by indicating that water consumption should be explicitly considered when sustainability indicators are adapted to resource-intensive industrial environments.

In contrast, fixed carbon dioxide emissions arising from facility establishment, support for green and humanitarian projects, and energy consumption were not retained. The rejection of fixed emissions from facility establishment may indicate that experts viewed continuing operational emissions as more relevant than one-time or relatively infrequent emissions associated with opening facilities. Support for green and humanitarian projects may have been regarded as an indirect or corporate social responsibility-related measure rather than a core operational environmental indicator. The exclusion of energy consumption is more surprising because energy is frequently considered a central environmental sustainability variable. However, its second-round crisp value of 6.83 suggests that experts may have perceived energy consumption as partially overlapping with operational emissions or other resource-use measures. Sector-specific prioritization has been observed in previous research, where different industries emphasize different environmental criteria. Azadi et al. showed that sustainability assessment structures in healthcare supply chains differ from those used in industrial manufacturing (Azadi et al., 2023), while Sadeghi Goughari et al. demonstrated that agricultural supply chains require sector-specific risk and sustainability indicators (Sadeghi Goughari et al., 2024). The present findings therefore reinforce the principle that environmental sustainability indicators should be empirically contextualized rather than adopted automatically from generic frameworks.

The social dimension also yielded important findings. Six of the eight initial social indicators were retained, including total employment, employment of women, occupational accidents and work-related diseases, number of trained employees, number of rewarded employees, and number of promoted employees. The retention of these indicators demonstrates that experts recognized social sustainability as an important component of supply chain performance rather than as a secondary concern. This finding is consistent with the growing recognition that sustainable supply chains depend on workforce well-being, human capital development, organizational coordination, and resilience. He et al. emphasized that sustainable supply chain resilience requires organizational solutions that address not only structural risk but also managerial and human dimensions (He et al., 2021). Liu et al. similarly showed that resilience and sustainability strategies must be considered together under constrained operational environments (Liu et al., 2023). The current findings extend this perspective by identifying concrete social indicators that experts regarded as meaningful in the nylon yarn supply chain.

The highest second-round score across all retained indicators was obtained for the number of occupational accidents and work-related diseases, with a crisp value of 8.38. This result demonstrates the strong importance attributed by experts to occupational health and safety. In industrial settings, accidents and work-related illnesses can generate substantial human, organizational, and economic consequences, including loss of productive capacity, compensation costs, reputational damage, and reduced employee well-being. The strong support for this indicator suggests that experts viewed safety performance as a core dimension of social sustainability. This is consistent with sustainable and resilient supply chain approaches that emphasize continuity, risk reduction, and protection of organizational resources. Hasani et al. highlighted the importance of integrating resilience and sustainability when designing supply chain systems under regional constraints (Hasani et al., 2021), while Jafari Eskandari and Emami Salout emphasized risk-sensitive approaches to sustainable closed-loop supply chains under uncertainty (Jafari Eskandari & Emami Salout, 2022). Although these studies address risk from broader operational perspectives, the present findings indicate that occupational health and safety should also be recognized as a key social risk dimension within industrial sustainability assessment.

Indicators related to employee development also received strong expert endorsement. The number of trained employees, rewarded employees, and promoted employees were all retained, with rewarded employees reaching a high crisp score of 8.23. These findings suggest that experts considered human resource development, recognition, and advancement important elements of social sustainability. Such indicators move the assessment of sustainability beyond basic employment creation and toward the quality and developmental characteristics of employment. Li et al. demonstrated that organizational coordination and behavioral relationships can substantially influence sustainability performance in complex supply chains (Li et al., 2019). The present findings complement that perspective by showing that internal workforce development mechanisms may also be important for sustaining organizational capability. Training, incentives, and promotion can support employee competence, motivation, retention, and adaptive capacity, all of which are relevant to long-term supply chain performance.

The retention of total employment and women's employment further indicates that experts associated sustainability with inclusive employment creation. However, the number of female managers was rejected in the first round, despite women's employment being retained. This distinction is conceptually interesting. It suggests that experts viewed women's participation in the workforce as a relevant social sustainability outcome but did not assign the same level of importance to female managerial representation within the specific framework under consideration. The difference may reflect the operational characteristics of the industry, the composition of available managerial positions, or the experts' interpretation of which indicators were sufficiently generalizable across supply chain organizations. Importantly, this result should not be interpreted as evidence that gender diversity in management lacks broader social importance. Rather, it indicates that, within this particular expert-derived framework, women's employment was perceived as a more immediately applicable social indicator than the number of women in managerial roles.

The fuzzy Delphi process itself also yielded an important methodological result. All 19 retained indicators showed an absolute difference of less than 0.20 between the defuzzified values of the first and second rounds, indicating that expert judgments had stabilized sufficiently and that a third round was unnecessary. This convergence strengthens the credibility of the final indicator framework because the retained indicators were not only accepted on the basis of their score but also demonstrated stability across repeated expert assessment. The use of iterative expert screening is particularly appropriate in sustainability research because many relevant constructs are difficult to measure objectively during the initial stages of framework development. Prior research increasingly employs fuzzy, robust, and uncertainty-sensitive methods to represent ambiguous or incomplete information in sustainable supply chain contexts (Ala et al., 2024; Rostamzadeh et al., 2025; Yousefi-Babadi et al., 2023). The present findings support this broader methodological direction by demonstrating that fuzzy expert judgment can effectively reduce a broad initial indicator pool to a stable and contextually validated sustainability framework.

Overall, the final framework demonstrates that sustainability within the nylon yarn supply chain is perceived by experts as an integrated combination of economic efficiency, environmental responsibility, and social performance. The economic dimension remained dominant in terms of the number of retained indicators, but high scores for occupational health and safety, water consumption, employee recognition, and carbon emissions show that sustainability priorities extend well beyond cost management. This pattern is consistent with the broader evolution of sustainable supply chain research from narrow cost-efficiency models toward integrated approaches encompassing resilience, resource conservation, circularity, workforce well-being, and environmental performance (Bastas & Liyanage, 2018; Madani et al., 2024). The results therefore provide a sector-specific evidence base for understanding which sustainability indicators are regarded as most relevant to the rubber and plastics industry with emphasis on the nylon yarn supply chain, while also demonstrating that generic sustainability frameworks should be refined through expert evaluation before being applied to specialized industrial settings.

The study has several limitations that should be considered when interpreting the findings. First, the expert panel consisted of 23 participants selected purposively on the basis of specialized academic and industrial experience, and although this approach is appropriate for Delphi research, the resulting framework reflects the knowledge and judgments of a relatively specific group of experts. Second, the study focused exclusively on the nylon yarn supply chain within the rubber and plastics industry, which may limit the direct transferability of all identified indicators to other industries or product categories. Third, although the fuzzy Delphi technique reduced ambiguity in linguistic judgments, expert assessments remain inherently subjective and may be influenced by professional experience, organizational position, and familiarity with particular sustainability issues. Finally, the predefined acceptance threshold influenced which indicators were retained or excluded, and alternative threshold values could potentially lead to a somewhat different final framework.

Future research should replicate the fuzzy Delphi procedure with broader and more heterogeneous expert panels, including participants from suppliers, manufacturers, logistics providers, customers, regulators, environmental organizations, and labor representatives. Comparative studies could also examine whether the relative importance of sustainability indicators differs across subsectors of the rubber and plastics industry or across different geographical and regulatory environments. Further studies may investigate the relationships among the 19 validated indicators, develop hierarchical structures among them, or assess their relative priority using complementary expert-

based techniques. Longitudinal research would also be valuable for determining whether expert perceptions change over time as environmental regulation, resource scarcity, technology, workforce expectations, and market conditions evolve.

From a practical perspective, managers can use the validated indicator set as a structured sustainability assessment framework for monitoring and reviewing Closed-Loop Supply Chain performance. Particular attention should be paid to operational and transportation emissions, water consumption, occupational accidents and work-related diseases, workforce training, employee recognition and advancement, and major categories of supply chain cost. Organizations should integrate these indicators into periodic sustainability reviews and internal performance dashboards rather than assessing economic, environmental, and social outcomes separately. The framework can also support cross-functional collaboration by providing procurement, production, logistics, human resources, and sustainability managers with a shared set of indicators for identifying weaknesses, setting improvement priorities, and tracking progress over time.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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