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Environmental Risk Assessment of Petrochemical Complexes Using a Fuzzy Systematic Analysis Approach

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Abstract

Petrochemical complexes play a pivotal role in industrial economies but present substantial environmental risks, including pollution of air, water, and soil, as well as ecological disturbances. This study applied fuzzy failure mode and effects analysis (FMEA) to perform an environmental risk assessment (ERA) of petrochemical operations. By incorporating fuzzy logic into the conventional FMEA framework, the approach effectively quantifies key risk dimensions—occurrence, severity, and detectability—using linguistic variables to reduce ambiguity. The data were obtained from operational records, environmental monitoring systems, and expert consultations to assess and prioritize risks. The main findings revealed several high-risk failure modes. It was concluded that major equipment leaks pose significant risks to soil and water, with a fuzzy risk priority number (RPN) of 0.778, necessitating measures such as advanced leak detection systems and regular maintenance. Toxic gas releases, impacting air quality, exhibited an RPN of 0.700, warranting enhanced gas monitoring and emergency response protocols. Based on the results, wastewater discharge non-compliance, with an RPN of 0.620, contributes substantially to water pollution, calling for upgraded treatment systems and stricter monitoring. The results demonstrated that water pollution accounts for the highest environmental impact (36.4%), followed by soil (31.8%) and air pollution (27.3%). Noise pollution was the least significant risk (4.5%). Mitigation strategies include advanced monitoring technologies, improved maintenance schedules, and targeted safety protocols. This study highlights fuzzy FMEA's ability to enhance risk management in complex industrial systems and recommends its broader implementation to address environmental challenges in petrochemical operations.

Keywords: Environmental risk assessment, Fuzzy logic, FMEA, Lorestan petrochemical complex

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1. Introduction

The rapid advancement of industrialization has undoubtedly fueled economic growth and technological progress, although it has brought about significant environmental challenges (1). Among the most notable industrial sectors, the petrochemical industry stands out due to its extensive impact on both the environment and human health (2). Petrochemical factories, which produce essential chemicals and materials used across various industries, are often associated with the release of hazardous substances, greenhouse gases, and other pollutants (3). Consequently, understanding and mitigating the environmental risks associated with these facilities are of paramount importance. Environmental risk assessment (ERA) serves as a critical tool in evaluating the potential adverse effects that petrochemical factories may have on the environment. This systematic process involves identifying, analyzing, and quantifying the environmental hazards posed by the operations of such facilities (4). By assessing these risks, stakeholders can develop strategies to manage and mitigate adverse impacts, ensuring regulatory compliance and promoting sustainable practices. ERA is crucial for petrochemical factories due to their substantial environmental and public health implications (5). By systematically identifying and mitigating potential hazards, ERA ensures compliance with stringent national and international environmental regulations, which is essential for maintaining operational permits and avoiding legal penalties. This process not only protects air, water, and soil quality but also safeguards biodiversity and ecosystem services (6). Effective risk management through ERA prevents environmental disasters and minimizes the health risks posed to nearby communities by hazardous emissions, thus preventing respiratory illnesses, cardiovascular diseases, and other health problems associated with pollution (7).

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Furthermore, ERA promotes sustainable industrial practices by encouraging the adoption of cleaner technologies, efficient resource use, and effective waste management strategies (8). These sustainable practices enhance the long-term viability of the petrochemical industry by ensuring resource availability for future generations and contributing to global environmental goals, such as those outlined in the Paris Agreement (9). Demonstrating a commitment to environmental stewardship through rigorous ERA processes also builds trust with stakeholders, enhances corporate reputation, and provides a competitive market advantage (10). In essence, ERA not only helps petrochemical companies avoid costly environmental damage and health issues but also drives innovation, fosters economic benefits, and aligns the industry with global sustainability efforts. The ERA of petrochemical factories employs various methods to systematically evaluate and manage potential environmental hazards (10-14). Among these, qualitative methods, such as checklists and expert judgment, offer a straightforward approach to identifying potential risks based on historical data and expert opinions (15). Quantitative methods, including statistical analysis and mathematical modeling, provide detailed numerical insights into the likelihood and impact of specific hazards by analyzing data on emissions, exposure levels, and environmental impacts (16). Semi-quantitative methods, such as failure modes and effects analysis (FMEA), use a combination of qualitative and quantitative techniques to assess risk by evaluating the severity, likelihood, and detectability of potential failure modes (17). Scenario analysis explores the potential outcomes of various environmental incidents under different conditions, helping to understand the broader implications of risk events. Additionally, fuzzy logic methods, such as fuzzy FMEA, address uncertainties in risk assessments by translating qualitative evaluations into fuzzy sets, allowing for a more nuanced risk prioritization (18). The fuzzy FMEA method enhances ERA for petrochemical factories by integrating traditional FMEA with fuzzy logic to handle the uncertainties and complexities associated with environmental hazards. In fuzzy FMEA, potential failure modes—such as chemical leaks or equipment malfunctions—are identified, and their effects on the environment are evaluated (14). Unlike traditional FMEA, which uses precise numerical ratings for severity, occurrence, and detection, fuzzy FMEA employs fuzzy logic to assess these factors, allowing for more nuanced and flexible risk prioritization (18). This approach translates qualitative assessments into fuzzy sets, which are then processed to determine a risk priority number (RPN) that more accurately reflects real-world uncertainties. By accommodating vagueness and subjectivity in expert judgments, fuzzy FMEA provides a more robust and realistic framework for prioritizing and mitigating environmental risks in petrochemical operations, leading to more effective risk management strategies (19). This study sets the stage for a comprehensive examination of the environmental risks linked to petrochemical factories. It underscores the necessity of ERA in fostering informed decision-making and safeguarding ecological and public health. Through rigorous analysis and proactive management, it is aimed to balance industrial progress with environmental stewardship, ensuring a sustainable future for generations to come. This study introduces an innovative application of fuzzy FMEA for assessing environmental risks in petrochemical complexes, addressing the challenges of uncertainty and subjectivity that traditional risk assessment methods face. The existing literature primarily focuses on conventional FMEA or qualitative assessments, which often lack precision in prioritizing complex, multifaceted risks. By integrating fuzzy logic into the FMEA framework, this study bridges this gap, offering a quantitative, systematic, and refined approach to evaluating failure modes. The innovation lies in using linguistic variables and fuzzy logic to quantify and mitigate ambiguities in risk evaluation, thereby enhancing the reliability and applicability of risk prioritization. This research goes beyond the state-of-the-art by providing a comprehensive, data-driven analysis of environmental risks specific to petrochemical operations, supported by insights from expert consultations and environmental monitoring. It also proposes targeted mitigation strategies for the identified high-risk failure modes, emphasizing practical, actionable solutions. This study contributes to the body of knowledge by demonstrating how fuzzy methodologies can optimize risk management practices in industries characterized by high uncertainty and environmental impact. Integrating fuzzy logic into the FMEA framework significantly improves the accuracy and reliability of ERAs in petrochemical complexes, enabling better prioritization and mitigation of risks compared to traditional methods.

2. Materials and Methods

2.1. Case Study

Lorestan Petrochemical Company is strategically located in Lorestan Province, 12 kilometers along the Khorramabad–Kuhdasht road, encompassing an area of 130 hectares (Fig. 1). This facility is entirely owned by Bakhtar Petrochemical Company and operates under licenses from renowned licensors Basell and Axens. The engineering and procurement for the process section were managed by a consortium of Tecnimont and Nargan. The project, initiated in 2009, officially began operations in 2013 (20). Lorestan Petrochemical Company produces essential feedstock for various downstream industrial units and a wide range of plastic products, including pipes, cables, and films. The establishment of this company has had profound social and economic impacts on the region. By increasing exports and adding significant value, it contributes to the national economy and promotes self-sufficiency in domestic production. The company plays a crucial role in preventing the outflow of local economic

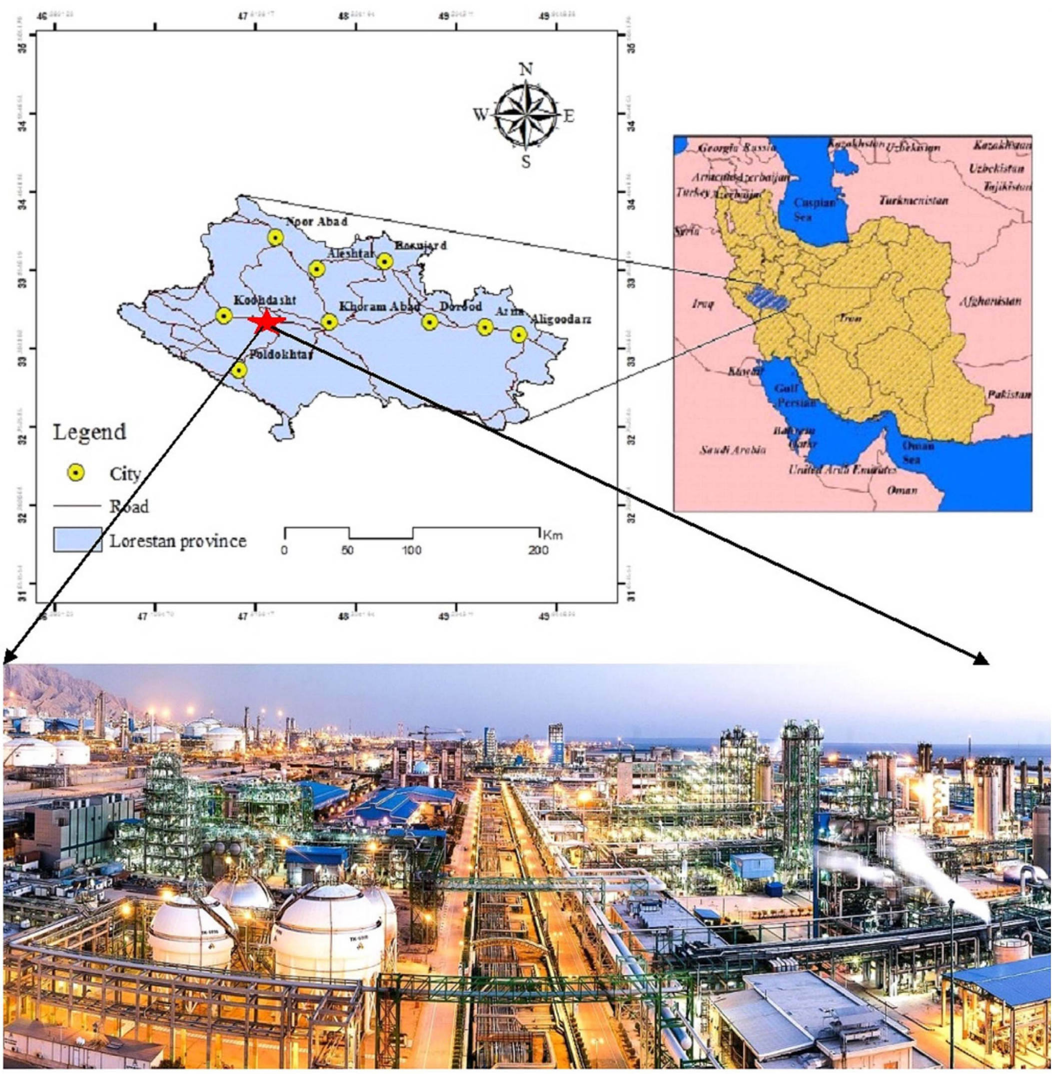

Fig. 1. The Location of Lorestan Petrochemical Complex

capital and fostering regional economic prosperity, thereby aiding in poverty alleviation. Additionally, it curtails migration by providing substantial employment opportunities. During the implementation phase, the project created up to 2000 jobs per day, and in the operational phase, it maintains around 300 jobs daily. Furthermore, it generates over 5000 jobs per day in the downstream industries, making it a pivotal player in regional development. By driving economic growth and offering consistent employment, Lorestan Petrochemical Company not only boosts the local economy but also enhances the quality of life for the residents, ensuring a sustainable future for the community. This comprehensive approach underscores its importance as a cornerstone in the region's industrial landscape.

2.2. Methodology

In this study, an ERA of the petrochemical complex was conducted using the fuzzy FMEA approach (Fig. 2). This method involves using fuzzy logic to handle inherent uncertainties and complexities in evaluating potential environmental risks (21). This approach begins by identifying key environmental risk factors. Each factor is then assigned a fuzzy variable, typically with linguistic values such as "low", "medium", or "high", based on expert judgment or historical data (22). These variables are processed through a fuzzy inference system that applies a set of fuzzy rules to assess the overall environmental risk. The output is a fuzzy risk score that quantifies the likelihood and severity of potential environmental risks, allowing for more nuanced and flexible decision-making compared to traditional deterministic methods (23). This method helps in making informed decisions for risk mitigation and regulatory compliance by incorporating the vagueness and subjectivity inherent in environmental assessments. Fuzzy FMEA for the ERA of Lorestan Petrochemical Factory involves the following steps:

- Defining the scope and objectives: Clearly outlining the boundaries of the assessment and the specific environmental aspects to be evaluated.
- Identifying environmental failure modes: Listing potential failure modes that could lead to environmental impacts, such as equipment leaks, accidental spills, or emissions.

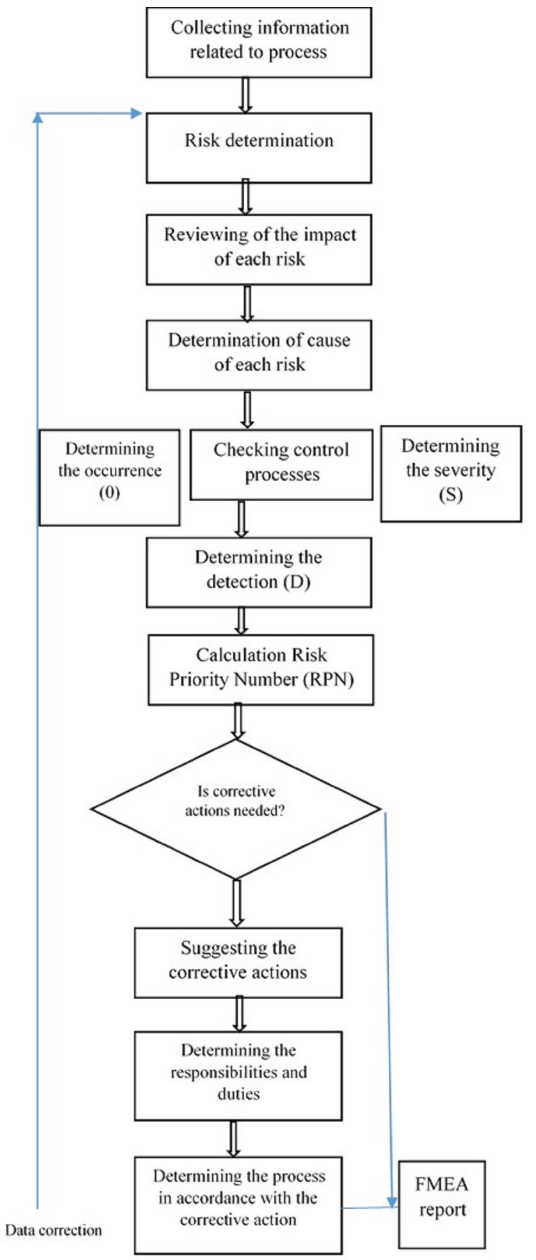

Fig. 2. Steps of Implementing the Systematic Method. *Note*. FMEA: Failure mode and effects analysis

- Determining FMEA parameters: Defining the three primary FMEA parameters, namely, severity (S), occurrence (O), and detection (D). In a fuzzy FMEA, these parameters are described using linguistic terms (e.g., low, medium, or high).
- Developing fuzzy rating scales: Creating fuzzy scales for each FMEA parameter using linguistic variables. These can be represented by triangular or trapezoidal fuzzy numbers to capture the uncertainty and subjectivity in the assessment (Table 1).
- Assigning fuzzy ratings: Assigning fuzzy ratings to the severity, occurrence, and detection parameters based on expert knowledge, historical data, and relevant regulations for each identified failure mode.
- Constructing fuzzy rule base: Developing a set of fuzzy if-then rules to combine the fuzzy ratings of severity, occurrence, and detection. These rules help infer the overall environmental risk for each failure mode.
- Using fuzzy inference system: Utilizing this system to process the input fuzzy ratings and apply the fuzzy rules. This involves the fuzzification of inputs, application of fuzzy rules, aggregation of rule outputs, and defuzzification to obtain a crisp RPN for each failure mode.
- Calculating fuzzy risk priority number: Calculating the fuzzy RPN by combining the fuzzy severity, occurrence, and detection ratings. The result is a defuzzified score that indicates the environmental risk level.
- Prioritizing risks: Ranking the failure modes based on their fuzzy RPNs. Higher RPN values denote higher environmental risks and therefore higher priority for mitigation measures.
- Developing mitigation strategies: Proposing and implementing mitigation strategies for high-priority failure modes to reduce their environmental impact. This may include equipment upgrades, process changes, or enhanced monitoring.

In this study, the probability of risk occurrence or its severity is represented using triangular fuzzy distributions (Fig. 3) as equation (1):

$$Ua(x)=\left\{\begin{matrix} 0.if\ x<a1 \\ \frac{x-a1}{a2-a1}.ifa^{1}\leq x\leq a2 \\ 1.if\ x=a2 \\ \frac{a3-X}{a3-a2}.ifa2\leq x\leq a3 \\ 0.if\ x>a3 \end{matrix}\right\}$$

This approach allows for the best estimates of environmental risks to be made based on accessible and known data. Additionally, fuzzification can be beneficial in making decisions related to environmental risk management.

3. Results and Discussion

The ERA of the Khorramabad Petrochemical Plant revealed significant risks associated with various failure modes (Table 2). The first major risk identified in this regard was a major equipment leak, which can lead to soil and water pollution. This failure mode is primarily caused by corrosion or wear and tear of equipment, faulty seals or gaskets, improper maintenance practices, overpressure or stress on equipment, and manufacturing defects. The severity (S), occurrence (O), and detection (D) scores for this risk are (8,9,10), (6,7,8), and (5,6,7) respectively, resulting in a high-risk level with a fuzzy FMEA output of 0.778. To mitigate this risk, it is recommended that researchers install advanced leak detection systems, conduct regular maintenance checks, and implement secondary containment systems. Another significant risk

Table 1. Description of Severity, Occurrence, and Detection Indices

Severity		Occurrence		Detection		Fuzzy Score
Uncertain realization	**Minimal effect, hard to notice**	**Highly unlikely**	**Incident or failure every 10 years or more**	**Unidentifiable**	**No tracking systems, no operator oversight**	**(1,1,2)**
Very slight	Minor impact, negligible consequences	Very rare	Incident or failure every 5-10 years	Almost unidentifiable	Detected only by very precise and rare tests	(1,2,3)
Slight	Low impact, minor inconvenience or disruption	Rare	Incident or failure every 3-5 years	Low detectability	Detected through periodic, detailed analyses	(2,3,4)
Very low	Slight impact on operations, minimal downtime	Very low	Incident or failure annually	Detectable	Detected with regular and simple routine tests	(3,4,5)
Low	Noticeable impact, moderate inconvenience, manageable within the team	Low	Incident or failure every 6 months to 1 year	Moderately detectable	50-50 chance of detection	(4,5,6)
Moderate	Clear impact on operations, possible delays or downtime	Moderate	Incident or failure every 3 months	Detectable	Detected in routine inspections and standard procedures	(5,6,7)
Moderate to high	Significant impact, affecting multiple processes or teams	Moderately high	Incident or failure every month	High detectability	Detected with daily visual and auditory alarms	(6,7,8)
High	Major impact on operations, significant downtime, affecting overall performance	High	Incident or failure every week	Very high detectability	Detected almost always with alarms	(7,8,9)
Very high	Severe impact, critical operations are compromised, substantial downtime	Very high	Incident or failure every 3-4 days	Almost certain detectability	Detected without the need for special tools or tests	(8,9,10)
Almost certain	Catastrophic impact, operations halted, severe safety, or environmental consequences	Almost certain	Incident or failure daily	Fully detectable	Completely identifiable and trackable	(9,10,10)

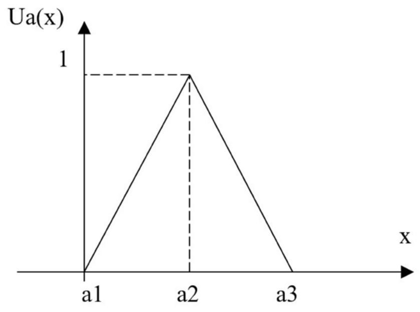

Fig. 3. Triangular Fuzzy Membership Function

is the toxic gas release, which poses a threat to air quality. This failure mode can result from process upsets or failures, equipment malfunctions such as valve failures, incorrect handling or storage of chemicals, human error during operations, and inadequate safety systems or protocols. The S, O, and D scores for this risk are (9,10,10), (5,6,7), and (4,5,6), leading to a high-risk level with a fuzzy FMEA output of 0.700. Recommended actions include enhancing gas monitoring systems, installing scrubbers, and implementing comprehensive emergency response plans. The risk of a chemical spill is also high, with potential effects on soil and water pollution. This failure mode is caused by improper handling or transfer of chemicals, equipment failure (e.g., pumps or hoses), accidental releases during loading/unloading, inadequate containment measures, and human error or procedural lapses. The S, O, and D scores are (7,8,9), (4,5,6), and (6,7,8), resulting in a fuzzy FMEA output of 0.580. Mitigation measures encompass using spill containment pallets, training staff on spill response, and storing chemicals in appropriate containment units. Wastewater discharge poses a high risk of water pollution due to the failure of wastewater treatment systems, overloading of treatment facilities, equipment malfunctions, chemical imbalances in treatment processes, and insufficient monitoring or maintenance. The S, O, and D scores are (6,7,8), (5,6,7), and (7,8,9), with a fuzzy FMEA output of 0.636. Suggested actions consist of upgrading wastewater treatment facilities, monitoring discharge quality, and implementing recycling processes. Noise pollution from equipment is another significant concern, primarily caused by aging or poorly maintained machinery, lack of proper noise control measures, equipment operating outside design specifications, inadequate insulation or soundproofing, and improper installation or alignment of machinery. The S, O, and D scores are (5,6,7), (6,7,8), and (4,5,6), leading to a fuzzy FMEA output of 0.510. Mitigation strategies include installing soundproofing around noisy equipment, scheduling noisy operations during less sensitive times, and regularly maintaining equipment. Minor leaks can lead to soil pollution and are caused by small cracks or fractures in equipment, faulty seals or gaskets, routine wear and tear, poorly executed repairs or maintenance, and equipment vibration causing the loosening of components. The S, O, and D scores are (2,3,4), (7,8,9), and (3,4,5), resulting in a low-risk level with a fuzzy FMEA output of 0.286. Mitigation actions consist of conducting regular inspections, using leak-proof fittings, and implementing a prompt leak repair program. Fugitive emissions, which contribute to air pollution, are caused by leaks in piping or fittings, inefficient process controls, equipment malfunctions, aging infrastructure, and inadequate maintenance or inspection routines. The S, O, and D scores are (4,5,6),

Table 2. Fuzzy FMEA Results for the Consequences and Effects of Environmental Risks

Potential Failure Modes	Effects of Failure	Potential Failure Causes	S *	O *	D *	Fuzzy FMEA Output	Risk Level	Actions for Evidence
Major equipment leak	Soil pollution and water pollution	o Corrosion or wear and tear of equipment o Faulty seals or gaskets o Improper maintenance practices o Overpressure or stress on equipment o Manufacturing defects	(8,9,10)	(6,7,8)	(5,6,7)	0.778	H	Installing advanced leak detection systems, conducting regular maintenance checks, and implementing secondary containment systems
Toxic gas release	Air pollution	o Process upsets or failures o Equipment malfunction (e.g., valve failure) o Incorrect handling or storage of chemicals o Human errors during operations o Inadequate safety systems or protocols	(9,10,10)	(5,6,7)	(4,5,6)	0.700	H	Enhancing gas monitoring systems, installing scrubbers, and implementing emergency response plans
Chemical spill	Soil pollution and water pollution	o Improper handling or transfer of chemicals o Equipment failure (e.g., pumps and hoses) o Accidental releases during loading/unloading o Inadequate containment measures o Human errors or procedural lapses	(7,8,9)	(4,5,6)	(6,7,8)	0.580	H	Using spill containment pallets, training staff on spill response, and storing chemicals in appropriate containment units
Wastewater discharge	Water pollution	o Failure of wastewater treatment systems o Overloading of treatment facilities o Equipment malfunction (e.g., pumps or filters) o Chemical imbalance in treatment processes o Insufficient monitoring or maintenance	(6,7,8)	(5,6,7)	(7,8,9)	0.636	H	Upgrading wastewater treatment facilities, monitoring discharge quality, and implementing recycling processes
Noise pollution from equipment	Noise pollution	o Aging or poorly maintained machinery o Lack of proper noise control measures o Equipment operating outside design specifications o Inadequate insulation or soundproofing o Improper installation or alignment of machinery	(5,6,7)	(6,7,8)	(4,5,6)	0.510	H	Installing soundproofing around noisy equipment, scheduling noisy operations during less sensitive times, and regularly maintaining equipment
Minor leak	Soil pollution	o Small cracks or fractures in equipment o Faulty seals or gaskets o Routine wear and tear o Poorly executed repairs or maintenance o Equipment vibration causing loosening of components	(2,3,4)	(7,8,9)	(3,4,5)	0.286	L	Conducting regular inspections, using leak-proof fittings, and implementing a prompt leak repair program
Fugitive emissions	Air pollution	o Leaks in piping or fittings o Inefficient process controls o Equipment malfunction (e.g., valves or flanges) o Aging infrastructure o Inadequate maintenance or inspection routines	(4,5,6)	(5,6,7)	(5,6,7)	0.340	M	Improving sealing on equipment, using emissions capture technologies, and regularly monitoring emission points
Stormwater runoff	Soil pollution and water pollution	o Insufficient stormwater management systems o Heavy rainfall events exceeding design capacity o Improper containment of potential contaminants o Erosion or damage to containment areas o Clogging or blockage in drainage systems	(5,6,7)	(4,5,6)	(6,7,8)	0.510	H	Implementing stormwater management systems, using permeable surfaces, and creating retention basins
Flare stack emissions	Air pollution	o Process upsets leading to flaring o Equipment failure (e.g., flare tips or gas flow control) o Inefficient combustion in the flare stack o Excessive gas production beyond handling capacity o Poorly maintained flare systems	(6,7,8)	(3,4,5)	(7,8,9)	0.524	H	Utilizing low-emission flare tips, optimizing combustion efficiency, and monitoring flare performance
Odor emissions	Air pollution	o Volatile organic compounds from processes o Improper handling or storage of odor-causing substances o Equipment leaks or malfunctions o Inefficient odor control systems o Poor ventilation in processing areas	(3,4,5)	(6,7,8)	(5,6,7)	0.428	M	Installing odor control systems, improving process ventilation, and monitoring odor sources

Table 2. Continued.

Potential Failure Modes	Effects of Failure	Potential Failure Causes	S *	O *	D *	Fuzzy FMEA Output	Risk Level	Actions for Evidence
Solid waste mismanagement	Soil pollution and water pollution	o Inadequate waste handling procedures o Improper segregation of hazardous and non-hazardous waste o Failure of containment systems (e.g., liners or barriers) o Illegal dumping or accidental spills o Lack of regular waste audits and inspections	(4,5,6)	(4,5,6)	(6,7,8)	0.445	M	Implementing waste segregation, ensuring proper disposal, and recycling waste where possible
Pipeline rupture	Soil pollution and water pollution	o Corrosion or material degradation o External damage (e.g., excavation or vehicular impact) o Overpressure or stress on pipelines o Manufacturing of defects in pipeline materials o Inadequate monitoring and maintenance	(8,9,10)	(3,4,5)	(4,5,6)	0.460	M	Regularly inspecting pipelines, using corrosion-resistant materials, and installing pressure monitoring systems
Cooling tower drift	Air pollution and water pollution	o Poor maintenance of cooling tower systems o Inefficient drift eliminators o Excessive water flow rates o High wind conditions affecting drift o Chemical imbalances in cooling water	(4,5,6)	(5,6,7)	(6,7,8)	0.580	H	Using drift eliminators, optimizing cooling tower operation, and treating cooling water properly
Effluent discharge non-compliance	Water pollution	o Failure of effluent treatment processes o Overloading of treatment facilities o Human errors in monitoring or reporting o Equipment malfunction (e.g., pumps or sensors) o Insufficient regulatory compliance checks	(7,8,9)	(4,5,6)	(6,7,8)	0.620	H	Regularly testing effluent quality, upgrading treatment processes, and ensuring compliance with regulations
Explosive release	Soil pollution and air pollution	o Chemical reactions or process upsets o Equipment failure (e.g., pressure vessels or reactors) o Improper handling or storage of explosive materials o Human errors or procedural lapses o Inadequate safety systems or protocols	(9,10,10)	(2,3,4)	(4,5,6)	0.400	M	Implementing explosion-proof equipment, conducting risk assessments, and having emergency response plans in place

Note. FMEA: Failure mode and effects analysis. * S: Severity; O: Occurrence; D: Detection.

(5,6,7), and (5,6,7), leading to a medium-risk level with a fuzzy FMEA output of 0.340. Recommended actions encompass improving sealing on equipment, utilizing emissions capture technologies, and regularly monitoring emission points. Stormwater runoff can lead to soil and water pollution, primarily due to insufficient stormwater management systems, heavy rainfall events exceeding design capacity, improper containment of potential contaminants, erosion or damage to containment areas, and clogging or blockage in drainage systems. The S, O, and D scores are (5,6,7), (4,5,6), and (6,7,8), with a high-risk level and a fuzzy FMEA output of 0.510. Mitigation measures include implementing stormwater management systems, employing permeable surfaces, and creating retention basins. Flare stack emissions contribute to air pollution and result from process upsets, resulting in flaring, equipment failure, inefficient combustion in the flare stack, excessive gas production beyond handling capacity, and poorly maintained flare systems. The S, O, and D scores are (6,7,8), (3,4,5), and (7,8,9), leading to a high-risk level with a fuzzy FMEA output of 0.524. Suggested actions consist of using low-emission flare tips, optimizing combustion efficiency, and monitoring flare performance. Odor emissions, which affect air quality, are caused by volatile organic compounds from processes, improper handling or storage of odor-causing substances, equipment leaks or malfunctions, inefficient odor control systems, and poor ventilation in processing areas. The S, O, and D scores are (3,4,5), (6,7,8), and (5,6,7), leading to a medium-risk level with a fuzzy FMEA output of 0.428. Mitigation strategies encompass installing odor control systems, improving process ventilation, and monitoring odor sources. Solid waste mismanagement can lead to soil and water pollution due to inadequate waste handling procedures, improper segregation of hazardous and non-hazardous waste, failure of containment systems, illegal dumping or accidental spills, and lack of regular waste audits and inspections. The S, O, and D scores are (4,5,6), (4,5,6), and (6,7,8), resulting in a medium-risk level with a fuzzy FMEA output of 0.445. Recommended actions include implementing waste segregation, ensuring proper disposal, and recycling waste where possible. Pipeline rupture poses a medium risk of soil and water pollution, caused by corrosion or material degradation, external damage, overpressure or stress on pipelines, manufacturing defects in pipeline materials, and inadequate monitoring and maintenance. The S, O, and D scores are (8,9,10), (3,4,5), and (4,5,6), with a fuzzy FMEA output of 0.460. Mitigation measures consist of regularly inspecting pipelines, using corrosion-resistant materials, and installing pressure monitoring systems. Cooling tower drift can lead to air and water pollution due to poor maintenance of cooling tower systems, inefficient drift eliminators, excessive water flow rates, high wind conditions affecting drift, and chemical imbalances in cooling water. The S, O, and D scores are (4,5,6), (5,6,7), and (6,7,8), resulting in a high-risk level with a fuzzy FMEA output of 0.580. Recommended actions include employing drift eliminators, optimizing cooling tower operation, and treating cooling water properly. Effluent discharge non-compliance poses a high risk of water pollution, caused by failure of effluent treatment processes, overloading of treatment facilities, human errors in monitoring or reporting, equipment malfunctions, and insufficient regulatory compliance checks. The S, O, and D scores are (7,8,9), (4,5,6), and (6,7,8), with a fuzzy FMEA output of 0.620. Mitigation measures encompass regularly testing effluent quality, upgrading treatment processes, and ensuring compliance with regulations. Explosive release poses a medium risk of soil and air pollution, caused by chemical reactions or process upsets, equipment failure, improper handling or storage of explosive materials, human error or procedural lapses, and inadequate safety systems or protocols. The S, O, and D scores are (9,10,10), (2,3,4), and (4,5,6), leading to a fuzzy FMEA output of 0.400. Recommended actions consist of implementing explosion-proof equipment, conducting risk assessments, and having emergency response plans in place. The ERA of the Khorramabad Petrochemical Plant revealed several high and medium risks that require immediate attention and mitigation. Our findings highlight the importance of regular maintenance, advanced monitoring systems, proper training, and adherence to safety protocols to minimize the environmental impact of the plant's operations.

The results of the ERA for petrochemical complexes demonstrated a varied distribution of potential effects on different environmental components (Fig. 4). Water pollution emerged as the most significant risk, with a notable impact factor of 36.4%, indicating that petrochemical activities pose a substantial threat to aquatic ecosystems through the discharge of contaminants. Soil pollution followed closely, accounting for 31.8% of the risk, which underscores the potential for hazardous substances to affect soil quality and, subsequently, agricultural and natural land use. Air pollution, with an impact factor of 27.3%, represents a considerable concern as emissions from petrochemical processes can degrade air quality and contribute to health problems and environmental issues. In contrast, noise pollution was identified as the least significant risk, with an impact factor of only 4.5%. This implies that while noise pollution is a factor, it poses a relatively lower threat compared to the other types of pollution. These results highlight the need for targeted mitigation strategies that address the most critical areas of concern—particularly water and soil pollution—while still considering the overall environmental impact of petrochemical complexes.

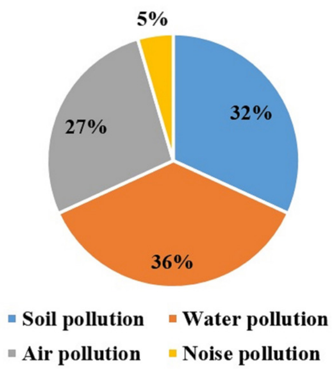

Fig. 4. Distribution of Potential Effects of Risks on the Environment Component

The ERA of the Khorramabad Petrochemical Plant, conducted using a fuzzy FMEA approach, underscores significant environmental hazards inherent in petrochemical operations. The results of this study not only reveal critical risks but also offer a comparative perspective with similar studies in the field, emphasizing the complex interplay of factors contributing to environmental degradation. The fuzzy FMEA method, characterized by its ability to handle uncertainty and vagueness in risk assessment, provides a nuanced understanding of these risks and their potential consequences, enabling a more informed decision-making process for mitigation strategies. The study identified several high-risk scenarios, with major equipment leaks emerging as a top concern. The fuzzy FMEA output of 0.778 for this failure mode, resulting from factors such as corrosion, equipment wear, and faulty maintenance, aligns with the findings of other studies in the field. For instance, the results of a study by Reniers (24) on chemical plants in Belgium also highlighted equipment failure due to corrosion and inadequate maintenance as a primary source of environmental risk, emphasizing the global relevance of such risks in the petrochemical industry. The recommended mitigation strategies, including advanced leak detection systems and regular maintenance, resonate with suggestions from other studies that advocate for proactive measures to prevent catastrophic environmental incidents. Toxic gas release, with a fuzzy FMEA output of 0.700, represents another significant risk, particularly in terms of air quality. This corroborates the findings of the study of Khan and Abbasi (25), identifying gas releases as a critical environmental hazard in their assessment of process plants. The high severity and occurrence scores in both studies underline the potential for widespread environmental and health impacts, necessitating robust gas monitoring systems and comprehensive emergency response plans. The conformity of these findings with those of previous research underscores the persistent challenge of managing toxic emissions in petrochemical complexes, where the consequences of failure are often severe and far-reaching. Chemical spills, with an FMEA output of 0.580, present a major threat to soil and water resources. The study's findings are consistent with those of Djemai et al (26), reporting chemical spills as a significant risk in their environmental assessment of industrial sites. The similarity in risk factors, such as equipment failure and improper handling of chemicals, suggests a commonality in the underlying causes across different petrochemical operations. The recommendation for using spill containment pallets and training staff on spill response is supported by these prior studies, emphasizing the importance of preparedness and containment in mitigating the impact of chemical spills. The risk associated with wastewater discharge, with a fuzzy FMEA output of 0.636, is particularly concerning, given the potential for water pollution. The study's results regarding the identification of overloading and equipment malfunctions as key contributors to this risk conform to the findings of a similar assessment in the context of oil refineries conducted by Waqar et al (27). Both studies highlight the critical need for upgrading wastewater treatment facilities and ensuring continuous monitoring to prevent environmental contamination. This shared emphasis on the importance of robust wastewater management systems reflects a broader consensus in the literature regarding the risks associated with petrochemical effluents. Noise pollution from equipment, with a fuzzy FMEA output of 0.510, also poses a significant environmental and occupational hazard. This issue, often overlooked in favor of more immediate chemical risks, is gaining attention in recent studies. For instance, the findings of Jo and Baek (28) on environmental noise in industrial settings emphasize similar concerns, with aging equipment and inadequate noise control measures being primary contributors. The recommended strategies in the current study, such as soundproofing and regular maintenance, are consistent with broader industry practices aimed at reducing noise pollution and protecting both workers and the environment. Interestingly, the study identifies minor leaks, with a low-risk FMEA output of 0.286, as relatively less critical in comparison to other failure modes. However, the recognition of even low-risk scenarios is crucial, as these can accumulate over time and lead to significant environmental impacts. This observation is supported by a study performed by Khan et al (29), arguing that the cumulative effect of minor leaks, if not properly managed, can contribute to substantial environmental degradation over time. The current study's recommendation for regular inspections and prompt leak repair underscores the importance of vigilance, even in seemingly minor issues. Fugitive emissions, stormwater runoff, and flare stack emissions, with fuzzy FMEA outputs of 0.340, 0.510, and 0.524, respectively, highlight the multifaceted nature of environmental risks in petrochemical plants. These findings corroborate the results of a study conducted by Gormley and Stewart (30), identifying these failure modes as significant contributors to air and water pollution in industrial complexes. The comparative analysis revealed a consistent pattern of risks across different studies, with similar causes and recommended mitigation strategies, such as improving sealing on equipment and optimizing stormwater management systems. Moreover, the study's findings on solid waste mismanagement and pipeline rupture, with FMEA outputs of 0.445 and 0.460, are in line with global concerns regarding waste handling and pipeline integrity. These issues have been extensively discussed in the literature in studies such as the one performed by Mustafa et al (31), highlighting the environmental risks associated with improper waste segregation and pipeline failures in industrial settings. The recommendations for proper waste disposal, recycling, and regular pipeline inspections in the current study echo the best practices suggested in these earlier works. The risk of effluent discharge non-compliance and cooling tower drift, with fuzzy FMEA outputs of 0.620 and 0.580, respectively, emphasizes the ongoing challenges in maintaining regulatory compliance and controlling pollution in petrochemical operations. Studies, such as the one conducted by Akingbasote et al (32), have similarly highlighted these risks, particularly in the context of increasingly stringent environmental regulations. The current study's focus on upgrading treatment processes and optimizing cooling tower operations reflects the broader industry trend toward enhancing compliance and reducing environmental footprints. This comparative analysis not only validates the study's conclusions but also contributes to a growing body of knowledge aimed at minimizing the environmental impact of industrial operations. The findings of this study reinforce the broader understanding that environmental risk management in petrochemical complexes is a dynamic and ongoing process requiring a multifaceted approach. The complexities of operating in an environment where multiple factors, such as equipment wear, human errors, and process inefficiencies, converge to create significant risks cannot be understated. The use of a fuzzy FMEA approach allows for the incorporation of uncertainties and variabilities in assessing these risks, making the analysis more robust and adaptable to real-world conditions. The alignment of this study with existing research highlights the global nature of these challenges and the universal applicability of the proposed mitigation strategies. As environmental regulations become increasingly stringent worldwide, the findings emphasize the necessity for industries to adopt proactive measures that go beyond mere compliance. This includes investing in technology upgrades, enhancing training programs, and fostering a culture of safety and environmental stewardship. Moreover, this study contributes to the growing recognition that addressing even low to medium risks is essential in preventing cumulative environmental damage. The research underscores the critical importance of an integrated and systematic approach to environmental risk management in safeguarding both the environment and public health in the face of industrial activities.

4. Conclusion

The ERA of the Khorramabad Petrochemical Plant, employing a fuzzy FMEA approach, has provided critical insights into the significant environmental risks associated with petrochemical operations. The analysis revealed that the plant is subject to several high- and medium-risk failure modes. The study's use of fuzzy logic within the FMEA framework has proven to be a valuable tool in handling the inherent uncertainties in risk assessment, offering a more comprehensive understanding of the potential consequences of each failure mode. This methodological approach allows for a more nuanced risk prioritization, aiding decision-makers in developing targeted mitigation strategies. This approach addresses the inherent uncertainties and complexities associated with petrochemical operations by integrating fuzzy logic into the risk assessment framework, thus allowing for a more nuanced evaluation of potential environmental hazards. The incorporation of fuzzy logic enables the model to handle imprecise and qualitative data more effectively, providing a more comprehensive and adaptable risk analysis compared to traditional methods. By employing fuzzy FMEA, this study not only identified and prioritized potential failure modes with greater accuracy but also facilitated the development of targeted mitigation strategies. The results underscore the importance of incorporating advanced analytical techniques to enhance the robustness of ERAs, particularly in industries characterized by high levels of complexity and uncertainty. Moreover, the application of this approach demonstrates its potential to improve decision-making processes by offering a clearer understanding of risk levels and their implications for environmental safety. Future research should continue to explore the integration of fuzzy logic with other risk assessment tools and methodologies, aiming to refine the approach and broaden its applicability across various industrial contexts. The findings of this study also contribute valuable insights into the optimization of environmental risk management practices, ultimately supporting the goal of minimizing adverse impacts on the environment while maintaining operational efficiency in petrochemical complexes. Recommendations for future research aimed at enhancing the practical impact of this study by promoting interdisciplinary approaches, scalable solutions, and real-time applications of the fuzzy FMEA framework across various industrial sectors are as follows:

- *Integration of advanced predictive models:* Future research could explore the integration of fuzzy logic with advanced machine-learning algorithms to enhance the predictive accuracy of ERAs. Such hybrid models could analyze large datasets from petrochemical operations, including real-time monitoring systems, to provide dynamic and adaptive risk evaluation frameworks.
- *Cross-sector application and validation:* While this study focused on petrochemical complexes, extending the methodology to other industries with high environmental risks (e.g., chemical manufacturing, mining, and power generation) would validate the approach's versatility. Comparative studies across different sectors could refine the model's applicability and improve generalizability.
- *Stakeholder-centric models:* Future research could incorporate the perspectives of diverse stakeholders, including community members, regulatory bodies, and environmental organizations, into the risk assessment process. This would ensure a more holistic evaluation of risks and improve the acceptance and implementation of mitigation strategies.
- *Environmental and health impact synergy:* Future research could investigate the interconnectedness between environmental risks and their direct or indirect impacts on human health. By integrating health risk assessment with environmental risk frameworks, researchers could provide a more comprehensive evaluation of petrochemical operations' broader societal impacts.
- *Development of user-friendly tools:* Developing software tools or platforms that implement the fuzzy FMEA framework with user-friendly interfaces could facilitate adoption in the industry. Research could focus on creating automated systems that simplify data input, analysis, and interpretation for industry practitioners.

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Competing Interests

The authors declare no conflicts of interest.

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