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Identification of Sustainable Supply Chain Risks Using the Fuzzy Delphi Method

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Abstract

Under current conditions, identifying opportunities and threats in industry and trade and assessing companies' ability to cope with risks and uncertainties are of particular importance. Accordingly, risk management in the supply chain has become one of the key topics attracting the attention of researchers and managers. The aim of this study is to present a decision-making-based approach for managing sustainable supply chain risks in the oil and gas industry. In the first stage, 10 major supply chain risks in this industry were identified based on previous studies. Then, using the fuzzy Delphi method and the opinions of experts active in the supply chain of Ilam Gas Refining Company, 6 risks were selected as the company's key risks. Subsequently, fuzzy DEMATEL was used to analyze the relationships among the risks; the results led to the development of an influence-dependence matrix and the clarification of causal relationships. The findings showed that risks related to support and distribution have the greatest importance in the company's supply chain, whereas risks related to production and transmission are at a lower level of importance.

Keywords: Sustainable supply chain, risk management, oil and gas industries, DEMATEL, fuzzy

1. Introduction

Supply chains have become increasingly complex systems in which economic efficiency, environmental responsibility, social accountability, technological integration, and operational continuity must be pursued simultaneously. This complexity has intensified the exposure of organizations to a wide range of risks that may originate from suppliers, production systems, logistics networks, information infrastructures, regulatory environments, market conditions, or broader socio-environmental pressures. In this context, sustainable supply chain management has evolved beyond the traditional objective of minimizing cost and maximizing service levels and now encompasses the coordinated management of economic, environmental, and social requirements across interconnected supply chain actors. At the same time, sustainability itself may introduce additional sources of uncertainty because organizations are expected to comply with environmental standards, maintain responsible sourcing, protect social interests, ensure transparency, and preserve long-term operational viability under volatile conditions. Consequently, supply chain risk management and sustainability management are increasingly regarded as interdependent domains rather than separate managerial concerns. Recent research has emphasized that sustainable supply chain practices influence performance outcomes and that their effectiveness depends on the organizational and interorganizational mechanisms through which such practices are implemented (Agyabeng-Mensah, 2025). Likewise, contemporary modeling studies indicate

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that sustainable supply chains should be understood as dynamic systems characterized by feedback relationships, uncertainty, nonlinear interactions, and multiple competing objectives (Kurniasih, 2025). These developments have strengthened the need for analytical approaches capable not only of identifying sustainability-related supply chain risks but also of determining how those risks influence one another.

Risk in a sustainable supply chain is multidimensional because disruptions may simultaneously affect operational performance, economic outcomes, environmental compliance, social responsibility, and organizational reputation. Conventional supply chain risk assessment often focuses on individual risks according to probability and impact, but such an approach may inadequately represent the systemic structure of modern supply chains. Risks rarely occur in isolation. A disruption affecting one element of the chain may generate secondary consequences elsewhere, while apparently minor risks may become strategically important because of their ability to trigger other disruptions. Xu et al. emphasized the need for systematic assessment of sustainability risks throughout supply chains and demonstrated that sustainability-related vulnerabilities must be evaluated across interconnected dimensions rather than through isolated operational indicators (Xu et al., 2019). Similarly, Warasthe et al. showed that sustainability, risk, and supply chain performance are closely intertwined and that risk management should account for the consequences of sustainability pressures across supply chain relationships (Warasthe et al., 2022). Accordingly, the analytical challenge is not limited to determining which risks exist; it also involves revealing their relative importance, causal position, and potential propagation through the supply chain network.

The increasing frequency of disruptions has further demonstrated the limitations of supply chains designed primarily around efficiency. Global crises, geopolitical instability, transportation interruptions, demand fluctuations, supplier failures, technological breakdowns, and public-health emergencies can expose structural weaknesses that remain unnoticed under normal operating conditions. Research conducted in different sectors indicates that effective supply chain risk management can reduce the adverse consequences of disruptions and strengthen flexibility and resilience. In the petrochemical industry, for example, supply chain risk management has been examined as an important mechanism for mitigating disruption effects and supporting supply chain flexibility, resilience, and financial performance (Dianati, 2023). In healthcare-related supply chains, recent bibliometric evidence similarly shows that risk has developed into a major research stream involving resilience, uncertainty, supplier dependency, disruption preparedness, and operational continuity (Yun & An, 2025). Such findings are especially relevant to energy industries, where disruptions can have consequences extending beyond individual firms to regional economic activity, infrastructure continuity, and public service provision.

The oil and gas industry represents one of the most risk-intensive industrial environments because its supply chains depend on complex technical assets, specialized suppliers, extensive transportation and distribution systems, information networks, maintenance activities, and strict safety and environmental requirements. Upstream, midstream, and downstream operations are highly interconnected, and disruptions in procurement, production, transmission, storage, maintenance, or distribution can propagate rapidly across the system. Furthermore, oil and gas companies operate under conditions of fluctuating prices, geopolitical uncertainty, environmental regulation, technological dependence, occupational hazards, and infrastructure constraints. These characteristics make risk management essential to both operational continuity and sustainability. Earlier supply chain optimization research has shown that risk and uncertainty should be integrated directly into supply chain decision-making rather than treated as external considerations after operational plans have been formulated (Aqlan & Lam, 2015). Industrial case studies of sustainable supply chain optimization have likewise demonstrated that economic and environmental objectives must be considered jointly in supply chain design and operational planning (Zhang et al., 2014). For oil and gas organizations, this integration is particularly important because short-term operational decisions may generate long-term sustainability consequences and because sustainability constraints can themselves influence supply continuity, supplier selection, and network performance.

Supplier-related risk is one of the central concerns in sustainable supply chains because organizations increasingly depend on external firms for materials, equipment, technology, specialized services, and logistics support. Supplier disruptions can influence cost, quality, production continuity, environmental performance, and regulatory compliance simultaneously. When sustainability requirements are incorporated into supplier selection, procurement decisions become even more complex because organizations must evaluate not only traditional criteria such as price, quality, and delivery but also environmental performance, social responsibility, reliability, and exposure to uncertainty. Nouri et al. demonstrated the importance of incorporating

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uncertainty and supplier-related risk into sustainable supply chain design (Nouri et al., 2019). This perspective is highly relevant to industrial supply chains in which a limited number of qualified suppliers may provide critical materials or technical services. Under such conditions, a supplier-related problem may generate production delays, maintenance interruptions, higher operating costs, or downstream distribution problems. Therefore, supplier risk should not be assessed independently from organizational, information, production, and external risks.

The growing emphasis on resilience has also changed how supply chain risk is conceptualized. A resilient supply chain is not simply one that avoids disruption; it is one capable of anticipating disturbances, absorbing shocks, adapting to changing conditions, and restoring performance within an acceptable period. Risk identification and prioritization are fundamental prerequisites for building this capacity. Arab Cham Khalifeh and Alavi emphasized the identification and prioritization of supply chain risks as a foundation for developing resilience-oriented responses (Arab Cham Khalifeh & Alavi, 2023). Similar concerns have been raised in sector-specific studies in which risk-ranking methods have been employed to determine which vulnerabilities require priority managerial attention. Shafiei Nikabadi and Helalian applied an integrated failure mode and effects analysis and grey-theory approach to rank supply chain risks in food-industry units, illustrating the value of structured multicriteria analysis when risk judgments involve ambiguity and incomplete information (Shafiei Nikabadi & Helalian, 2023). These studies indicate that risk prioritization is most useful when it supports practical allocation of managerial attention and resources rather than merely generating descriptive lists of potential threats.

Risk structures also vary substantially across sectors, meaning that generic risk classifications should be refined according to organizational context. In healthcare and pharmaceutical systems, for instance, continuity, accessibility, product safety, and timely delivery may dominate the sustainability agenda. Shah Bahrami et al. prioritized factors affecting sustainable pharmaceutical supply chain management and demonstrated the importance of sector-specific assessment in identifying critical sustainability determinants (Shah Bahrami et al., 2020). Similarly, Babazadeh Rafiei et al. investigated risks in the blood supply chain during the COVID-19 pandemic, highlighting the vulnerability of critical supply systems to sudden and large-scale disruptions (Babazadeh Rafiei et al., 2023). Although the operational characteristics of healthcare supply chains differ from those of oil and gas, these studies reinforce a broader methodological principle: meaningful risk management requires the identification of context-specific risks rather than exclusive reliance on general risk taxonomies.

Information and technology constitute another important dimension of sustainable supply chain risk. Modern supply chains depend heavily on digital systems for coordination, inventory management, procurement, forecasting, transportation planning, communications, monitoring, and decision support. Failures in information systems can delay decisions, reduce visibility, disrupt coordination, and amplify the effects of other operational problems. Gholizadeh et al., in examining sustainable information-technology supply chain risks in knowledge-based companies, demonstrated that technology-related risks possess interactive relationships and should be understood through a systemic analytical framework (Gholizadeh et al., 2020). In industrial organizations such as gas refineries, information-system risk may influence procurement, maintenance, production, and distribution simultaneously. This interdependence strengthens the argument for analytical techniques capable of distinguishing between risks that primarily generate effects and risks that mainly receive or absorb effects from other parts of the system.

Sustainability-related risk management also becomes more difficult when supply chains extend across multiple tiers. Organizations often possess relatively strong visibility over direct suppliers but substantially less information about second-tier and third-tier suppliers, subcontractors, logistics providers, and other indirect actors. Sustainability violations, capacity constraints, labor issues, material shortages, and environmental risks can originate deep within the supply network and eventually affect the focal organization. Kähkönen et al. emphasized the importance of practices and strategies for sustainability-related risk management in multi-tier supply chains, showing that effective management requires broader visibility and coordination beyond immediate buyer–supplier relationships (Kähkönen et al., 2023). Jamalnia et al. similarly developed a decision-support perspective for selecting and managing sustainability governance approaches in multi-tier supply chains, underscoring the complexity of evaluating governance mechanisms under multiple risk conditions (Jamalnia et al., 2023). These findings suggest that sustainable supply chain risk management must move from firm-centric analysis toward network-based understanding.

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The design of sustainable and reliable supply chain networks further illustrates the interaction between sustainability objectives and risk. Network configuration decisions determine supplier dependencies, transportation paths, inventory positions, production locations, and the ability of the system to respond to disruption. Saffari et al. addressed sustainable and reliable closed-loop supply chain network design while explicitly considering risk and combined transportation, demonstrating how sustainability and reliability objectives can be incorporated into integrated decision models (Saffari et al., 2023). Such approaches are important because sustainability cannot be achieved if supply networks are environmentally desirable but operationally fragile, just as resilient networks cannot be considered sustainable if their continuity depends on environmentally or socially unacceptable practices. Sustainable supply chain management therefore requires balancing resilience, reliability, cost, resource utilization, environmental responsibility, and social expectations.

A major methodological difficulty in assessing supply chain risks arises from the qualitative and uncertain nature of expert judgments. Managers and specialists commonly express risk relationships using linguistic evaluations such as low influence, moderate influence, high influence, or very high influence. These judgments cannot always be represented adequately by precise numerical values because experts may differ in experience, interpretation, and confidence. Fuzzy approaches provide a useful mechanism for representing such ambiguity by translating linguistic assessments into fuzzy numbers. This is particularly valuable in situations where historical data are incomplete or where emerging risks cannot be evaluated exclusively through statistical evidence. In addition, methods that identify causal relationships among criteria can provide more managerial insight than simple ranking techniques because they reveal whether a risk functions primarily as a driver or as an outcome of other risks.

The use of fuzzy Delphi methods is especially appropriate during the risk-identification and screening stage. Conventional Delphi procedures facilitate expert consensus through iterative assessment, while fuzzy logic reduces the loss of information associated with converting linguistic opinions into crisp values. This combination enables researchers to refine broad lists of risks into a smaller set of contextually relevant factors while retaining uncertainty in expert evaluations. Once the principal risks have been identified, however, prioritization alone remains insufficient. It becomes necessary to examine their mutual influence. Sustainable supply chain systems frequently contain feedback effects in which organizational problems influence information performance, information failures affect production, production disruptions influence distribution, and external risks intensify several internal vulnerabilities simultaneously. This means that the relative importance of a risk depends not only on its own severity but also on its position within the causal structure of the system.

The Decision-Making Trial and Evaluation Laboratory method provides an appropriate basis for analyzing this type of interdependence because it can transform pairwise influence judgments into a structured causal network. When integrated with fuzzy logic, fuzzy DEMATEL can accommodate uncertainty in expert assessments while determining the degree to which each criterion influences and is influenced by other criteria. The resulting prominence measure, commonly derived from the sum of influence and dependence, indicates the overall importance of each risk, whereas the relation measure derived from their difference distinguishes causal risks from effect risks. This distinction has direct managerial value. Risks with positive net influence can be interpreted as potential drivers whose mitigation may reduce several downstream problems, while risks with negative net influence may represent dependent outcomes whose improvement requires addressing more fundamental causes. Accordingly, fuzzy DEMATEL provides a basis for moving from descriptive risk identification toward intervention-oriented risk management.

The importance of such an approach is reinforced by evidence that sustainability-related risks should be managed as interconnected portfolios rather than as independent items. Sustainable supply chain performance depends on coordinated practices across sourcing, production, logistics, governance, technology, and stakeholder relationships (Agyabeng-Mensah, 2025). Likewise, system-dynamics perspectives emphasize feedback structures and temporal interactions in sustainable supply chain modeling (Kurniasih, 2025). When these insights are considered alongside multi-tier governance research (Jamalnia et al., 2023), sustainability-related risk practices (Kähkönen et al., 2023), and integrated risk-assessment frameworks (Xu et al., 2019), it becomes clear that managerial decision-making should focus not only on which risks appear most severe but also on which risks occupy the most influential positions within the wider risk network.

Despite the expansion of sustainable supply chain research, an important practical gap remains in applying integrated expert-based methods to organization-specific industrial settings, particularly where operational data are limited and the relationships

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among risks are uncertain. Many studies concentrate on network optimization, sustainability performance, resilience, supplier selection, or individual categories of risk, whereas fewer studies combine systematic risk screening with explicit causal mapping in a specific oil and gas supply chain. This gap is significant because managers require decision tools that identify a manageable set of locally relevant risks and clarify which of them should receive priority intervention. In the context of gas-refining supply chains, risks associated with procurement and suppliers, support and distribution, organizational conditions, information systems, production and transmission, and external conditions may interact in ways that cannot be understood through isolated ranking alone. An integrated fuzzy Delphi–fuzzy DEMATEL framework can therefore provide a structured means of reducing a broad initial set of risks, incorporating expert knowledge, quantifying uncertain judgments, and revealing the causal architecture among the final risk factors.

The aim of this study is to identify and prioritize the key sustainable supply chain risks of Ilam Gas Refining Company and to determine their causal relationships, influence, and dependence using an integrated fuzzy Delphi and fuzzy DEMATEL approach.

2. Methods and Materials

The present study is applied in terms of purpose and quantitative in terms of the nature of the data. The study population is Ilam Gas Refining Company. Data were collected using two approaches: a library-based method to extract the theoretical foundations and review the literature from sources such as articles, research projects, and scientific databases, and a field method to collect the data required for implementing multi-criteria decision-making techniques. Accordingly, a questionnaire was designed and distributed among experts active in the supply chain of Ilam Gas Refining Company. The experts were selected purposively and systematically to ensure the greatest possible fit with the field under study. In the data-analysis stage, sustainable supply chain risks were first identified through a review of the research literature. The fuzzy Delphi technique and expert opinions were then used to screen and finalize the selected risks. Next, fuzzy DEMATEL was employed to model the interrelationships among the risks and determine the intensity of their influence and dependence. This process made it possible to identify and prioritize the key risks in the sustainable supply chain of Ilam Gas Refining Company.

3. Findings and Results

In this study, sustainable supply chain risks at Ilam Gas Refining Company were identified through a combination of literature review and the opinions of supply-chain experts. First, a set of general risks in the oil and gas industry was extracted by reviewing relevant articles, research projects, and scientific sources. Then, using the fuzzy Delphi method and opinions obtained from experts working at the company, the identified risks were screened and finalized, and a list of key risks relevant to the company under study was developed. This process made it possible to focus on the risks that are important and relevant to the company's operating conditions.

The fuzzy Delphi process consisted of several stages. In the first stage, the risks were ranked by experts, and each risk was evaluated using triangular fuzzy numbers based on its importance and probability of occurrence. In the second stage, the experts' opinions were averaged and aggregated fuzzy numbers were formed in order to reduce disagreement. Finally, risks with a defuzzified value greater than 0.7 were accepted as the key, company-specific risks of Ilam Gas Refining Company. In this way, six of the ten identified risks were finalized and entered into the interaction-effects analysis stage.

Table 1. Company-Specific Supply Chain Risks of Ilam Gas Refining Company

Initial Code	Risks	Mean			Defuzzified	Result
		l	m	u		
C1	Supply and supplier risks	0.53	0.75	0.89	0.73	Accepted
C2	Support and distribution risks	0.56	0.75	0.87	0.73	Accepted
C3	Supply risks	0.35	0.75	0.88	0.68	Rejected
C4	Energy consumption	0.41	0.60	0.75	0.59	Rejected
C5	Organizational risks	0.52	0.74	0.89	0.722	Accepted
C6	Information system risks	0.51	0.73	0.89	0.715	Accepted
C7	Production and transmission risks	0.53	0.73	0.87	0.715	Accepted

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C8	Human rights violations	0.38	0.60	0.77	0.587	Rejected
C9	Human error	0.36	0.58	0.75	0.567	Rejected
C10	External risks	0.52	0.74	0.89	0.722	Accepted

Given the inherent complexities of a sustainable supply chain and the multidimensional nature of its associated risks, merely identifying the risks cannot provide a comprehensive picture of the existing situation, because these risks do not operate independently and are generally in interaction with and mutually affect one another. Therefore, analyzing the causal relationships among the risks is essential for a more precise understanding of the position and importance of each risk. Accordingly, after identifying the key sustainable supply chain risks at Ilam Gas Refining Company, the present study employed fuzzy DEMATEL to determine the intensity of the risks' influence and dependence and to map the network of interrelationships among them. In addition to distinguishing causal from effect risks, this approach provides a scientific and practical basis for prioritizing and effectively managing sustainable supply chain risks.

Determination of Influence and Dependence Matrices and Criterion Weights

DEMATEL is a method for representing the complex structure of causal relationships by means of a diagram or matrix. These matrices or diagrams show the relationships among the elements of a system, and the numbers shown on the diagrams indicate the intensity of the influence of each element. Because the use of DEMATEL requires expert judgments, and such judgments include verbal and potentially ambiguous expressions, it is preferable to convert these expressions into fuzzy numbers in order to integrate them and reduce ambiguity. To address this issue, Lin and Wu proposed a model that applies DEMATEL in a fuzzy environment. The stages of the method are described below.

Stage 1: Obtaining Expert Opinions and Averaging Them

Assume that P experts have expressed their opinions about the relationships among sustainable supply chain risks using the linguistic expressions presented in Table 2. Accordingly, P matrices are formed, each corresponding to the opinions of one expert, with its entries specified by the relevant fuzzy numbers. Equation (1) is used to calculate the matrix representing the average of the expert opinions.

Table 2. Correspondence between Linguistic Expressions and Triangular Fuzzy Numbers

Linguistic expressions	Fuzzy numbers
Very high influence	(0.75, 1, 1)
High influence	(0.50, 0.75, 1)
Low influence	(0.25, 0.50, 0.75)
Very low influence	(0, 0.25, 0.50)
No influence	(0, 0, 0.25)

$$\tilde{z} = \frac{\tilde{x}^1 \oplus \tilde{x}^2 \oplus \tilde{x}^3 \oplus \ldots \oplus x^p}{p}$$

Matrix Z is called the initial fuzzy direct-relation matrix.

Stage 2: Calculation of the Normalized Direct-Relation Matrix

Equations (2) and (3) are used to normalize the matrix obtained.

$$\tilde{H}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right) = (l''_{ij}, m''_{ij}, u''_{ij})$$

where r is obtained from the following relationship.

$$r = \max_{1 \le i \le n}\left(\sum_{j=1}^{n} u_{ij}\right)$$

Stage 3: Calculation of the Fuzzy Total-Relation Matrix T

The fuzzy total-relation matrix is obtained using Equations (4) through (7).

$$T = \lim \left(\tilde{H}^1 \oplus \tilde{H}^2 \oplus \ldots \oplus \tilde{H}^k\right)$$

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$$[l_{ij}^{t}] = H_l \times (I - H_l)^{-1}$$
$$[m_{ij}^{t}] = H_m \times (I - H_m)^{-1}$$
$$[u_{ij}^{t}] = H_u \times (I - H_u)^{-1}$$

In these equations, I is the identity matrix, and H_l, H_m, and H_u are each n x n matrices whose entries are, respectively, the lower, middle, and upper values of the triangular fuzzy numbers in matrix H.

Stage 4: Obtaining the Sums of the Rows and Columns of Matrix T

The row and column sums are obtained using Equations (8) and (9).

$$\tilde{D} = (\tilde{D}_i)_{n\times 1} = [\sum_{j=1}^{n} \tilde{T}_{ij}]_{n\times 1}$$
$$\tilde{R} = (\tilde{R}_i)_{1\times n} = [\sum_{i=1}^{n} \tilde{T}_{ij}]_{1\times n}$$

where D and R are n x 1 and 1 x n matrices, respectively.

Stage 5: Determining the Importance of the Indices (D_i + R_i) and the Relationship among the Criteria (D_i - R_i)

If D_i - R_i > 0, the corresponding criterion is influential; if D_i - R_i < 0, the corresponding criterion is dependent.

Stage 6: Defuzzification of the Fuzzy Values D_i + R_i and D_i - R_i Obtained in the Previous Stage

The fuzzy values D_i + R_i and D_i - R_i obtained in the previous stage are defuzzified according to Equation (10).

$$B = \frac{l + 2m + u}{4}$$

where B is the defuzzified value of the triangular fuzzy number (l, m, u).

Stage 7: Obtaining the Influence and Impact Weights of the Criteria

The relative importance of the criteria is calculated using Equation (11).

$$w_j = [(D_i + R_i)^2 + (D_i - R_i)^2]^{\frac{1}{2}}$$

The implementation of the fuzzy DEMATEL technique for identifying causal relationships among the identified risks is described below:

Table 3. Coding of the Identified Risks

Code	Identified risks
R1	Supply and supplier risks
R2	Support and distribution risks
R3	Organizational risks
R4	Information system risks
R5	Production and transmission risks
R6	External risks

To determine the causal relationships, a questionnaire was designed and distributed among the members of the decision-making group (5 organizational experts). The relationships were then determined using the fuzzy DEMATEL method. The implementation steps of the fuzzy DEMATEL method are presented below:

Step 1: Formation of the Aggregated Normalized Direct-Relation Matrix of Expert Opinions

At this stage, the five members of the decision-making team evaluated the identified risks. The table below presents the average of their opinions, after normalization, in the form of the aggregated normalized direct-relation matrix.

Table 4. Aggregated Normalized Direct-Relation Matrix

R1			R2			R3			R4		R5			R6			Risk
R1	0.19	0.19	0.19	0.047	0.095	0.142	0.047	0.095	0.142	0	0.04	0.09	0.04	0.09	0.14	0.04	0.95	0.14

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R2	0.12	0.17	0.19	0.19	0.19	0.19	0.07	0.12	0.17	0.05	0.09	0.14	0.05	0.09	0.14	0.09	0.14	0.17
R3	0.09	0.14	0.19	0.05	0.09	0.14	0.19	0.19	0.19	0.02	0.07	0.12	0.02	0.07	0.12	0	0.5	0.09
R4	0.02	0.07	0.12	0.05	0.09	0.14	0	0.05	0.09	0.19	0.19	0.19	0.7	0.12	0.17	0.14	0.19	0.19
R5	0.05	0.09	0.14	0.07	0.12	0.17	0	0.02	0.07	0	0.05	0.09	0.19	0.19	0.19	0.07	0.12	0.17
R6	0.07	0.12	0.14	0.05	0.09	0.14	0.05	0.09	0.14	0.09	0.14	0.19	0	0.05	0.09	0.19	0.19	0.19

Step 2: Determining the Intensity of Influence and Dependence of the Identified Risks

At this stage, by calculating the sums of the rows and columns in the defuzzified matrix from the previous stage, the importance of the indices (D + R) and the relationship among the criteria (D - R) are obtained using the mathematical relationships described above.

Table 5. Values of Criterion Importance and Their Relationships

Risks	D + R	D - R
Supply and supplier risks	6.4	-0.54
Support and distribution risks	6.8	0.32
Organizational risks	5.7	0.15
Information system risks	6.03	0.35
Production and transmission risks	2.8	-0.07
External risks	6.6	-0.22

Step 3: Drawing the Fuzzy DEMATEL Diagram

The fuzzy DEMATEL diagram can now be plotted using the influence values and the total-effect values of the criteria.

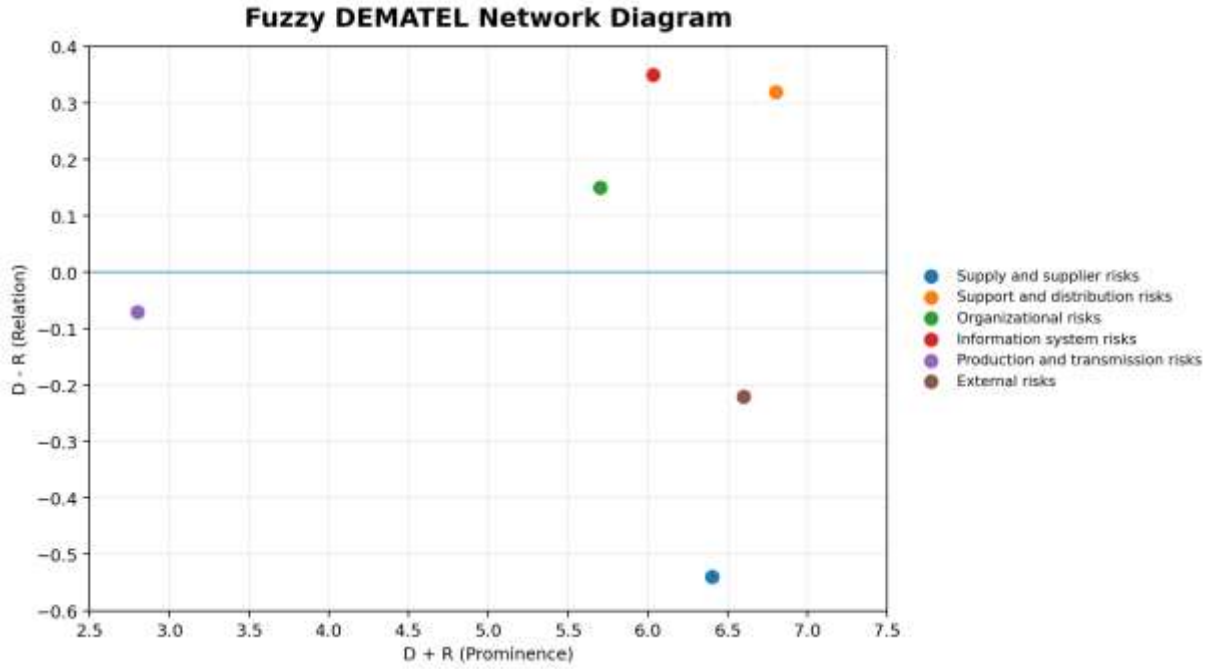


Figure 1. Fuzzy DEMATEL Network Diagram

Risks located above the horizontal axis, whose net effect is greater than zero, are classified as causal, driving, or influential criteria, whereas risks located below the horizontal axis are clustered as dependent criteria. In addition, the higher the criteria are positioned, the greater their degree of influence; the lower they are positioned, the greater their degree of dependence. Furthermore, the greater the total effect of a criterion (i.e., the farther to the right it is located in this diagram), the more important it becomes, because its combined influence and dependence is greater.

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4. Discussion and Conclusion

The findings of the present study provide a structured interpretation of sustainable supply chain risks in Ilam Gas Refining Company by combining fuzzy Delphi screening with fuzzy DEMATEL causal analysis. In the first stage, six risks were retained from the initial list of ten risks: supply and supplier risks, support and distribution risks, organizational risks, information-system risks, production and transmission risks, and external risks. The fuzzy Delphi results indicate that these six factors were regarded by experts as sufficiently important and contextually relevant to represent the principal sustainable supply chain risk dimensions of the company. This result supports the view that sustainable supply chain risk is multidimensional and cannot be reduced to a single operational or environmental concern. Previous studies have similarly emphasized that sustainability-related risk emerges from the interaction of sourcing, organizational, technological, logistical, environmental, and external dimensions rather than from isolated disruption factors (Warasthe et al., 2022; Xu et al., 2019). The identification of a limited number of locally significant risks is also consistent with the argument that supply chain risk assessment should be adapted to industry and organizational context rather than relying solely on generic risk taxonomies (Babazadeh Rafiei et al., 2023; Shafiei Nikabadi & Helalian, 2023).

Among the retained risks, support and distribution risks showed the highest overall importance in the fuzzy DEMATEL analysis, with the largest D+R value of 6.8 and a positive D−R value of 0.32. This finding indicates that support and distribution risks are both highly connected to the overall risk system and belong to the causal or influential group. In practical terms, disruptions in logistics support, maintenance services, distribution processes, transportation coordination, or downstream operational support may generate effects across several other parts of the supply chain. This result is compatible with the systemic nature of sustainable supply chain management, in which logistics and support activities often serve as connecting mechanisms between procurement, production, information flows, and final delivery. Studies on sustainable and reliable supply chain network design have similarly shown that transportation configuration, logistics reliability, and network continuity are central determinants of overall supply chain performance (Saffari et al., 2023). Likewise, research on sustainability-related risk management in multi-tier supply chains has highlighted that coordination failures across supply chain tiers can intensify disruptions and sustainability problems because risks propagate through interdependent actors and processes (Kähkönen et al., 2023).

The high importance of support and distribution risks can also be interpreted in light of the operational characteristics of the oil and gas industry. Gas refining operations depend on continuous logistical coordination, technical support, maintenance availability, equipment movement, spare-parts accessibility, and reliable distribution structures. A failure in any of these supporting functions may not remain confined to logistics but may influence production continuity, supplier responsiveness, and service reliability. This interpretation is consistent with prior evidence from the petrochemical industry, where supply chain risk management has been shown to reduce the disruptive effects that threaten flexibility, resilience, and financial performance (Dianati, 2023). Furthermore, Arab Cham Khalifeh and Alavi emphasized that effective supply chain resilience requires identifying risks that have strong interdependencies with other parts of the system and prioritizing them for managerial intervention (Arab Cham Khalifeh & Alavi, 2023). The present result therefore suggests that support and distribution should be treated not merely as downstream functions but as central causal components of sustainable supply chain stability.

External risks also demonstrated a high overall importance, with a D+R value of 6.6, although their D−R value was negative at −0.22, indicating that they belong to the effect group rather than the causal group. This is an important finding because it suggests that external risks are highly significant in the overall risk system but may be more influenced by the configuration and interaction of other factors than they are capable of independently driving the entire system. External risks may include regulatory pressures, market uncertainty, environmental constraints, macroeconomic instability, geopolitical conditions, or disruptions originating outside organizational boundaries. Their high prominence confirms that sustainable supply chains operate in open environments and are continuously exposed to changes beyond direct managerial control. Xu et al. emphasized that sustainability risks should be evaluated beyond firm-level boundaries because external environmental and institutional factors can substantially alter supply chain vulnerability (Xu et al., 2019). Similarly, Agyabeng-Mensah highlighted that sustainable supply chain performance is shaped by broader organizational and interorganizational mechanisms, indicating that external pressures may significantly condition the effectiveness of sustainability practices (Agyabeng-Mensah, 2025).

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The negative causal value of external risks may initially appear counterintuitive because external conditions are commonly considered major disruption sources. However, within the context of the present DEMATEL model, this finding can be interpreted as evidence that the consequences of external uncertainty become more severe when internal supply chain structures are insufficiently prepared to absorb them. In other words, external shocks may be unavoidable, but their realized impact depends on the resilience of internal support systems, information systems, organizational coordination, and supply mechanisms. This interpretation is consistent with the resilience literature, which emphasizes that supply chain performance during disruption depends not only on the presence of external threats but also on internal preparedness and adaptive capacity (Warasthe et al., 2022). The literature on healthcare and critical supply chains also demonstrates that external crises can expose pre-existing internal weaknesses and transform latent vulnerabilities into major operational failures (Babazadeh Rafiei et al., 2023; Yun & An, 2025). Therefore, the practical importance of external risks lies partly in strengthening internal capabilities that reduce the consequences of uncontrollable environmental disturbances.

Supply and supplier risks had a D+R value of 6.4, placing them among the most prominent risks in the model, but they had the most negative D−R value, −0.54. This means that supply and supplier risks are highly important but strongly dependent on the influence of other risk categories. This result suggests that problems related to supplier continuity, material availability, procurement delays, supplier reliability, or quality may represent downstream manifestations of broader organizational, informational, logistical, and external weaknesses. The finding is consistent with sustainable supply chain research showing that supplier-related risk is rarely independent and often results from interactions among sourcing strategy, uncertainty, transportation conditions, information visibility, and governance mechanisms. Nouri et al. demonstrated the importance of explicitly integrating supplier-related uncertainty into sustainable supply chain design because supplier performance is sensitive to multiple interconnected conditions (Nouri et al., 2019). Aqlan and Lam likewise showed that supply chain optimization under uncertainty requires simultaneous consideration of supplier and network-level risks rather than independent evaluation of sourcing factors (Aqlan & Lam, 2015).

The dependent position of supply and supplier risks may also indicate that supplier problems can be mitigated indirectly through improvements in internal decision-making and supply chain coordination. If organizational processes, information exchange, support systems, and distribution structures are strengthened, supplier-related disruptions may become easier to anticipate and manage. This interpretation is supported by multi-tier sustainability governance research emphasizing that supplier risk management requires visibility, coordination, and governance across several levels of the supply chain (Jamalnia et al., 2023; Kähkönen et al., 2023). Supplier reliability is therefore not simply a property of the supplier itself but also a function of relationship management, information quality, contracting practices, risk-sharing mechanisms, and the focal firm's capacity to respond to disruption. This is particularly relevant in the oil and gas context, where specialized equipment and technical inputs may be sourced from limited supplier bases, increasing dependency on effective coordination mechanisms.

Information-system risks showed a D+R value of 6.03 and a positive D−R value of 0.35. Among the six risks, information-system risk had the largest positive causal value, indicating that it represents the strongest causal driver in the model. This is one of the most important findings of the study. It implies that weaknesses in information infrastructure, data quality, system integration, communication accuracy, digital coordination, or information accessibility may trigger or intensify multiple other supply chain risks. Modern supply chains rely heavily on information for procurement planning, inventory control, supplier coordination, maintenance scheduling, production management, transportation, and disruption response. Therefore, inaccurate, delayed, fragmented, or inaccessible information can create cascading effects throughout the entire supply chain. Gholizadeh et al. similarly demonstrated that risks in sustainable information technology supply chains are interactive and systemic rather than independent, and that information-related vulnerabilities may influence broader organizational outcomes (Gholizadeh et al., 2020).

The causal role of information-system risks is also consistent with contemporary sustainable supply chain modeling, which treats supply chains as dynamic systems involving feedback loops, delayed information, and interdependent decision structures (Kurniasih, 2025). When information systems function effectively, they improve transparency, facilitate early risk detection, support coordination, and enable faster response to disruptions. Conversely, poor information visibility may amplify uncertainty across supplier relationships, production planning, logistics, and external risk response. The present finding also

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complements Jamalnia et al., who emphasized the importance of decision-support systems in sustainability governance and multi-tier supply chain risk management (Jamalnia et al., 2023). In this respect, strengthening information infrastructure may have disproportionate benefits because it can reduce multiple downstream risks simultaneously.

Organizational risks had a D+R value of 5.7 and a positive D−R value of 0.15, indicating that they belong to the causal group but have lower overall prominence than support and distribution, external, supply, and information-system risks. Their positive causal position nevertheless shows that organizational factors can influence other supply chain risks. Organizational risk may include deficiencies in managerial coordination, strategic alignment, workforce competence, decision-making procedures, interdepartmental cooperation, risk culture, governance structures, or resource allocation. These internal characteristics determine how effectively an organization can anticipate disruptions and coordinate responses. Previous research has emphasized that sustainable supply chain outcomes depend on organizational practices and management mechanisms rather than on technical interventions alone (Agyabeng-Mensah, 2025). Research on pharmaceutical supply chains has similarly demonstrated that management-related and organizational factors are important determinants of sustainable supply chain performance (Shah Bahrami et al., 2020).

The causal classification of organizational risk suggests that weaknesses in internal governance can create secondary vulnerabilities in information systems, procurement, logistics, and operational response. Organizations with fragmented structures or weak cross-functional coordination may fail to identify risk signals early or may respond slowly when disruption occurs. This interpretation is consistent with resilience-oriented research, which stresses that risk management requires coordinated organizational structures capable of translating information into timely action (Arab Cham Khalifeh & Alavi, 2023). Organizational capacity therefore acts as an enabling condition for the effectiveness of other risk-management mechanisms. Even when technological and logistical resources are available, poor managerial coordination may prevent their effective use.

Production and transmission risks had the lowest D+R value, 2.8, and a slightly negative D−R value of −0.07. This result indicates that production and transmission risks had the lowest overall prominence in the network and were classified as dependent rather than causal. Although production and transmission are central operational activities in gas refining, the findings suggest that their risks may largely reflect problems generated elsewhere in the system. For example, production interruptions may result from supplier delays, information failures, inadequate organizational coordination, insufficient maintenance support, or external disturbances. Thus, production risk may be more accurately interpreted as an outcome of upstream causal factors than as an independent root cause. This result aligns with systems-oriented supply chain research, which emphasizes that operational disruptions often arise through interactions among sourcing, logistics, information, and uncertainty rather than solely from production processes themselves (Aqlan & Lam, 2015; Zhang et al., 2014).

The comparatively low prominence of production and transmission risks should not be interpreted as evidence that they are unimportant. Rather, the DEMATEL results indicate that they are less structurally influential within the identified risk network. This distinction between importance and causality is critical. A risk can have serious consequences even if it is not a major causal driver. The value of the DEMATEL approach lies precisely in revealing this difference. Production and transmission risks may require direct operational controls, but sustainable risk reduction may be more effectively achieved by addressing the causal factors that precede them, especially information-system, support and distribution, and organizational risks. This interpretation is compatible with sustainable supply chain optimization studies showing that improvements in one operational dimension are most effective when coordinated with procurement, logistics, and network-level decision-making (Saffari et al., 2023; Zhang et al., 2014).

Taken together, the causal structure of the findings indicates that information-system risks, support and distribution risks, and organizational risks constitute the primary causal group, whereas supply and supplier risks, production and transmission risks, and external risks belong to the dependent group. This classification provides a more informative basis for managerial prioritization than simple ranking alone. It suggests that the company should focus first on causal risks because improvements in these areas may indirectly reduce the intensity of several dependent risks. This conclusion is consistent with the broader literature emphasizing integrated, system-level risk management in sustainable supply chains (Kähkönen et al., 2023; Xu et al., 2019). It also supports the view that resilience is strengthened when organizations identify structural drivers of disruption

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rather than reacting only to visible consequences (Warasthe et al., 2022). The findings therefore extend previous research by demonstrating how fuzzy Delphi screening and fuzzy DEMATEL causal analysis can be combined to distinguish between prominent risks and root-level causal risks in an oil and gas supply chain.

This study has several limitations that should be considered when interpreting the findings. First, the empirical analysis was conducted within a single organization, Ilam Gas Refining Company, and therefore the identified risk structure reflects the operational, organizational, and environmental characteristics of this specific context. Second, the fuzzy Delphi and fuzzy DEMATEL analyses relied on the judgments of a limited group of organizational experts, which means that the results may be influenced by professional experience, subjective interpretation, and organizational perspectives. Third, the study focused on a predefined set of risk categories derived from the literature and expert assessment, and emerging risks that were not included in the initial framework may therefore have been excluded. Fourth, DEMATEL represents perceived causal relationships at a particular point in time and does not directly capture temporal changes in risk relationships. Finally, the study evaluated interrelationships among risk categories but did not quantify the financial, environmental, social, or operational consequences of each risk in objective performance units.

Future research can extend the present study by applying the proposed framework across multiple refineries, petrochemical companies, or other energy-sector organizations and comparing the resulting causal structures. Longitudinal research could also examine whether the importance and causal position of risks change under different market, regulatory, technological, or geopolitical conditions. Future studies may integrate fuzzy DEMATEL with methods such as ANP, BWM, ISM, MICMAC, system dynamics, Bayesian networks, or structural equation modeling to provide complementary perspectives on dependency, feedback, and predictive relationships. Researchers may also incorporate objective operational indicators, historical disruption data, financial loss estimates, environmental performance measures, and supplier performance records alongside expert judgments. Another useful direction would be to investigate emerging risks associated with cybersecurity, digital transformation, artificial intelligence, climate-related regulation, geopolitical sanctions, and energy-transition pressures. Comparative research across upstream, midstream, and downstream segments could further clarify whether the causal structure of sustainable supply chain risk differs across different parts of the oil and gas value chain.

From a practical perspective, managers should prioritize risk-mitigation initiatives according to causal influence rather than focusing only on risks with visible operational consequences. Particular attention should be given to strengthening information-system reliability, data integration, real-time visibility, communication accuracy, and digital continuity because information-system risks emerged as the strongest causal factor. Support and distribution processes should also be reinforced through logistics contingency planning, maintenance readiness, transportation redundancy, and stronger coordination with service providers. Organizational risk can be reduced by clarifying responsibilities, improving cross-functional coordination, institutionalizing risk-management procedures, and developing a stronger risk-aware culture. Because supply and supplier risks were highly prominent but dependent, supplier diversification, supplier monitoring, strategic inventory policies, and alternative sourcing should be supported by improved information and organizational capabilities. Production and transmission risks should be managed through preventive maintenance, contingency capacity, and operational redundancy, while external risks should be addressed through scenario planning, early-warning systems, regulatory monitoring, and emergency response protocols. Overall, managers should use the causal network as a prioritization map so that investments are directed toward risk drivers capable of reducing multiple downstream vulnerabilities simultaneously.

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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