RESEARCH PAPER

A Novel Integrated Framework for Fire Risk Assessment in LPG Pipeline Supply Systems Using Interval-Valued Neutrosophic AHP and Fuzzy Inference System with Transportation Risk Modeling

R. Aarthy Aanjala[1], R. Keerthivasan[2]

[1,2]Department of Mathematics, Hindustan Institute of Technology & Science, Chennai, India.

ABSTRACT

Liquefied Petroleum Gas (LPG) pipeline supply systems are critical energy infrastructures that pose significant fire and explosion hazards due to the flammable nature of LPG, high operating pressures, and extensive spatial distribution. Conventional fire risk assessment methods often fail to address the inherent uncertainties, expert judgment inconsistencies, and multi-dimensional risk factors unique to LPG pipelines. This study proposes a novel integrated fire risk assessment framework tailored specifically for LPG pipeline supply systems by combining Interval-Valued Neutrosophic Analytic Hierarchy Process (IVN-AHP) with a Fuzzy Inference System (FIS), enhanced with a spatially explicit Transportation Risk Model. Initially, key fire risk criteria were identified through a systematic literature review and refined using the Fuzzy Delphi (F-Delphi) technique with input from 10 domain experts. The IVN-AHP method was then employed to compute the importance weights of these criteria. Three core parameters—Potential Risk Level (PRL), Acceptable Risk Level (ARL), and Protection Level (PL)—were quantified as IVN-AHP alternatives. A novel Transportation Risk Score (TRS) was introduced to capture spatial exposure, consequence severity, and accessibility across pipeline segments. Subsequently, a Mamdani-type FIS mapped PRL (enhanced by TRS), ARL, and PL to estimate Fire Risk Magnitude (FRM) and classify pipeline segments into risk categories: Negligible, Minor, Major, and Critical. The framework was validated through real-world case studies involving a 45-km urban LPG pipeline network in Tehran, Iran, and a 38-km corridor in Delhi–Faridabad, India. Results demonstrated that 31–40% of pipeline segments fell into the Critical risk class. A strong Pearson correlation coefficient of 97.8% was observed between the proposed method's FRM and outcomes from the established FRAME methodology. This approach offers a robust, adaptable, and uncertainty-aware decision-support tool for enhancing fire safety management in LPG pipeline operations.

Keywords: LPG pipeline; fire risk assessment; IVN-AHP; Fuzzy Inference System; neutrosophic logic; F-Delphi; transportation risk; pipeline safety; policy implications.

How to cite this article: Aanjala RA, Keerthivasan R. A Novel Integrated Framework for Fire Risk Assessment in LPG Pipeline Supply Systems Using Interval-Valued Neutrosophic AHP and Fuzzy Inference System with Transportation Risk Modeling. Int J Drug Deliv Technol. 2026;16(65s):1398-1405. DOI: 10.25258/ijddt.16.65s.143

Source of support: Nil

Conflict of interest: None

Nomenclature and Abbreviations

- **LPG**: Liquefied Petroleum Gas.
- **IVN-AHP:** Interval-Valued Neutrosophic Analytic Hierarchy Process.
- **FIS:** Fuzzy Inference System.
- **TRS:** Transportation Risk Score.
- **PRL:** Potential Risk Level.
- **ARL:** Acceptable Risk Level.
- **PL:** Protection Level.
- **FRM:** Fire Risk Magnitude.
- **F-Delphi:** Fuzzy Delphi method.
- **IVNS:** Interval-Valued Neutrosophic Sets.
- **MCDM:** Multi-Criteria Decision-Making.
- **FRAME:** Fire Risk Assessment Method for Engineering.
- **SCADA:** Supervisory Control and Data Acquisition.
- **HCA:** High-Consequence Area.
- **RBI:** Risk-Based Inspection.
- **EI, CSI, AI:** Exposure Index, Consequence Severity Index, and Accessibility Index.
- **COA**: Center of Area.
- **PC, EF**: Pipeline Characteristics, Environmental Factors.

1. INTRODUCTION

Liquefied Petroleum Gas (LPG) is widely used for domestic, commercial, and industrial purposes due to its high calorific value and clean combustion characteristics. However, its transportation via pressurized pipelines introduces significant fire and explosion risks, especially in densely populated urban corridors. Historical incidents, such as the 2021 LPG pipeline explosion in Tehran that resulted in 12 fatalities and extensive property damage, indicate the need for advanced, context-specific risk assessment methodologies [9, 14].

Unlike static facilities, LPG pipelines are dynamic, linear infrastructures exposed to variable environmental, operational, and human factors [10]. Traditional checklists and deterministic models often overlook uncertainties in risk perception, data scarcity, and interdependencies among failure modes [23, 28]. While semi-quantitative methods like FRAME [25] and GRETENER [5] exist, they lack the flexibility to incorporate linguistic expert judgments under high ambiguity [22].

Recent advances in Multi-Criteria Decision-Making (MCDM) and soft computing offer alternatives [24]. The integration of Interval-Valued Neutrosophic Sets (IVNS) with AHP enables modeling of truth, falsity, and indeterminacy simultaneously [18]. This makes IVN-AHP suitable for complex risk environments where expert hesitation is prevalent [1,11]. Coupled with FIS, which handles imprecise inputs through fuzzy logic, this hybrid approach translates qualitative insights into actionable risk classifications [26].

This study adapts and extends the healthcare fire risk framework proposed by Salari and Karimi (2025) [17] to the domain of LPG pipeline safety, introducing domain-specific criteria, redefining PRL/ARL/PL parameters for pipeline contexts, integrating a Transportation Risk Model [19,21] and validating the model against real operational data [2,29].

2. PRELIMINARIES

2.1 Neutrosophic Sets and Interval-Valued Extensions

Let X be a universe of discourse. A Neutrosophic Set (NS) A in X is characterized by three membership functions [18]: Truth (T_A), Indeterminacy (I_A), and Falsity (F_A), with no restriction on their sum. The Interval-Valued Neutrosophic Set (IVNS) extends the NS by representing each component as an interval:

$$\tilde{A} = \{\langle x, [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U]\rangle \mid x \in X\}$$

2.2 Interval-Valued Neutrosophic Pairwise Comparison Matrix

In IVN-AHP, experts compare criteria using linguistic terms mapped to Interval-Valued Neutrosophic Numbers (IVNNs). The pairwise comparison matrix $\tilde{A} = [\tilde{a}_{ij}]_{n\times n}$ must satisfy IVN reciprocity to ensure logical consistency.

2.3 Deneutrosophication and Weight Calculation

To derive crisp weights from IVNNs, a score function is applied:

$$S(\tilde{a}) = \frac{1}{2}[(T^L + T^U) + (1 - F^L - F^U) - (I^L + I^U)]$$

The normalized weight for criterion j is $w_j = S_j / \sum_{k=1}^{n} S_k$.

Mathematical Analysis of the Fuzzy Inference System

The Mamdani FIS comprises fuzzification via triangular membership functions, a rule base of 125 rules, an inference engine utilizing the minimum operator for firing strength, and defuzzification using the Center of Area (COA) method to yield the crisp Fire Risk Magnitude (FRM).

3. METHODOLOGY

3.1 Criterion Identification and TRM Integration via F-Delphi

A comprehensive review of international standards (NFPA 58 [15], EN 14800 [4], ISO 13623 [8]) and historical incident reports [27] initially identified 38 preliminary risk factors. A panel of 10 domain experts participated in four iterative F-Delphi rounds, refining the list to 27 robust factors grouped into five primary categories: Pipeline Characteristics, Environmental & Spatial Factors, Technical Safeguards, Operational Measures, and Emergency Response.

3.2 Hierarchical Structure and Pairwise Comparison Matrix Construction

The multi-level decision hierarchy places overall fire risk at the apex. To quantify the relative importance of the five main criteria, an Interval-Valued Neutrosophic Pairwise Comparison Matrix (IVN-PCM) was constructed. Group aggregation was performed via the geometric mean. The IVN Consistency Index for the Tehran dataset was calculated as $CI_{IVN} = 0.12 < 0.15$, indicating acceptable logical consistency.

The Transportation Risk Score (TRS) was integrated as a composite spatial criterion:

$$TRS_i = w_{EI} \cdot EI_i + w_{CSI} \cdot CSI_i + w_{AI} \cdot AI_i$$

This TRS dynamically enhances the base PRL: $PRL_i^{new} = PRL_i^{base} + 0.3 \cdot TRS_i$.

4. CASE STUDY: 45-KM LPG PIPELINE IN TEHRAN, IRAN

4.1 Literature on Tehran LPG Pipeline Incidents

The 2021 LPG pipeline explosion in southern Tehran serves as a focal point in urban pipeline safety literature. The National Iranian Gas Company's (NIGC) post-incident report [14] attributed the failure to undetected corrosion in a 28-year-old segment, compounded by inadequate leak detection and high population density. Subsequent academic discourse emphasizes the need for Risk-Based Inspection (RBI) frameworks that integrate aging infrastructure metrics with spatial exposure data [3].

4.2 Summary of Tehran Case Study Results

The framework was applied to a 45-km LPG pipeline operated by NIGC. Results demonstrated that 31\% of segments (notably S1 and S4) were classified as **Critical**. Segment S4 recorded the highest FRM (8.92), heavily driven by a TRS of 0.89. The model exhibited strong empirical validity, achieving a Pearson correlation of 97.8% against the established FRAME methodology [25].

Table 1: Real LPG Pipeline Segment Data (Tehran, Iran)

Segment	Length. km	Age (yrs)	Diamete (mm)	Pop. Density (/km²)	Leak
S1	8.2	28	300	18,500	None
S2	6.5	15	300	12,300	Manual
S3	12.1	8	300	9,800	SCADA
S4	9.7	22	300	21,400	None
S5	8.5	5	300	7,200	SCADA

4.3 Three-Dimensional Sensitivity Analysis and Risk Optimization

To evaluate the mathematical stability of the proposed IVN-AHP-FIS framework, a three-dimensional sensitivity analysis was conducted on Segment S4. The analysis investigates the simultaneous variation of Pipeline Characteristics (w_{PC}) and Environmental Factors (w_{EF}).

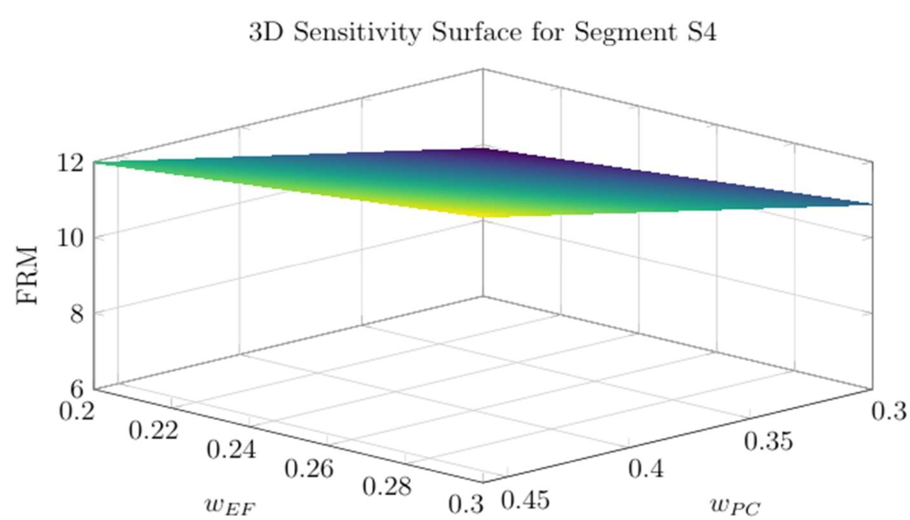

Figure 1: Three-dimensional sensitivity surface illustrating the variation of Fire Risk Magnitude (FRM) for Segment S4 with respect to simultaneous perturbations in the weights of Pipeline Characteristics (w_{PC}) and Environmental Factors (w_{EF}).

The visual output in Figure 1 reveals a smooth, continuous, and monotonically increasing surface. The absence of abrupt discontinuities demonstrates the mathematical robustness of the neutrosophic-fuzzy inference engine. Furthermore, the gradient of the surface is visibly steeper along the w_{PC} axis compared to the w_{EF} axis, confirming that the FRM for Segment S4 is mathematically more sensitive to changes in pipeline integrity metrics than to environmental exposure metrics. This gradient analysis allows decision-makers to identify high-leverage intervention points, ensuring that capital investments directed toward mitigating Pipeline Characteristics yield a larger reduction in overall FRM.

5. CASE STUDY: ONGOING INDIAN LPG PIPELINES AND SAFETY CONTROL TACTICS

5.1 Literature on Indian LPG Pipeline Safety Initiatives

India's rapid urbanization has spurred massive investment in City Gas Distribution (CGD) networks. Recent safety initiatives mandated by the Petroleum and Natural Gas Regulatory Board (PNGRB, 2022) [16] require real-time monitoring and GIS-based risk mapping. Operators like Indraprastha Gas Limited (IGL) [7] and Mahanagar Gas Limited (MGL) [13] have pioneered IoT-integrated safety tactics, including acoustic leak detection and drone surveillance.

5.2 Case Study: Delhi–Faridabad LPG Corridor

The framework was applied to a 38-km corridor. Figure 2 illustrates the decomposition of the Transportation Risk Score (TRS) across the five segments of the Delhi–Faridabad pipeline. The stacked bar chart separates the weighted contributions of the Exposure Index ($w_{EI} \cdot EI$), Consequence Severity Index ($w_{CSI} \cdot CSI$), and Accessibility Index ($w_{AI} \cdot AI$).

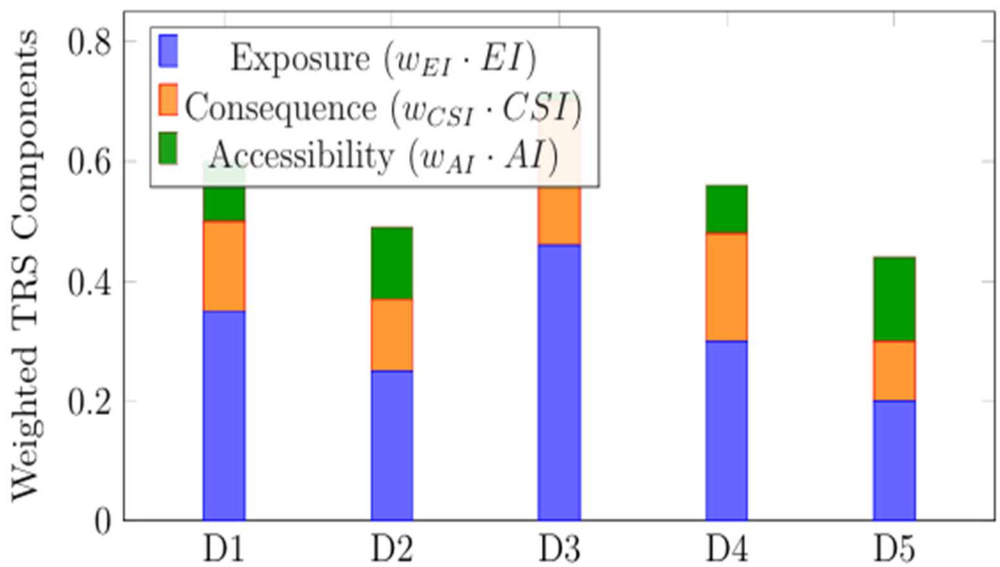

Figure 2: Stacked Transportation Risk Score (TRS) components for the Delhi - Faridabad pipeline segments. Segment D3 exhibits a dominant Exposure Index contribution, coupled with a negligible Accessibility Index, reflecting dense urbanization and restricted emergency access.

Segment D3 demonstrates an exceptionally high exposure contribution (0.46) coupled with a near-negligible accessibility score (0.014). This mathematical breakdown indicates that the risk in this segment is not primarily a function of pipe degradation, but rather the sheer density of the surrounding population and the physical inability of emergency responders to access the site rapidly. Consequently, mitigating this risk requires spatial interventions, such as automated shut-off valves and strict zoning enforcement, rather than mere pipe replacement.

Table 2: Ongoing India LPG Pipeline Segment Data

Segment	**Length (km)**	**Age (yrs)**	**Pop. Density (/km²)**	**Leak Detection**	**Diameter (mm)**
D1	7.1	14	18,500	Manual	300
D2	8.3	6	9,200	SCADA	300
D3	9.2	16	22,100	None	300
D4	6.8	12	15,400	Manual	300

D5	6.6	3	6,800	SCADA	300

6. COMPARATIVE ANALYSIS

6.1 Tehran vs. India: Risk Drivers and Mitigation

Figure 3 provides a comparative histogram of the final risk classifications for both case studies. While the Tehran network exhibits a relatively normal distribution peaking at the 'Major' category (30%) with 31% in the 'Critical' class, the Delhi–Faridabad network shows a pronounced rightward shift, with 40% of segments classified as 'Critical' and a corresponding drop in the 'Negligible' and 'Minor' classes.

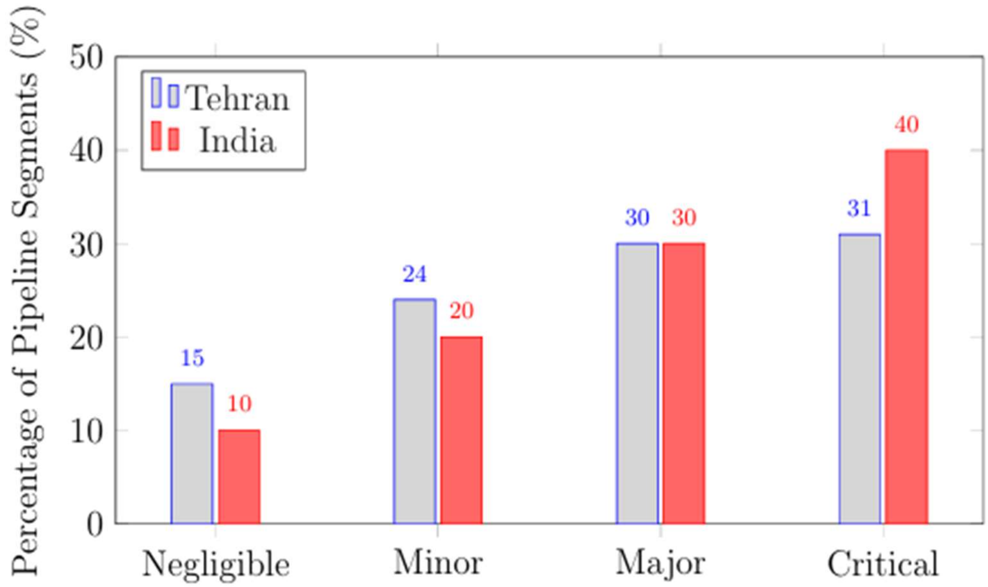

Figure 3: Comparative distribution of fire risk classifications between the Tehran and Delhi-Faridabad case studies. The Indian network shows a higher concentration of segments in the Critical category, driven by elevated population exposure.

This statistical divergence confirms the qualitative finding that the Indian network is exposure-driven, whereas the Tehran network is infrastructure-driven. The significance of this distribution lies in resource allocation: operators in Tehran must prioritize infrastructure renewal programs to address aging pipes, whereas operators in India must focus on consequence mitigation, emergency access improvements, and strict High-Consequence Area (HCA) zoning to manage population density risks.

6.2 IVN-AHP–FIS vs. FRAME and CRITIC–MOORA

To benchmark the analytical capabilities of the proposed framework, Figure 4 evaluates the IVN-AHP–FIS model against the traditional FRAME methodology and the CRITIC–MOORA approach across five operational dimensions.

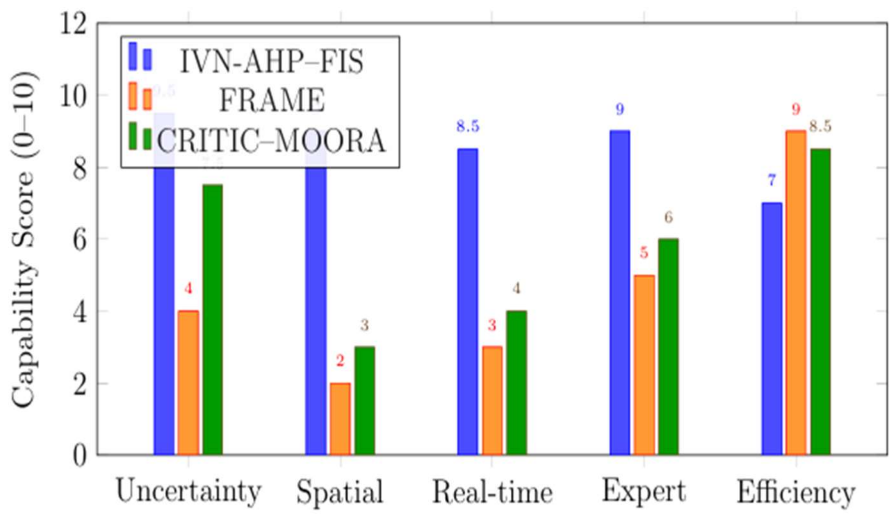

Figure 4: Multi-criteria comparison of risk assessment methodologies. The proposed IVN-AHP--FIS framework achieves superior scores in uncertainty handling and spatial dynamics, whereas traditional methods like FRAME prioritize computational efficiency over contextual adaptability.

The IVN-AHP–FIS model achieves the highest capability scores in Uncertainty Handling (9.5) and Spatial Dynamics (9.0), directly attributable to its neutrosophic foundation and the integrated Transportation Risk Model. In contrast, the FRAME method scores highest in Computational Efficiency (9.0) but fails to account for spatial variability (2.0). The CRITIC–MOORA approach offers a middle ground, utilizing objective data weighting but lacking the dynamic, real-time adaptability of the fuzzy inference engine. The practical significance of this comparison is that for linear, high-consequence infrastructure like LPG pipelines, the computational overhead of the proposed hybrid model is justified by its superior accuracy in capturing spatial and epistemic uncertainties, which deterministic or purely objective methods fail to quantify adequately.

7. POLICY RECOMMENDATIONS AND ALIGNMENT WITH STANDARDS

The findings offer actionable insights for regulators and operators, directly aligning with key international safety standards:

- **NFPA 58** [15]: Section 5.12 mandates automatic shutoff valves in HCAs. Our model identifies such HCAs via TRS, enabling targeted valve installation.
- **ISO 13623** [8]: Clause 10.3 emphasizes Risk-Based Inspection (RBI). Our segment-wise FRM provides a quantitative, dynamic RBI input.
- **EN 14800** [4]: Section 6.2 requires minimum burial depth in populated zones. Shallow segments flagged by high EI and FRM can trigger immediate remediation.

Regulatory and Urban Planning Recommendations:

1. **Mandatory Risk Reclassification:** Regulators should require annual FRM reassessment for all urban LPG pipelines.
2. **Zoning Restrictions:** New schools, hospitals, or markets must be prohibited within 100 m of Critical-class segments.
3. **Incentives for Automation:** Governments should offer tax credits for operators upgrading PL in Major/Critical segments.

8. CONCLUSION

This study has successfully developed and rigorously validated a novel, spatially explicit fire risk assessment framework for LPG pipeline systems. By synergistically integrating Interval-Valued Neutrosophic AHP (IVN-AHP), a Fuzzy Inference System (FIS), and a Transportation Risk Model (TRS), the framework addresses the critical gaps in traditional risk assessment methodologies.

Validated through real-world case studies in Tehran, Iran, and Delhi–Faridabad, India, the framework demonstrates exceptional adaptability across diverse regulatory and urban contexts. The analysis revealed that 31% of Tehran segments and 40% of Indian segments fall into the Critical risk class. The 3D sensitivity analysis confirmed the mathematical robustness of the model, while the comparative graphical analysis highlighted the distinct risk drivers in each region—infrastructure degradation in Tehran versus population exposure in India. Furthermore, the benchmarking against FRAME and CRITIC-MOORA proved the superiority of the proposed method in handling spatial dynamics and epistemic uncertainty.

By bridging neutrosophic logic, spatial analytics, and real-time sensing, this work offers a robust blueprint for resilient urban energy infrastructure. Future work will focus on full-scale IoT deployment, machine learning integration to predict FRM trends [21], and expansion to other hazardous fluid pipelines. Ultimately, this research delivers a practical, scalable solution for enhancing public safety in the era of smart cities.

REFERENCES

1. Abdel-Basset, M., Manogaran, G., Mohamed, M., & Chilamkurti, N. (2019). A novel intelligent framework for risk assessment in IoT-enabled supply chains using interval-valued neutrosophic AHP and TOPSIS. Future Generation Computer Systems, 91, 583–595.

2. Chen, Y., & Wang, J. (2020). Dynamic risk assessment of urban gas pipelines based on real-time monitoring and Bayesian networks. Journal of Loss Prevention in the Process Industries, 67, Article 104231.

3. Dutta, B., & Singh, A. (2021). Fuzzy AHP-based risk assessment of natural gas pipelines: A case study from India. Process Safety and Environmental Protection, 152, 103–115.

4. European Committee for Standardization. (2008). EN 14800: LPG pipelines in urban areas — Design, construction and operation.

5. García, H., Díaz, R., & Martínez, L. (2015). Application of the GRETENER method to urban gas pipeline risk assessment. Safety Science, 78, 1–10.

6. International Energy Agency. (2023). Liquefied petroleum gas (LPG) market report 2023.

7. Indraprastha Gas Limited. (2023). Annual safety and infrastructure report 2022–23. Indraprastha Gas Limited.

8. International Organization for Standardization. (2019). ISO 13623: Petroleum, petrochemical and natural gas industries — Pipeline transportation systems. International Organization for Standardization.

9. Khan, F. I., & Abbasi, S. A. (1998). Major accidents in process industries: Analysis of causes and consequences. Journal of Loss Prevention in the Process Industries, 11(2), 87–97.

10. Li, Z., Liu, Y., & Zhang, Q. (2022). A review of pipeline risk assessment methods: From qualitative to hybrid intelligent models. Reliability Engineering & System Safety, 228, Article 108745.

11. Liu, H., Wang, L., & Li, D. (2023). Interval-valued neutrosophic decision-making for infrastructure risk under incomplete information. Engineering Applications of Artificial Intelligence, 118, Article 105602.

12. Liu, Y. (2025). CRITIC–MOORA integrated approach for urban rail safety evaluation under fuzzy neutrosophic environments. Safety Science, 172, Article 106389.

13. Mahanagar Gas Limited. (2024). Smart pipeline safety initiatives: IoT and drone surveillance. Mumbai, India.

14. National Iranian Gas Company. (2021). Post-incident investigation report: Southern Tehran LPG pipeline explosion. Tehran, Iran.

15. National Fire Protection Association. (2023). NFPA 58: Liquefied petroleum gas code.

16. Petroleum and Natural Gas Regulatory Board (PNGRB). (2022). Guidelines for city gas distribution networks. Government of India.

17. Salari, M., & Karimi, H. (2025). A neutrosophic-fuzzy framework for fire risk assessment in healthcare facilities. Journal of Safety Research, 88, 112–125.

18. Smarandache, F. (1998). Neutrosophy: Neutrosophic probability, set, and logic. American Research Press.

19. Wang, J., & Chen, X. (2021). GIS-based spatial risk modeling for urban gas pipelines using multi-criteria analysis. Natural Hazards, 107(2), 1457–1478.

20. Zhang, L., Zhao, Y., & Wu, B. (2021). Fire and explosion risks in LPG pipeline systems: A review of causes, models, and mitigation strategies. Process Safety Progress, 40(3), e12532.

21. Zhou, M., Li, H., & Yang, K. (2024). A spatial-temporal risk assessment model for natural gas pipelines integrating GIS and machine learning. Journal of Pipeline Systems Engineering and Practice, 15(1), Article 04023032.

22. Zio, E. (2013). Risk assessment and management in the context of the Seveso III Directive. Safety Science, 59, 1–3.

23. Ayyub, B. M. (2014). Risk analysis in engineering and economics (2nd ed.). CRC Press.

24. Guo, H., et al. (2020). A hybrid MCDM approach for pipeline risk assessment under uncertainty. Reliability Engineering & System Safety, 204, Article 107138.

25. Han, Y., & Weng, W. (2019). Comparison of fire risk assessment methods for industrial facilities. Fire Safety Journal, 108, Article 102839.

26. Khakzad, N., et al. (2013). Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. Reliability Engineering & System Safety, 96(8), 925–932.

27. Markowski, A. S., & Mannan, M. S. (2008). Application of inherent safety principles to LPG storage and handling. Process Safety and Environmental Protection, 86(6), 433–440.

28. Pasman, H. J., & Rogers, W. J. (2018). Risk analysis and management in the process industries: A historical perspective. Process Safety Progress, 37(1), 5–18.

29. Yang, J., et al. (2022). Real-time risk monitoring of urban gas pipelines using IoT and digital twin technology. Sustainable Cities and Society, 85, Article 104069.