



Resilience in Petrochemical Industries facing NaTech Accidents: Identification of Key Dimensions and Components - A Systematic Review

Fereshteh Taheri¹ | Hesam Seyedin¹ | Saber Moradi Hanifi² | Mohsen Dowlati³✉

1. Department of Disaster & Emergency Health, School of Health Management & Information Sciences, Iran University of Medical Sciences, Tehran, Iran.

2. Occupational Health Research Center, Department of Occupational Health Engineering, School of Public Health, Iran University of Medical Sciences, Tehran, Iran.

3. Department of Disaster & Emergency Health, School of Health Management & Information Sciences, Health Management and Economics Research Center, Health Management Research Institute, Iran University of Medical Sciences, Tehran, Iran.

Article Info	ABSTRACT
Article type: Review Article	Petrochemical industries are vulnerable to NaTech accidents, in which natural hazards trigger technological failures that may cause fires, explosions, hazardous releases, and environmental contamination. Resilience is therefore essential not only for industrial safety and operational continuity, but also for pollution prevention, public health protection, and environmental risk reduction. This systematic review synthesized evidence on the dimensions and operationalization of resilience in petrochemical industries exposed to NaTech risks.
Article history: Received: 24 May 2026 Revised: 30 Jul 2026 Accepted: 07 Oct 2026	Following PRISMA 2020 guidelines, international and national databases were searched for studies published up to July 2025. Eligible English- and Persian-language empirical studies, technical reports, and official guidelines were included. Two reviewers independently performed study selection, data extraction, and quality appraisal using CASP and JBI tools. Findings were synthesized through Graneheim and Lundman's qualitative content analysis approach with MAXQDA.
Keywords: <i>Resilience</i> <i>Petrochemical Industries</i> <i>NaTech Accidents</i> <i>Emergency Preparedness</i> <i>Risk Management</i> <i>Hazardous Material Release</i> <i>Environmental Contamination</i> <i>Pollution Prevention</i>	Twenty-three studies from seven countries met the inclusion criteria. Analysis of 346 initial codes identified seven themes: preparedness, comprehensive risk management, infrastructure and equipment development, emergency response, operational continuity, recovery, and knowledge and technology management. Resilience emerged as a dynamic capability shaped by technical, human, organizational, and institutional factors. Risk identification, hazardous material control, safe design, monitoring, and layered barriers were central, while post-event recovery, environmental remediation, and long-term pollution impacts remained underexplored overall.

Cite this article: Taheri, F., Seyedin, H., Moradi Hanifi, S., & Dowlati, M. (2026). Resilience in Petrochemical Industries facing NaTech Accidents: Identification of Key Dimensions and Components - A Systematic Review. *Pollution*, 12(4), 1091-1110.
<https://doi.org/10.22059/poll.2026.415095.3346>



© The Author(s).

Publisher: The University of Tehran Press.

DOI: <https://doi.org/10.22059/poll.2026.415095.3346>

INTRODUCTION

Petrochemical facilities are vulnerable because they process hazardous substances under high pressure and temperature. Natural Hazard Triggered Technological (NaTech) events occur when earthquakes, floods, storms, or other hazards damage industrial systems and cause fires, explosions, toxic releases, or environmental contamination (RODRIGUEZ et al., 2025b;

*Corresponding Author Email: mohsendowlati.69@gmail.com

Suárez-Paba et al., 2025). Interconnected tanks, pipelines, utilities, and neighboring installations allow failures to escalate into domino effects that intensify damage (Jin et al., 2025; Misuri & Cozzani, 2022).

Because these events can harm workers and contaminate air, soil, and water, resilience must cover hazardous material control, public health, pollution prevention, environmental recovery, and operational continuity (Ghaljahi et al., 2025). Climate change is altering floods, storms, heat waves, and extreme rainfall (Luo et al., 2024). NaTech incidents have risen in coastal and low-lying industrial regions (Barquet et al., 2024; Cozzani et al., 2010), making stronger preparedness essential (Fekete & Nehren, 2024; Yahaya et al., 2024).

Resilience is the capacity to anticipate, withstand, adapt to, and recover from disruption while maintaining essential functions (Hollnagel et al., 2006; Tao Zeng et al., 2022). In petrochemical settings, it includes vulnerability assessment, prevention, preparedness, response, recovery, and learning (Çetinyokuş, 2024; Pasma et al., 2020), as well as managing performance loss and cascading failures (Zeng et al., 2023).

Despite growing attention, many frameworks assess facilities in isolation and overlook links with communities, critical infrastructure, and environmental systems (David J Castro Rodriguez et al., 2025; Q. H. Zheng et al., 2024; Jimoh-Hamza & Ajao, 2025). Standardized preparedness methods remain limited (Suarez-Paba & Cruz, 2022), while natural and technological hazards are often examined separately rather than through integrated multi-hazard approaches (Arosio et al., 2020; Nicotra et al., 2024).

Escalation can be rapid. Post-earthquake simulations show that an uncontrolled fire may spread to tanks within nine minutes and involve the site within forty minutes (Baser & Behnam, 2020). Targeted chain-breaking and lifecycle strategies can reduce such domino risks (Yang et al., 2023).

Preparedness varies across regions, and stakeholders may remain poorly prepared for flood-induced NaTech events (Yahaya et al., 2024). Evidence is scattered across industrial safety, disaster risk reduction, climate adaptation, and emergency management (Krausmann & Cruz, 2013; Luo et al., 2024; RODRIGUEZ et al., 2025b; Suárez-Paba et al., 2025). No synthesis has identified the dimensions and components of petrochemical resilience across the NaTech lifecycle. This review addresses that gap by organizing the evidence into a framework for resilience assessment, industrial decision-making, environmental risk management, and pollution prevention.

MATERIAL & METHODS

This systematic review was conducted and reported according to PRISMA 2020 guidelines (Page et al., 2021). The protocol was prospectively registered in PROSPERO (CRD420251133236), and the review was completed between May 5 and September 27, 2025.

Published and unpublished English- or Persian-language sources addressing resilience in petrochemical industries exposed to natural hazard-triggered technological accidents were eligible. These included original studies, theses, technical reports, and official guidelines or protocols issued by recognized national and international organizations, including Iranian authorities and WHO, EPA, IFRC, NIOSH, and OSHA, to capture both scientific and relevant policy-related evidence. Reviews, conference abstracts without full papers, and unavailable full texts were excluded. When necessary, authors were contacted twice before a record was excluded.

PubMed, Scopus, Web of Science, Embase, ProQuest, SID, Magiran, and Irandoc were searched for records published from 1956 to July 1, 2025. Search strategies were adapted to each database and combined controlled vocabulary and free-text terms using Boolean operators. Terms were grouped into three domains: resilience, petrochemical and process industries, and

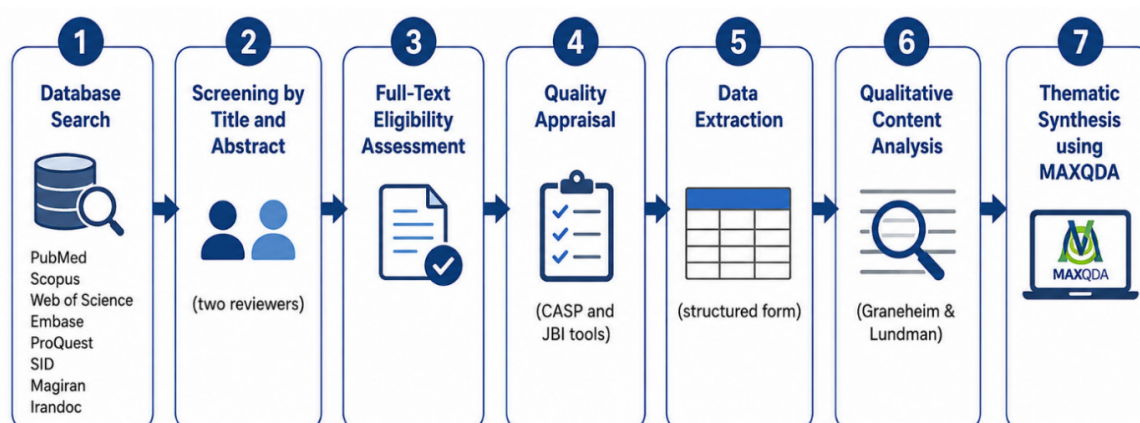


Fig. 1. Schematic representation of the systematic review methodology, including search strategy, study selection, quality appraisal, data extraction, and thematic synthesis.

NaTech accidents, including related concepts such as preparedness, emergency response, business continuity, cascading events, fires, explosions, toxic releases, floods, earthquakes, lightning, and extreme heat.

Two reviewers independently screened titles and abstracts and then assessed potentially eligible full texts. Disagreements were resolved through discussion or consultation with a third reviewer. Data were extracted independently using a structured form covering study characteristics, setting, design, data collection, and resilience-related components, frameworks, and findings.

Methodological quality was assessed independently by two reviewers. Qualitative studies were evaluated using the Critical Appraisal Skills Programme checklist, while descriptive studies, case studies, and gray literature were assessed with relevant Joanna Briggs Institute tools. Studies were rated as high, moderate, or low quality, and these ratings informed interpretation.

Because the included studies varied considerably in design, setting, and outcomes, meta-analysis was not appropriate. Findings were synthesized through narrative synthesis and qualitative content analysis following Graneheim and Lundman (Graneheim & Lundman, 2004). Meaning units were identified, condensed, coded, and grouped into subcategories, categories, and seven overarching themes, which were then integrated into a conceptual framework.

MAXQDA 2022 supported data management, coding, and conceptual organization (VERBI Software, 2022). Publication bias and sensitivity analysis were not applicable to this qualitative synthesis. Trustworthiness was strengthened through independent screening, duplicate extraction and appraisal, and a transparent synthesis process that preserved the conceptual context of findings (Thomas & Harden, 2008). The review process is summarized in Figure 1.

RESULTS & DISCUSSION

The database search identified 4,035 records from PubMed, Scopus, Embase, Web of Science, Irandoc, Magiran, and SID. After removing 950 duplicates, 3,085 records remained for title and abstract screening. Of these, 170 were considered potentially relevant, and 50 were retained for full-text assessment, while 120 were excluded because they did not meet the review objectives. An additional search of Google Scholar and the reference lists of relevant studies identified 10 records, three of which were eligible for full-text review. Overall, 53 full-text articles were assessed against the eligibility criteria. Thirty studies were excluded because of limited relevance, insufficient methodological detail, or unavailable full text, leaving 23 studies for inclusion in the qualitative synthesis. The study selection process is shown in the PRISMA

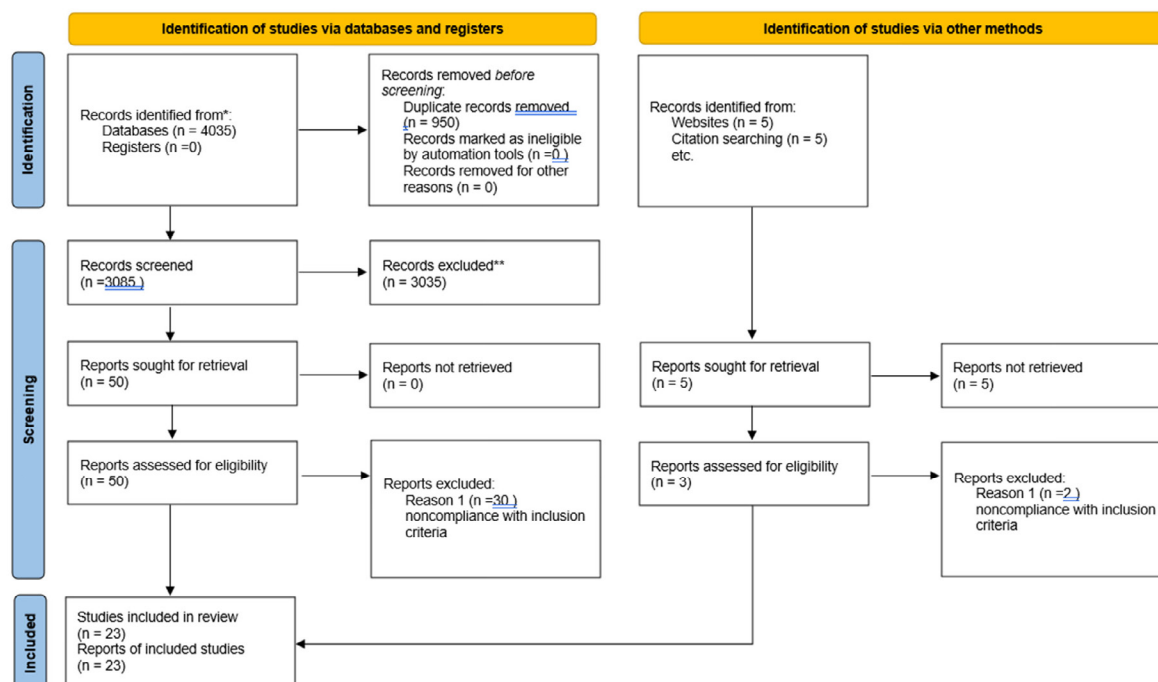


Fig. 2. The PRISMA flowchart of literature search and inclusion/exclusion process.

flow diagram in Figure 2.

The 23 included studies were published between 2014 and 2025 and represented research from seven countries: Iran ($n = 8$), China ($n = 6$), Italy ($n = 5$), the Netherlands ($n = 2$), the United States ($n = 2$), Japan ($n = 1$), and Belgium ($n = 1$). The total country counts exceed the number of studies because some involved international collaborations, including China–Netherlands and Netherlands–Belgium partnerships. Study designs included quantitative modelling ($n = 11$), qualitative research ($n = 4$), mixed methods ($n = 1$), applied or scenario-based studies ($n = 3$), conceptual or framework-development studies ($n = 4$).

Most studies were conducted in petrochemical or related industrial settings and addressed NaTech risk management, resilience assessment, vulnerability analysis, or accident prevention. Units of analysis ranged from individual petrochemical plants and Seveso-regulated facilities to chemical industrial clusters, national NaTech databases, and policy frameworks. Several Iranian studies collected primary data from operating petrochemical facilities (Abbassinia et al., 2020; Pirani et al., 2022; Shafiei Moghaddam et al., 2022), whereas other studies used simulations or secondary datasets (Caputo et al., 2020; Castro Rodriguez et al., 2023; Zeng et al., 2023).

The analytical methods reflected the diversity of study aims and designs. Quantitative approaches included Bayesian networks, Monte Carlo simulations, capacity diagrams, GIS-based multi-hazard vulnerability modelling, entropy-TOPSIS, fuzzy AHP-TOPSIS, and data envelopment analysis. Qualitative and conceptual studies used content analysis, the Functional Resonance Analysis Method, Delphi techniques, and scenario-based analysis to examine preparedness, emergency response, and organizational resilience. Several studies also proposed structured frameworks for barrier management or NaTech performance assessment by combining infrastructural, organizational, governance, and environmental dimensions.

Quality appraisal using the Joanna Briggs Institute and Critical Appraisal Skills Programme checklists showed that most studies were of moderate to high methodological quality and clearly reported their objectives and methods. Table 1 summarizes the authors, publication year, country, design, objectives, key findings, and appraisal results of all included studies.

Table 1. Summary of all included studies

No.	Article Title	First Author	Year	Country	Study Method	Study Type	Objective	Key Findings	Appraisal Checklist
1	Multi-risk NaTech vulnerability indicator: A step further	Castro Rodriguez DJ (D. J. Castro Rodriguez et al., 2025)	2025	Italy	Statistical–numerical model development, indicator assessment , case study	Quantitative modeling	To develop a multi-risk NaTech vulnerability index for industrial risk assessment	Composite index integrating type and quantity of hazardous materials and equipment sensitivity to natural hazards; identification of environmental and human vulnerability hotspots; recommendations for improving dynamic models	JB1
2	Enhancing emergency response planning for NaTech accidents in process operations using FRAM	Zheng QH (Q. H. Zheng et al., 2024)	2024	China / Netherlands	Qualitative FRAM modeling and emergency system analysis	Qualitative study	To improve NaTech emergency response planning in fuel storage facilities through a systems approach	Identification of functional relationships in emergency response; analysis of variability; continuous improvement cycle; importance of coordination and resource management under time constraints	CASP
3	Resilience assessment of chemical industrial areas during NaTech-related cascading multi-hazards	Zeng T (Zeng et al., 2023)	2023	China	Quantitative modeling using dynamic Bayesian networks, resilience analysis	Quantitative modeling	To assess industrial system resilience against cascading multi-hazard NaTech events	Improved resilience through combining active and passive safety barriers; slower performance degradation; need for consequence-specific models	JB1
4	A Quantitative Framework for Propagation Paths of NaTech Domino Effects in Chemical Industrial Parks: Part II- Risk Assessment and Mitigation System Foresight of the Consequences of the Hazmat Release From an Oil Refinery on the Surrounding Urban Community Following an Earthquake: A NaTech Scenario Analysis	Yang YF (Yang et al., 2023)	2023	China	Quantitative modeling and mathematical framework	Quantitative modeling	To propose a quantitative framework for identifying and modeling propagation paths in NaTech domino accidents	Identification of propagation paths and critical nodes; introduction of the “cut-chain” concept to mitigate risks	CASP
5		Shafiei Moghaddam P (Shafiei Moghaddam et al., 2023)	2023	Iran	Literature review, Scenario-based risk assessment , Risk Management Plan (RMP) framework	Applied Scenario-Based Study	To predict the impacts of hazardous material release from refineries on surrounding populations and infrastructure	Dispersion of toxic materials over several kilometers; high residential vulnerability; weaknesses in critical infrastructure; evacuation challenges	JB1

Continued Table 1. Summary of all included studies

No.	Article Title	First Author	Year	Country	Study Method	Study Type	Objective	Key Findings	Appraisal Checklist
6	Implementation of a NaTech Vulnerability Index in a Seveso Establishment	Castro Rodriguez DJ (Castro Rodriguez et al., 2023)	2023	Italy	Quantitative indicator development and field testing in an industrial unit	Applied semi-quantitative Study	To design and implement a NaTech vulnerability index for Seveso-regulated industries	Quantitative evaluation of vulnerability level; identification of key factors (equipment, materials, climate); managerial applicability of the index	JB1
7	Developing a barrier management framework for dealing with NaTech domino effects and increasing chemical cluster resilience A paradigm shift in NaTech risk management: Development of a rating system framework for evaluating the performance of industry	Zeng T (T. Zeng et al., 2022)	2022	China	Literature review, conceptual framework development, case study	Conceptual framework development	To develop a systematic barrier management framework for coping with NaTech domino effects in chemical industrial areas	Comprehensive four-phase framework (design, operation, accident, recovery); challenges include complex scenario analysis and integration with quantitative risk assessment; case study demonstrated risk reduction	CASP
8	Development of a rating system framework for evaluating the performance of industry	Suarez-Paba MC (Suarez-Paba & Cruz, 2022)	2022	Japan	Literature review, qualitative content analysis (QCA), comparison of rating systems	Conceptual framework development	To propose the "NaTech RateME" framework for evaluating industrial performance in NaTech risk management	Framework includes four domains (infrastructure, organization, governance, environment) and 90 evaluation criteria; rating levels range from platinum to bronze based on risk exposure	CASP
9	Challenges of emergency evacuation of residential areas caused by chemical release due to the earthquake: a NaTech event scenario	Shafiei Moghaddam P (Shafiei Moghaddam et al., 2022)	2022	Iran	Two-phase study: literature review and scenario analysis	Applied scenario-based study	To identify challenges of emergency evacuation in a NaTech scenario (earthquake and H ₂ S release) affecting residential areas near a refinery	High simultaneous exposure of population to earthquake and toxic gas; inadequacy of designated evacuation sites; interruption of emergency operations; multiple and unnecessary evacuations; need for updated evacuation maps, public education, and interagency coordination	JB1
10	Factors Affecting Petrochemical Industry Preparedness in Fire: A Qualitative Study	Pirani D (Pirani et al., 2022)	2022	Iran	Qualitative case study with content analysis and semi-structured interviews	Qualitative study	To explore factors influencing petrochemical industry preparedness for fire incidents	Six main categories and sixteen subcategories identified, including fire control, policymaking, management factors, support factors, safety culture, and consequences of sanctions	CASP
11	Vulnerability assessment method for domino effects analysis in chemical clusters	Huang KX (Huang et al., 2022)	2022	China	Quantitative vulnerability assessment with case study	Analytical quantitative stud	To develop and validate a vulnerability assessment method for analyzing NaTech-induced domino effects in chemical storage clusters	Considers exposure, sensitivity, and resilience; optimization of safety barriers in the case study	CASP

Continued Table 1. Summary of all included studies

No.	Article Title	First Author	Year	Country	Study Method	Study Type	Objective	Key Findings	Appraisal Checklist
12	The Management of Na-Tech Risk Using Bayesian Network	Ancione G (Ancione & Milazzo, 2021)	2021	Italy	Bayesian network modeling with GIS, applied to case study	Quantitative / modeling	To develop a dynamic and adaptive tool for NaTech risk management using Bayesian networks To evaluate crisis management systems in five petrochemical plants from organizational, human, and technical perspectives	Discrete variable risk index; implemented in a flood case study in Italy	JB1
13	An entropy-based TOPSIS approach for analyzing and assessing crisis management systems in petrochemical industries	Salehi V (Salehi et al., 2020)	2020	Iran	Multi-criteria decision-making (MCDM) using entropy and TOPSIS; questionnaire survey	Quantitative	To develop a methodology for computing process plant resilience against earthquakes	Organizational and human factors had the greatest influence (58% and 49%); plants ranked using TOPSIS	CASP
14	Computing resilience of process plants under Na-Tech events: Methodology and application to seismic loading scenarios A fuzzy analytic hierarchy process-TOPSIS	Caputo AC (Caputo et al., 2020)	2020	Italy	Quantitative simulation with Monte Carlo and capacity diagrams	Quantitative	To prioritize emergency scenarios in petrochemical industries for corrective actions	The proposed approach predicts capacity reduction, recovery time, and economic losses; successful case study in a nitric acid plant	CASP
15	framework for prioritizing emergency in a petrochemical industry Natural hazard impacts on industry and critical infrastructure:	Abbassinia M (Abbassinia et al., 2020)	2020	Iran	Delphi technique, Fuzzy AHP, and TOPSIS	Quantitative	To identify NaTech risk drivers and propose performance indicators for risk management	Identified three major high-priority scenarios: warehouse fire, hydrogen leakage, and turbine gas leak	JB1
16	NaTech risk drivers and risk management performance indicators A methodology for quantitative vulnerability assessment of coupled multi-hazard in Chemical Industrial Park	Krausmann E (Krausmann et al., 2019)	2019	Italy	Mixed-method analysis of past cases and indicator development	Qualitative	To quantitatively assess vulnerability of chemical industrial parks to compound disasters	NaTech events account for 18% of pipeline damage; proposed indicators assess national preparedness	CASP
17		Chen GH (Chen et al., 2019)	2019	China	Quantitative GIS-based modeling	Quantitative modeling		Multi-hazard vulnerability higher than single-hazard; identified sensitive zones in southern China	JB1
18	Determination of Effective Criteria and Prioritization	Abbassinia M (ABBASSI)	2019	Iran	Qualitative, questionnaires, and	Qualitative	To identify and prioritize main criteria for	Identified five main criteria: severity, probability, extent, production	CASP

Continued Table 1. Summary of all included studies

No.	Article Title	First Author	Year	Country	Study Method	Study Type	Objective	Key Findings	Appraisal Checklist
	of Emergency Situations in a Petrochemical Industry	NIA et al., 2019)			Delphi method		emergency management in petrochemical industries	downtime, environmental pollution; classified emergencies into three levels (high, medium, low)	
19	The Impact of Nature on Chemical Industrial Facilities: Dealing with Challenges for Creating Resilient Chemical Industrial Parks	Reniers G (Reniers et al., 2018)	2018	Netherlands/ Belgium/	Literature review, case studies, conceptual framework design	Analytical – review	To design the EPIC framework for managing NaTech events and enhancing resilience of chemical industries	Introduced EPIC framework: (E) Education, (P) Proactive risk reduction, (I) Inspection & data analysis, (C) Collaboration & transparency; emphasized chemical ethics education, intrinsic safety design, and cooperation between industry, government, and academia	JB1
20	A resilience-based integrated process systems hazard analysis (RIPSHA) approach: Part II management system layer	Jain P (P. Jain et al., 2018)	2018	USA	Quantitative modeling of system resilience under seismic NaTech scenario	Quantitative analytical stud	To apply and validate the RIPSHA framework through quantitative resilience analysis	Developed resilience index linking capacity loss and recovery; applied to LNG case; demonstrated predictive capability and integration with process safety tools	CASP
21	A Resilience-based Integrated Process Systems Hazard Analysis (RIPSHA) approach: Part I plant system layer	Jain P (Prerna Jain et al., 2018)	2018	USA	Integration of resilience concepts into HAZOP for socio-technical hazard analysis	Conceptual framework study	To develop a resilience-based framework (RIPSHA) for identifying and assessing system vulnerability	Introduced dual-level socio-technical model; defined core resilience functions (anticipate, monitor, respond, learn); enhanced hazard identification beyond traditional HAZOP	CASP
22	Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant	Azadeh A (Azadeh, Salehi, Ashjari, et al., 2014)	2014	Iran	Survey + Data Envelopment Analysis (DEA)	Quantitative case study	To evaluate and rank the performance of resilience engineering factors in a petrochemical plant	Integrated Resilience Engineering (IRE) framework outperformed traditional models; preparedness and awareness were key determinants	JB1
23	Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant	Azadeh A (Azadeh, Salehi, Arvan, et al., 2014)	2014	Iran	Fuzzy cognitive maps + survey	Mixed-method case study	To determine the weight and importance of resilience engineering factors in petrochemical industries	Preparedness, awareness, and flexibility had the highest influence; redundancy had the least	CASP

Table 2. Themes and Related Analytical Structure

Theme	No. of Categories	No. of Sub-categories	No. of Codes	Studies with the Highest Number of Codes in Each Theme
Comprehensive NaTech Risk Management	3	8	60	(Rodriguez et al., 2025a) (12 codes)
Infrastructure and Equipment Development	2	6	52	(Reniers et al., 2018)(7 codes) (P. Jain et al., 2018) (16 codes),
Preparedness	5	10	122	(Azadeh, Salehi, Ashjari, et al., 2014) and (Shafiei Moghaddam et al., 2023) (10 codes each)
Response	3	6	31	(Shafiei Moghaddam et al., 2023) (9 codes)
Operational Continuity	1	2	17	(Zeng et al., 2023) (3 codes)
Recovery and Rehabilitation	2	4	20	(Caputo et al., 2020) and (T. Zeng et al., 2022) (4 codes each)
Knowledge and Technology Management	2	4	44	(Azadeh, Salehi, Arvan, et al., 2014; Azadeh, Salehi, Ashjari, et al., 2014)(5 codes each)

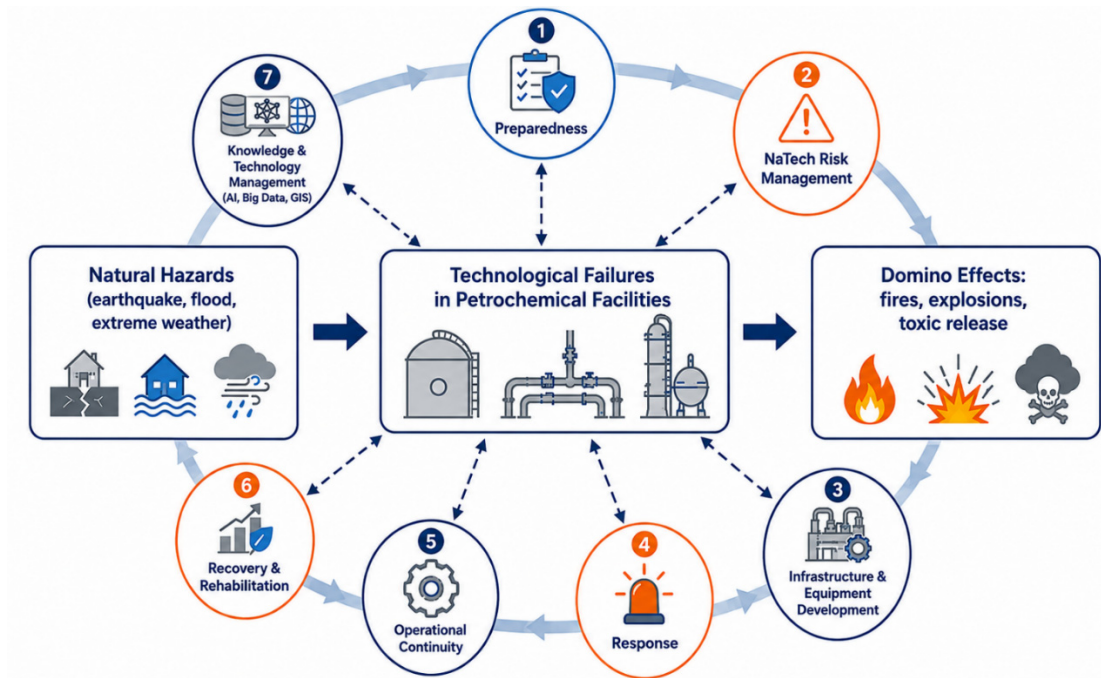


Fig. 3. Conceptual framework of resilience dimensions in petrochemical industries exposed to NaTech (Natural Hazard Triggered Technological) events.

The thematic synthesis yielded 346 initial codes from the 23 included studies. Through repeated comparison and refinement, these codes were grouped into 40 subcategories, 18 categories, and seven overarching themes representing the main dimensions of resilience and NaTech risk management in petrochemical industries (Figure 3).

Table 2 presents the seven themes, their related categories and subcategories, the number of codes assigned to each theme, and the studies contributing the greatest number of codes. The detailed thematic analysis is provided in Table 3.

The 346 codes were distributed across seven themes, covering the technical, organizational, and knowledge-related aspects of petrochemical resilience. Preparedness was the most prominent theme, with 122 codes (35%) related mainly to training, safety culture, coordination,

Table 3. Thematic Content Analysis of Included Studies on NaTech Resilience in Petrochemical Settings

Theme 1: Comprehensive NaTech Risk Management			
Theme	Category	Subcategory	Code (Article number from Table 1 corresponding to this code)
Comprehensive NaTech Risk Management	Risk Assessment and Prioritization	Risk Identification and Evaluation	Identification of the range of natural hazards (1); Prioritization of hazards (1,15); Risk assessment of hazardous materials and equipment (1); Analysis of internal facility risks (1); Integration of infrastructure and hazardous material risk assessment (3); Application of hierarchical and advanced risk analysis models in risk management (12); Individual risk modeling (4); Risk analysis of adjacent facilities (1); Identification of critical points with the highest damage potential (18); Assessment and management of NaTech (Natural-Technological) risks (1,4,8,12,16,17,18)
		Uncertainty Management	Modeling and management of uncertainty in risk analysis (3,21); Reassessment after implementing risk-reduction measures (4); Continuous updating of NaTech risk uncertainty (12)
		Domino/Cascading Effects	Analysis of domino and cascading accident effects (1,3,4,6,11,16,19,21,23); Identification of cascading vulnerability processes (1); Investigation of system-level domino propagation patterns (7); Modeling interactions among domino-amplifying factors (11,16); Characterization of fire dynamics and chain reactions (10)
	Consequence Analysis of NaTech Events	Economic Consequences	Estimation of direct economic losses (3,16); Economic assessment of operational capacity loss and recovery time (14)
		Health Consequences	Modeling social and health risks of accidents (4); Reducing physical vulnerability of surrounding residential buildings (5); Assessing health impacts on local communities (8); Analyzing spatial distribution of vulnerable populations (12); Evaluating accident impacts on residential areas (1); Assessment of human consequences of accidents (6,16); Evaluation of social and health consequences of accidents (8,15,21)
	Hazardous Materials Management	Environmental Consequences	Evaluation of environmental consequences (1,6,16,21)
		Classification and storage	Classification of hazardous materials (1, 6, 11) Determination of permissible storage capacity of materials (1)
		Leak and contamination control	Simulation of hazardous substances and gas dispersion (9) Control and prevention of gas leaks (5, 15) Fire control in chemical storage (15)
Theme 2: Development of Infrastructure and Equipment			
Theme	Category	Subcategory	Code (Article number from Table 1 corresponding to this code)
Infrastructure and Equipment Development	Design and Safety of Equipment	Safe Design	Inherently safe design of equipment and systems (10, 13)
			Plant design adapted to real and environmental conditions (14)
			Integration of climatic factors and climate change into design (16, 6, 19)
			Elimination or substitution of hazardous materials (19)
			Simplification of processes (19)
	Reinforcement and Optimization	Increasing fault tolerance in process design (20)	
		Reinforcement of critical infrastructures and key equipment (4, 5, 9, 11, 19, 22)	
		Strengthening and improving equipment design (6)	
		Enhancing the resilience of protective systems and critical infrastructures (17)	
		Establishing redundancy for equipment and resources (22, 23)	
Safety Barriers	Creating fault-tolerant systems (23)		
	Designing fault-resistant systems with automated safety systems (21)		
	Increasing equipment reliability and reducing dependence on human error (21)		
	Integration of active and passive barriers (1)		
	Establishing layered safety systems (23, 13)		
			Optimizing the placement of safety barriers based on vulnerability analysis (7, 20, 11)
			Physical segregation of sensitive units (19)
			Defining and controlling operational safety limits (20)

Continued Table 3. Thematic Content Analysis of Included Studies on NaTech Resilience in Petrochemical Settings

		Equipment Classification	Comprehensive classification of equipment based on performance and vulnerability criteria (1) Categorization of equipment based on hazards (6) Classification of facilities according to high-risk industry risk management standards (12) Identification of sensitive equipment and vulnerable infrastructures (7, 6) Determining the position and assessing the resistance of equipment against disasters (6) Optimization of equipment layout (11) Assessment of equipment vulnerability (8, 3, 11) Examination of physical and functional interconnections between equipment (1) Analysis of equipment performance and effectiveness of safety systems (3) Evaluation of layout and interactions among safety system components (3) Continuous monitoring and preventive maintenance of safety barriers (8, 7) Implementation of preventive maintenance programs and backup systems (13) Continuous risk management and equipment monitoring focused on natural disasters (19, 10) Performance evaluation and maintenance of equipment (20) Strengthening and regular maintenance of physical equipment (20, 14) Periodic inspections and real-data analysis (19)
	Equipment Risk Management	Equipment Vulnerability Reduction	
		Maintenance and Monitoring	
Theme 3: Preparedness			
Theme	Category	Subcategory	Code (Article number from Table 1 corresponding to this code)
Preparedness	Forecasting and Early Warning Systems	Prediction	Real-time monitoring and information sharing (22) Monitoring and early detection of anomalies (20, 21, 23) Early detection of external threats (20, 23) Monitoring and analysis of safety indicators (20)
		Early Warning	Design and implementation of early warning systems (4, 6, 15, 20) Designing warning systems tailored to specific hazards (earthquake, flood, fire) (18) Managing and reducing operational discrepancies during emergencies (2)
	Training and Capacity Building	Training	Specialized and continuous training of personnel for emergency preparedness (4, 5, 7, 8, 9, 10, 11, 13, 15, 16, 19, 20, 21, 22, 23) Continuous training for domino and cascading scenarios (19) Community training for disaster preparedness (5) Emergency evacuation training (5, 9) Training of response teams to reduce confusion (5) Strengthening knowledge and skills of supervisory units (6) Enhancing leadership and decision-making capabilities of managers (8, 10, 13)
		Safety Culture	Reducing human error and improving personnel knowledge (20) Establishing a culture of safety and transparent reporting (20, 22, 23) Monitoring and managing human errors (20) Continuous organizational culture-building and interaction (17) Strategic management commitment to safety (20, 22, 23, 10) Evaluating the effectiveness of safety promotion strategies (20) Assessing human and organizational aspects in crisis management systems (13) Developing supportive regulations and employee incentives for safety compliance (8) Using insurance incentives to enhance preparedness (10) Disseminating safety information to build public trust (19)
	Planning	Development of Guidelines and Technical Manuals	Providing guidelines aligned with preparedness levels (1) Designing an integrated plan for NaTech (Natural-Hazard Triggered Technological) accidents (5)

Continued Table 3. Thematic Content Analysis of Included Studies on NaTech Resilience in Petrochemical Settings

Exercises and Simulation	Coordination and Communication		Developing policies for low-probability but high-consequence events (6) Defining crisis levels and corresponding responses (15) Developing NaTech risk management performance indicators for national monitoring (16) Formulating a framework for managing safety barriers in NaTech events (7)
		Emergency Response Planning	Developing and updating emergency response plans (2, 4, 5, 9, 10, 18, 19, 20, 21, 22) Up-to-date planning for NaTech event response (13) Developing and testing accident and recovery scenarios (17) Developing prioritized corrective and control programs (15) Developing a Business Continuity Plan (BCP) (22) Developing a Disaster Recovery Plan (DRP) (22) Management of Change (20)
		Scenario Design and Drills	Conducting regular and diverse emergency drills for preparedness (4, 5, 13, 15, 18, 20, 21, 22, 23) Utilizing advanced simulation programs (1)
		Simulation	(Computer-based) simulation of NaTech accidents (3, 20, 2, 19) Quantitative modeling of NaTech scenarios (11, 21, 22) Application of analytical and hybrid simulation models for NaTech events (14)
		Intra-organizational Coordination	Strengthening intra-organizational coordination (5, 2, 13, 19, 20, 21, 23) Establishing communication and information exchange systems among units (10) Enhancing communication systems (13) Developing multi-layer communication channels (2) Strengthening emergency communication systems for improved coordination (5)
		Inter-organizational Coordination	Inter-organizational coordination with emergency and governmental agencies (2, 5, 9, 10, 16, 19, 20, 21, 22) Cross-disciplinary collaboration (1) Strengthening local, national, and international cooperation networks (16) Promoting strategic partnerships among government, industry, and academia (16, 19) Creating regional and international knowledge exchange networks (16) Enhancing stakeholder engagement in NaTech risk management (8) Developing coordination protocols among industries for joint response (8, 19) Increasing community participation in NaTech risk management (16)
Theme 4: Response			
Theme	Category	Subcategory	Code (Article number from Table 1 corresponding to this code)
Response	Emergency Response Management	Rapid Response Teams	Preparedness of emergency response teams (11) Capability for rapid identification and assessment of incidents (11) Ability for rapid activation and effective implementation of emergency response operations (11, 21)
		Incident Management	Crisis management and relief operations in multi-hazard conditions (17) Integrated approach to crisis management (19, 5)
	Resource and Equipment Management	Resource Supply and Allocation	Rapid allocation of sufficient human and equipment resources (10, 13, 11, 23) Assessment of critical infrastructure capacity (5) Provision of specialized equipment for handling toxic substances (5) Provision of equipment for rescue and evacuation (9) Provision of firefighting and operational equipment (10) Provision of personal protective equipment (PPE) (10) Increasing resources and establishing backup plans (2)

Continued Table 3. Thematic Content Analysis of Included Studies on NaTech Resilience in Petrochemical Settings

	Evacuation Management	Resource Optimization	Dynamic interaction and optimization of resources and equipment (2) Allocation of sufficient financial and logistical resources for crisis management (5) Smart resource management (22, 15) Optimal resource management to avoid competition during simultaneous incidents (5)
		Emergency Evacuation Planning	Updating emergency evacuation maps and identifying vulnerable areas (9) Evacuation planning for residential areas at risk (9, 5) Tripartite planning for containment of hazardous releases, evacuation, and exposure limitation (12)
		Evacuation Route Design	Managing unnecessary or repetitive evacuations (9, 5) Optimization of rescue routes for rapid and safe access (5) Establishment of safe and suitable routes and sites for emergency evacuation (5, 9)
		Theme 5: Operational Continuity	
		Theme	Category
		Subcategory	Code (Article number from Table 1 corresponding to this code)
Operational Continuity	Equipment and Organizational Continuity	Equipment Performance Continuity	Dynamic assessment of system performance variations (1) Development of a quantitative framework for chain performance continuity (3) Evaluation of equipment operational continuity considering temporal variations (3) Addressing time-dependent and dynamic vulnerability of key items and equipment (3) Risk reduction across the entire equipment life cycle (4) Structural and technical resilience of equipment against natural hazards (22, 14, 19, 12) Maintaining system functionality and rerouting operational pathways (23) Increasing flexibility of systems and infrastructures (19) Modeling the temporal recovery trend of capacity after NaTech events (14)
			Strengthening organizational resilience (22, 20, 21) Enhancing regional and urban resilience (8) Flexibility and adaptability to challenges (23)
		Organizational and Social Resilience	Theme 6: Recovery and Rehabilitation
Recovery and Rehabilitation	Recovery	System and Process Recovery	Analysis of post-event recovery capability (14, 3) Modeling the recovery trend of system capacity and performance (14) Planning and implementation of post-damage improvement actions (4, 7)
		Equipment and Safety Barrier Recovery	Improvement of safety barriers after an incident (7) Fault-tolerant design and rapid recovery (20, 21) Reinforcement of equipment against damage (14, 6, 9, 11, 17)
		Return to Stability	Enhancing the ability to return to a stable condition (7, 8) Increasing system flexibility and adaptability to environmental changes (19, 23)
	Rehabilitation	Improvement and Reconstruction	Monitoring and implementation of post-damage restoration activities (4, 7) Assessing equipment resilience under specific damage scenarios and damage probabilities (14)
			Theme 7: Knowledge and Technology Management
Knowledge and Technology Management	Advanced Technologies	Intelligent Safety Monitoring and Management	Theme
			Category
			Subcategory
			Code (Article number from Table 1 corresponding to this code)
			Utilization of Safety Instrumented Systems (SIS) (23) Development of disaster prediction technologies (19) Deployment of monitoring systems (15) Integrated management of various safety barriers using smart technologies (7) Application of simulation and emerging technologies (22)

Continued Table 3. Thematic Content Analysis of Included Studies on NaTech Resilience in Petrochemical Settings

Information Management	Spatial Risk Modeling and Analysis	Utilization of innovative technologies (Artificial Intelligence and Big Data) (2, 4, 16, 19, 20, 22, 23)
		Spatial prioritization for modeling natural hazard impacts (3)
		Application of GIS for spatial modeling and risk analysis (21, 16, 12)
	Data Collection and Analysis	Use of quantitative models and GIS for dynamic vulnerability assessment (17)
		Recording and analysis of accident and near-miss data (4, 7, 10, 20, 21, 22, 23)
		Collection and integration of safety and environmental data (6)
	Documentation of Lessons Learned	Integration of data into emergency and urban planning systems (6)
		Continuous updating of information and datasets (16, 17)
		Data monitoring (23)
		Controlling and minimizing the impact of uncertainties in data and analyses (19)
		Use of baseline data (spatial, geological, etc.) in risk assessment (17)
		Learning from incidents and lessons learned (7, 1, 10, 20, 23, 21, 22, 18)
		Documentation of crisis management processes (15)
		Sharing risk data and lessons learned (19, 21, 22, 8)

and emergency planning. Comprehensive NaTech Risk Management followed with 60 codes (17%), addressing hazard identification and prioritization, uncertainty, consequence assessment, domino and cascading effects, and socio-environmental impacts. Infrastructure and Equipment Development accounted for 52 codes (15%) and included inherently safe design, protection of critical systems, safety barriers, and fault-tolerant equipment.

Knowledge and Technology Management comprised 44 codes (13%) and highlighted artificial intelligence, Big Data, GIS-based modelling, digital monitoring, predictive safety, and organizational learning. Response included 31 codes (9%) related to evacuation, resource allocation, emergency actions, and organizational adaptability. Recovery and Rehabilitation accounted for 20 codes (6%), focusing on post-event restoration, safety-barrier improvement, and adaptive recovery, while Operational Continuity was the least represented theme, with 17 codes (5%), and concerned maintaining or restoring essential functions during and after disruption.

Overall, the literature focused more strongly on preparedness, risk management, and technical protection than on operational continuity and long-term recovery. Despite growing attention to knowledge and technology, empirical evidence on digital transformation, post-crisis adaptation, and sustained recovery remains limited, indicating that research on petrochemical NaTech resilience is expanding but still uneven.

This review identified seven connected dimensions of petrochemical resilience to NaTech events: comprehensive risk management, infrastructure and equipment, preparedness, response, operational continuity, recovery and rehabilitation, and knowledge and technology management. Together, they show that resilience is a dynamic capability shaped by learning, adaptation, coordinated decisions, and interaction among technical, human, organizational, and institutional systems (Suarez-Paba & Cruz, 2022).

Comprehensive risk management provides the foundation. Natural hazards can damage process units, tanks, pipelines, utilities, and nearby facilities, causing fires, explosions, toxic releases, contamination, and prolonged disruption. Assessment should therefore integrate hazards, uncertainty, consequences, and hazardous material control. NaTech RateME extends

risk assessment to infrastructure interdependencies, governance, and environmental interactions, while national systems should also include NaTech scenarios in highly industrialized areas (Suarez-Paba & Cruz, 2022; Girgin et al., 2019). Domino effects are particularly important because failures may spread across units and neighboring facilities. Propagation models can identify critical nodes (Yang et al., 2023), while consequence analysis should include environmental, health, and community impacts (Rodriguez et al., 2025a).

Bayesian networks, GIS, multi-risk indicators, and accident databases have improved NaTech analysis, but fragmented data and non-standardized indicators still limit comparison and learning (Girgin et al., 2019; Brignone et al., 2025). Economic losses, recovery time, remediation, and community recovery also require attention, although post-event validation remains limited (Kalemi et al., 2024). Accident analysis can identify vulnerable process stages (Kim et al., 2024), while storage control, dispersion modelling, leak prevention, and fire protection can reduce hazardous releases (Azadeh et al., 2008; Jung et al., 2024). This integrated approach connects industrial safety with disaster risk reduction, environmental protection, and public health, but requires shared databases and comparable indicators (Rakowska, 2024; Valente et al., 2025).

Infrastructure resilience should be managed across the facility lifecycle. Safety barriers must be monitored as operating conditions and hazard levels change (T. Zeng et al., 2022). Structural strengthening alone may be insufficient; redundancy and rapid repair can be equally important (Chen et al., 2022; Kalemi et al., 2024). However, barrier-management procedures remain poorly validated in operating facilities, and interdependencies among electricity, water, cooling, communication, and other utilities are still underexamined (Misuri, 2022; T. Zeng et al., 2022).

Preparedness was the most prominent theme, covering workforce competence, safety culture, planning, early warning, and coordination, consistent with the EPIC framework (Reniers et al., 2018). NaTech planning should combine scenario-based and capability-based approaches (Karagiannis, 2024), yet NaTech scenarios are still rarely included in exercises. Drills should address hazardous releases, utility failures, communication breakdowns, and evacuation difficulties. Sensor-based monitoring and the Functional Resonance Analysis Method may improve situational awareness, but only when supported by trained staff and embedded in organizational decisions (O'Reilly et al., 2023; Karagiannis, 2024; Reniers et al., 2018).

Response requires timely decisions and coordinated action. Propagation models and functional-variability monitoring can identify escalation points and emerging weaknesses (Yang et al., 2023; Q. Zheng et al., 2024). Incident command systems should combine expertise in natural hazards, hazardous materials, process safety, and emergency management (Karagiannis, 2024). Iranian studies also show that concurrent natural and technological emergencies complicate communication, evacuation, and coordination, although evaluations of performance during real events remain limited (Shafiei Moghaddam et al., 2022; Shafiei Moghaddam et al., 2023).

Operational continuity connects response with recovery and depends on protection, redundancy, flexibility, critical resources, and rapid restoration. Equipment vulnerability and expected recovery time affect continuity and insurance decisions (Kalemi et al., 2024), while flexible operations and repair capacity may shorten disruption (Chen et al., 2022; Yang et al., 2023). Recovery should identify recurring weaknesses rather than simply restore previous conditions. The resilience-based NaTech cycle links awareness, preparedness, response, and recovery, while incident analysis can guide priorities and reveal persistent vulnerabilities (RODRIGUEZ et al., 2025b; Brignone et al., 2025). Cost–benefit analysis is also needed when comparing prevention, repair capacity, and long-term recovery investments (Chen et al., 2022; Kalemi et al., 2024).

Knowledge and technology management supports prediction, monitoring, response, recovery, and learning. AI, Big Data, GIS, sensors, and simulation models can capture interactions

that static assessments may overlook. Current applications include sensor monitoring and stochastic models of risk propagation, damage, and economic loss (O'Reilly et al., 2023; Chen et al., 2022; Yang et al., 2023). However, many tools remain limited to models or small case studies. Harmonized databases, validated decision-support systems, real-world evaluation, and integration with training, procedures, and governance are therefore required (Karagiannis, 2024; RODRIGUEZ et al., 2025b).

Together, the seven dimensions form a single resilience lifecycle, as shown in Figure 3, and align with Hollnagel's capabilities of anticipating, monitoring, responding, and learning (Patriarca et al., 2018). The framework also adds petrochemical-specific priorities, including infrastructure resilience, hazardous material control, and cascading-effect management. The main challenge is not the absence of frameworks, but their limited routine application. Future studies should validate NaTech RateME and EPIC in operating facilities, develop harmonized indicators, and integrate AI, Big Data, and GIS into risk governance. In practice, resilience requires regular training, realistic multi-hazard exercises, inter-agency coordination, and reliable monitoring and decision-support systems. Integrated health, safety, environment, and ergonomics approaches support this coordinated model (Azadeh et al., 2009; Azadeh et al., 2008).

CONCLUSION

This review identified seven interconnected dimensions of resilience across the NaTech lifecycle in petrochemical industries. The findings show that resilience extends beyond maintaining operations or restoring production; it also involves preventing hazardous releases, controlling dangerous materials, protecting workers and nearby communities, and limiting environmental and public health impacts.

Although NaTech resilience frameworks have advanced in recent years, their application and validation in real petrochemical facilities remain limited. By bringing the available evidence together, this review presents resilience as an integrated process that links risk management, preparedness, infrastructure, response, continuity, recovery, and knowledge and technology management.

The review was limited by the small number of included studies, their concentration in Iran, China, and Italy, and the predominance of conceptual and model-based research. More field-based, longitudinal, and multi-hazard studies are therefore needed to evaluate resilience under real operating and post-event conditions.

Overall, the main challenge is not simply the lack of knowledge, but the limited translation of existing knowledge into routine practice. Strengthening petrochemical resilience requires continuous learning, closer integration of technical and organizational measures, and practical actions that reduce hazardous releases, environmental contamination, and public health impacts throughout the NaTech lifecycle.

ETHICS APPROVAL

This research approved by the Ethics Committee of Iran University of Medical Sciences (IUMS). The study protocol was reviewed and approved under the ethics code IR.IUMS.REC.1403.441. All procedures were conducted in accordance with institutional ethical standards and relevant national research regulations.

ACKNOWLEDGMENTS

This work was supported by Iran University of Medical Sciences as part of a PhD dissertation

project. The authors gratefully acknowledge the contributions of academic supervisors, institutional reviewers, and experts whose constructive comments improved the quality of this study.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

AUTHOR CONTRIBUTIONS

Fereshteh Taheri: Conceptualization, Methodology, Literature Search, Data Curation, Formal Analysis, and Writing – Original Draft.

Hesam Seyedin: Methodological Guidance, Validation, and Writing – Review & Editing.

Saber Moradi Hanifi: Expert Consultation, Conceptual Refinement, and Critical Review of the Manuscript.

Mohsen Dowlati: Supervision, Project Administration, and Writing – Review & Editing (Corresponding Author).

All authors contributed to the interpretation of findings, reviewed the manuscript critically for important intellectual content, and approved the final version for publication.

REFERENCES

- Abbassinia, M., Kalatpour, O., Motamedzade, M., Soltanian, A., & Mohammadfam, I. (2020). A fuzzy analytic hierarchy process-TOPSIS framework for prioritizing emergency in a petrochemical industry. *Archives of Trauma Research*, 9(1), 35–40. https://doi.org/10.4103/atr.atr_85_19
- Abbassinia, M., Kalatpour, O., Soltanian, A. R., Mohammadfam, I., & Ganjipour, M. (2019). Determination of effective criteria and prioritization of emergency situations in a petrochemical industry. *Occupational Hygiene and Health Promotion*, 3(1), 1–12.
- Ancione, G., & Milazzo, M. F. (2021). The management of Na-Tech risk using Bayesian network. *Water*, 13(14), Article 1966. <https://doi.org/10.3390/w13141966>
- Arosio, M., Martina, M. L. V., & Figueiredo, R. (2020). The whole is greater than the sum of its parts: A holistic graph-based assessment approach for natural hazard risk of complex systems. *Natural Hazards and Earth System Sciences*, 20(2), 521–547. <https://doi.org/10.5194/nhess-20-521-2020>
- Azadeh, A., Fam, I. M., & Azadeh, M. A. (2009). Integrated HSEE management systems for industry: A case study in gas refinery. *Journal of the Chinese Institute of Engineers*, 32(2), 235–241.
- Azadeh, A., Fam, I. M., Nouri, J., & Azadeh, M. A. (2008). Integrated health, safety, environment and ergonomics management system (HSEE-MS): An efficient substitution for conventional HSE-MS. *Journal of Scientific and Industrial Research*, 67(6), 403–411.
- Azadeh, A., Salehi, V., Arvan, M., & Dolatkah, M. (2014). Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant. *Safety Science*, 68, 99–107. <https://doi.org/10.1016/j.ssci.2014.03.004>
- Azadeh, A., Salehi, V., Ashjari, B., & Saberi, M. (2014). Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant. *Process Safety and Environmental Protection*, 92(3), 231–241. <https://doi.org/10.1016/j.psep.2013.03.002>
- Barquet, K., Englund, M., Inga, K., André, K., & Segnestam, L. (2024). Conceptualising multiple hazards and cascading effects on critical infrastructures. *Disasters*, 48(1), Article e12591. <https://doi.org/10.1111/disa.12591>
- Baser, B., & Behnam, B. (2020). An emergency response plan for cascading post-earthquake fires in fuel storage facilities. *Journal of Loss Prevention in the Process Industries*, 65, 104155.
- Brignone, M., Santamato, F., Ravina, M., Busini, V., & Panepinto, D. (2025). NaTech database and methodologies

- for its risk assessment: A review. *Natural Hazards*, 121(17), 19565–19590.
- Caputo, A. C., Kalemi, B., Paolacci, F., & Corritore, D. (2020). Computing resilience of process plants under Na-Tech events: Methodology and application to seismic loading scenarios. *Reliability Engineering & System Safety*, 195, Article 106685. <https://doi.org/10.1016/j.ress.2019.106685>
- CASP. (n.d.). CASP qualitative checklist. <https://casp-uk.net/casp-tools-checklists/>
- Castro Rodriguez, D. J., Barresi, A. A., & Demichela, M. (2025a). Multi-risk NaTech vulnerability indicator: A step further. *Journal of Loss Prevention in the Process Industries*, 95, Article 105588. <https://doi.org/10.1016/j.jlp.2025.105588>
- Castro Rodriguez, D. J., Barresi, A. A., & Demichela, M. (2025b). Resilience-based framework for enhancing NaTech risk management in industrial critical infrastructures. *Environment Systems and Decisions*, 45(4), 63.
- Castro Rodriguez, D. J., Pilone, E., Camuncoli, G., & Demichela, M. (2023). Implementation of a NaTech vulnerability index in a Seveso establishment. *Chemical Engineering Transactions*, 100, 43–48. <https://doi.org/10.3303/CET23100008>
- Çetinyokuş, S. (2024). Development of a new holistic process safety management system model based on business continuity and organizational resilience standards. *Journal of Turkish Operations Management*, 8(2), 322–338.
- Chen, C., Reniers, G., & Yang, M. (2022). A resilience-based approach for the prevention and mitigation of domino effects. In *Springer Series in Reliability Engineering* (pp. 155–176). Springer. https://doi.org/10.1007/978-3-030-88911-1_7
- Chen, G. H., Huang, K. X., Zou, M. T., Yang, Y. F., & Dong, H. Y. (2019). A methodology for quantitative vulnerability assessment of coupled multi-hazard in chemical industrial park. *Journal of Loss Prevention in the Process Industries*, 58, 30–41. <https://doi.org/10.1016/j.jlp.2019.01.008>
- Cozzani, V., Campedel, M., Renni, E., & Krausmann, E. (2010). Industrial accidents triggered by flood events: Analysis of past accidents. *Journal of Hazardous Materials*, 175(1–3), 501–509.
- Fekete, A., & Nehren, U. (2024). Climate change increased risk of forest fire, winter storm and technical failure risks related to power transmission lines – A spatial GIS risk assessment at Cologne district, Germany. *Progress in Disaster Science*, 24, Article 100387. <https://doi.org/10.1016/j.pdisas.2024.100387>
- Ghaljahi, M., Omid, L., & Karimi, A. (2025). Resilience assessment in process industries: A review of literature. *Heliyon*, 11(4), e43000.
- Girgin, S., Necci, A., & Krausmann, E. (2019). Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents. *International Journal of Disaster Risk Reduction*, 35, 101072.
- Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: Concepts, procedures and measures to achieve trustworthiness. *Nurse Education Today*, 24(2), 105–112.
- Hollnagel, E., Woods, D. D., & Leveson, N. (2006). *Resilience engineering: Concepts and precepts*. Ashgate Publishing.
- Huang, K. X., Chen, G. H., & Khan, F. (2022). Vulnerability assessment method for domino effects analysis in chemical clusters. *Process Safety and Environmental Protection*, 164, 539–554. <https://doi.org/10.1016/j.psep.2022.06.021>
- Jain, P., Rogers, W. J., Pasman, H. J., Keim, K. K., & Mannan, M. S. (2018a). A resilience-based integrated process systems hazard analysis (RIPSHA) approach: Part I plant system layer. *Process Safety and Environmental Protection*, 116, 92–105.
- Jain, P., Rogers, W. J., Pasman, H. J., & Mannan, M. S. (2018b). A resilience-based integrated process systems hazard analysis (RIPSHA) approach: Part II management system layer. *Process Safety and Environmental Protection*, 118, 115–124. <https://doi.org/10.1016/j.psep.2018.06.037>
- Jimoh-Hamza, O. K., & Ajao, A. T. (2025). Biodegradation of Total Petroleum Hydrocarbons and EPA-16 PAHs in Crude Oil by *Pseudomonas aeruginosa* KUD2. *Pollution*, *11*(2), 312–328. <https://doi.org/10.22059/poll.2024.378584.2438>
- Jin, Y. F., Tong, X., Zheng, X. Z., Li, Y., Dong, B. B., & Liu, Q. Y. (2025). Integrated cloud assessment of emergency response capability maturity in chemical parks based on “4SM” and improved portfolio empowerment. *Journal of Loss Prevention in the Process Industries*, 97, Article 105696. <https://doi.org/10.1016/j.jlp.2025.105696>
- Jung, J.-Y., Park, S.-H., Moon, J.-E., Yoon, J.-H., Yoon, S.-W., & Lee, C.-M. (2024). Aggregate risk assessment for multi-route exposure to hazardous chemicals caused by chemical accidents, with a focus on toluene. *Asian Journal of Atmospheric Environment*, 18(1), 17.
- Kalemi, B., Caputo, A. C., Corritore, D., & Paolacci, F. (2024). A probabilistic framework for the estimation of resilience of process plants under Na-Tech seismic events. *Bulletin of Earthquake Engineering*, 22(1), 75–106.
- Karagiannis, G. M. (2024). Natech emergency preparedness and response. In *Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press.

- Kim, L. S., Yoon, C., Lee, D., Shin, G., & Jung, S. (2024). A study on the sustainability of petrochemical industrial complexes through accident data analysis. *Processes*, 12(12), 2637.
- Krausmann, E., & Cruz, A. M. (2013). Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. *Natural Hazards*, 67(2), 811–828. <https://doi.org/10.1007/s11069-013-0607-0>
- Krausmann, E., Girgin, S., & Necci, A. (2019). Natural hazard impacts on industry and critical infrastructure: Natech risk drivers and risk management performance indicators. *International Journal of Disaster Risk Reduction*, 40, Article 101163. <https://doi.org/10.1016/j.ijdrr.2019.101163>
- Luo, X., Tzioutzios, D., Suárez-Paba, M. C., & Cruz, A. M. (2024). Climate change impacts on Natech risk. In *Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press.
- Misuri, A. (2022). Development of a comprehensive framework for the assessment of technological scenarios triggered by natural events (Natech) in the chemical and process industries [Doctoral dissertation]. University of Bologna.
- Misuri, A., & Cozzani, V. (2022). An innovative framework for chemical and process facilities to support a comprehensive Natech risk assessment. *Chemical Engineering Transactions*, 90, 175–180.
- Nicotra, G., Rossi, E., Decarli, L., Di Talia, V., Tugnoli, A., & Cozzani, V. (2024, June 3–5). Natech (natural hazard triggering technological disasters) events risk management: An operational approach [Conference paper]. SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability.
- O'Reilly, G. J., Shahnazaryan, D., Dubini, P., Brunesi, E., Rosti, A., Dacarro, F., Gotti, A., Silvestri, D., Mascetti, S., & Ducci, M. (2023). Risk-aware navigation in industrial plants at risk of NaTech accidents. *International Journal of Disaster Risk Reduction*, 88, 103620.
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71.
- Pasman, H., Kottawar, K., & Jain, P. (2020). Resilience of process plant: What, why, and how resilience can improve safety and sustainability. *Sustainability*, 12(15), 6152.
- Patriarca, R., Bergström, J., Di Gravio, G., & Costantino, F. (2018). Resilience engineering: Current status of the research and future challenges. *Safety Science*, 102, 79–100.
- Pirani, D., Gholamnia, R., Ghomian, Z., Ebadi, A., Ghaffari, M., Jamshidi, N., & Khorasani-Zavareh, D. (2022). Factors affecting petrochemical industry preparedness in fire: A qualitative study. *Archives of Trauma Research*, 11(4), 189–198. https://doi.org/10.4103/atrr.atrr_46_22
- Rakowska, J. (2024). Searching for a sustainable solution to increasing chemical pollution. *Environmental Science and Pollution Research*, 31(28), 40903–40915.
- Reniers, G., Khakzad, N., Cozzani, V., & Khan, F. (2018). The impact of nature on chemical industrial facilities: Dealing with challenges for creating resilient chemical industrial parks. *Journal of Loss Prevention in the Process Industries*, 56, 378–385. <https://doi.org/10.1016/j.jlp.2018.09.010>
- Rodriguez, D. J. C., Barresi, A. A., & Demichela, M. (2025). Multi-risk NaTech vulnerability indicator: A step further. *Journal of Loss Prevention in the Process Industries*, 95, 105588.
- Salehi, V., Zarei, H., Shirali, G. A., & Hajizadeh, K. (2020). An entropy-based TOPSIS approach for analyzing and assessing crisis management systems in petrochemical industries. *Journal of Loss Prevention in the Process Industries*, 67, Article 104241. <https://doi.org/10.1016/j.jlp.2020.104241>
- Shafiei Moghaddam, P., Jahangiri, K., Sohrabizadeh, S., Hassani, N., Hoseini Moghaddam, M., & Monazami Tehrani, G. (2022). Challenges of emergency evacuation of residential areas caused by chemical release due to the earthquake: A Natech event scenario. *Journal of Injury and Violence Research*, 14(1), 33–41. <https://doi.org/10.5249/jivr.v14i1.1698>
- Shafiei Moghaddam, P., Jahangiri, K., Sohrabizadeh, S., Hassani, N., Hoseini Moghaddam, M., & Tehrani, G. M. (2023). Foresight of the consequences of the hazmat release from an oil refinery on the surrounding urban community following an earthquake: A Natech scenario analysis. *Disaster Medicine and Public Health Preparedness*, 17, Article e79. <https://doi.org/10.1017/dmp.2021.349>
- Suarez-Paba, M. C., & Cruz, A. M. (2022). A paradigm shift in Natech risk management: Development of a rating system framework for evaluating the performance of industry. *Journal of Loss Prevention in the Process Industries*, 74, 104615.
- Suárez-Paba, M. C., Luo, X., Tzioutzios, D., & Cruz, A. M. (2025). Natech risk governance initiatives and way forward. In *Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press.
- Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Medical Research Methodology*, 8(1), 45.
- Valente, M., Ricci, F., & Cozzani, V. (2025). A systematic review of resilience engineering applications to Natech

- accidents in the chemical and process industry. *Reliability Engineering & System Safety*, 255, 110670.
- VERBI Software. (2022). MAXQDA 2022 [Computer software]. <https://www.maxqda.com/>
- Yahaya, N. S., Pereira, J. J., Taha, M. R., & Yaacob, W. Z. W. (2024). Natech potential due to emerging climate hazards and awareness of the local stakeholders in the coastal industrial site of Kuala Selangor, Malaysia. *Chemosphere*, 367, 143551.
- Yang, Y. F., Chen, G. H., & Zhao, Y. F. (2023). A quantitative framework for propagation paths of Natech domino effects in chemical industrial parks: Part II—Risk assessment and mitigation system. *Sustainability*, 15(10), Article 8306. <https://doi.org/10.3390/su15108306>
- Zeng, T., Chen, G., & Reniers, G. (2022a). Coping with flood Natech events: A safety framework to make chemical clusters more resilient. *Chemical Engineering Transactions*, 90, 805–810.
- Zeng, T., Chen, G. H., Reniers, G., & Hu, K. (2023). Resilience assessment of chemical industrial areas during Natech-related cascading multi-hazards. *Journal of Loss Prevention in the Process Industries*, 81, Article 104967. <https://doi.org/10.1016/j.jlp.2022.104967>
- Zeng, T., Chen, G. H., Reniers, G., & Men, J. K. (2022b). Developing a barrier management framework for dealing with Natech domino effects and increasing chemical cluster resilience. *Process Safety and Environmental Protection*, 168, 778–791. <https://doi.org/10.1016/j.psep.2022.10.024>
- Zheng, Q., Liu, X., Yang, M., Wang, W., & Adriaensen, A. (2024). Enhancing emergency response planning for Natech accidents in process operations using functional resonance analysis method (FRAM): A case of fuel storage tank farm. *Process Safety and Environmental Protection*, 188, 514–527. <https://doi.org/10.1016/j.psep.2024.05.132>