

Article

A Screening-Level Multi-Criteria Decision-Support Framework for Prioritizing Dual-Use Chemical Scenarios in Emergency Preparedness

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Abstract

The increasing availability of dual-use chemicals has created emerging challenges for chemical emergency preparedness and CBRN risk management. Unlike conventional single-agent hazards, dual-use chemicals may be combined, diverted, or repurposed in ways that complicate regulatory control, early detection, and operational response. However, existing risk assessment approaches remain largely oriented toward individual hazardous substances and provide limited support for systematically prioritizing dual-use chemical scenarios. This study proposes a screening-level multi-criteria decision-support framework for evaluating dual-use chemical scenarios in emergency preparedness contexts. The framework integrates four key criteria—toxicity, reactivity, accessibility, and detection difficulty—and applies an expert-based semi-quantitative scoring model using Analytic Hierarchy Process (AHP)-derived weights to representative scenarios in high-risk public environments, including transportation hubs and urban public spaces. The results show that operational risk is not determined by toxicity alone. The TATP scenario produced the highest relative priority score, followed by VX binary and sarin precursor scenarios, indicating that accessibility and reactivity can substantially influence risk prioritization when combined with detection difficulty. These findings demonstrate the need to incorporate both intrinsic hazard characteristics and operational response constraints into CBRN preparedness planning. The proposed framework provides a practical tool for preliminary risk screening, scenario prioritization, emergency response planning, regulatory review, and inter-agency coordination for emerging dual-use chemical risks.

Keywords: chemical emergency preparedness; dual-use chemicals; CBRN risk management; multi-criteria decision-making; Analytic Hierarchy Process (AHP); scenario-based risk prioritization



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1. Introduction

In recent years, CBRN (Chemical, Biological, Radiological, and Nuclear) threats have evolved in both complexity and unpredictability, creating significant challenges for emergency preparedness and response. CBRN incidents are often characterized by high uncertainty, low-probability but high-consequence outcomes, and the need for rapid coordination among multiple agencies, including law enforcement, fire services, emergency medical teams, public health authorities, environmental agencies, and infrastructure operators. In the early phase of an incident, responders may not immediately know whether the

event is accidental, criminal, or terrorist in nature. This uncertainty complicates substance identification, protective action decisions, risk communication, scene control, evacuation or shelter-in-place decisions, and the deployment of specialized detection and decontamination resources [1–6].

Dual-use chemical agents represent a particularly challenging subset of emerging CBRN threats. Many dual-use chemicals have legitimate industrial, commercial, laboratory, agricultural, or transportation-related applications, but they may also be diverted, combined, concentrated, or repurposed for malicious purposes [1,6,7]. Unlike highly restricted chemical warfare agents, some dual-use substances are embedded in ordinary supply chains and may be accessible through legitimate commercial or industrial channels. Their risk is therefore not determined by intrinsic toxicity alone. A substance or precursor may become operationally significant when it is easily accessible, chemically reactive, difficult to recognize in the field, or capable of producing hazardous effects through combination with other materials.

Another important challenge is that dual-use chemical incidents may initially resemble ordinary hazardous-material releases or industrial accidents. This ambiguity can delay threat recognition and response escalation, especially when responders must distinguish between accidental release, negligence, criminal misuse, or intentional CBRN attack under incomplete information [3]. In addition, field-level identification may be constrained by limited sensory cues, overlapping industrial hazards, false alarms, and the need for specialized detection equipment or laboratory confirmation. These characteristics create a preparedness problem that extends beyond conventional substance-specific hazard classification.

Existing CBRN and hazardous-material risk assessment approaches have contributed substantially to chemical safety, emergency planning, and risk governance. However, many conventional approaches are primarily designed for known industrial processes, predefined hazardous substances, or single-agent consequence assessment. Such approaches may be insufficient for prioritizing dual-use chemical scenarios that involve accessible materials, combinatorial hazards, uncertain intent, delayed recognition, and response-relevant operational constraints. In particular, toxicity-centered ranking may underestimate scenarios in which moderate toxicity is combined with high accessibility, high reactivity, and high detection difficulty. Therefore, emergency preparedness agencies require a transparent screening-level tool that can compare representative scenarios before more detailed consequence modeling, dispersion analysis, or site-specific risk assessment is conducted.

To address this gap, this study develops a screening-level, scenario-based multi-criteria decision-support framework for prioritizing dual-use chemical scenarios in CBRN emergency preparedness. The framework integrates two types of criteria. The first type consists of intrinsic hazard attributes, including toxicity and reactivity, which describe the inherent potential of a chemical scenario to cause severe health effects, physical damage, or rapid hazardous transformation. The second type consists of operational feasibility and response-relevant factors, including accessibility and detection difficulty, which reflect the likelihood of material availability or diversion before an incident and the difficulty of recognizing and confirming the agent during the early response phase.

The proposed framework applies the Analytic Hierarchy Process (AHP) to derive expert-based criterion weights and uses Simple Additive Weighting (SAW) to aggregate scenario-level scores into relative composite chemical risk priorities. Environmental vulnerability is classified separately from the composite score and is used as a contextual interpretation layer for emergency response planning. This separation is important because built-environment factors, such as enclosure, crowd density, ventilation constraints, spatial connectivity, and evacuation complexity, can amplify operational consequences without being part of the chemical risk score itself. Thus, the composite score supports

baseline scenario prioritization, whereas environmental vulnerability supports site-specific interpretation for preparedness planning, training design, and resource allocation.

Specifically, this study aims to (1) define multi-dimensional evaluation criteria that capture both intrinsic hazard potential and response-relevant operational factors; (2) derive criterion weights using expert-based AHP informed by multidisciplinary CBRN response and chemical safety expertise; (3) calculate relative composite risk priority scores for representative dual-use chemical scenarios using SAW-based aggregation; (4) interpret the resulting priorities in relation to built-environment vulnerability and emergency response implications; and (5) examine the robustness of the prioritization results through sensitivity analysis. An overview of the framework workflow, including scenario definition, criteria identification, expert evaluation, AHP weighting, scenario scoring, SAW-based aggregation, risk ranking, environmental vulnerability interpretation, and sensitivity analysis, is provided in Figure 1 and described in detail in Section 3.1.

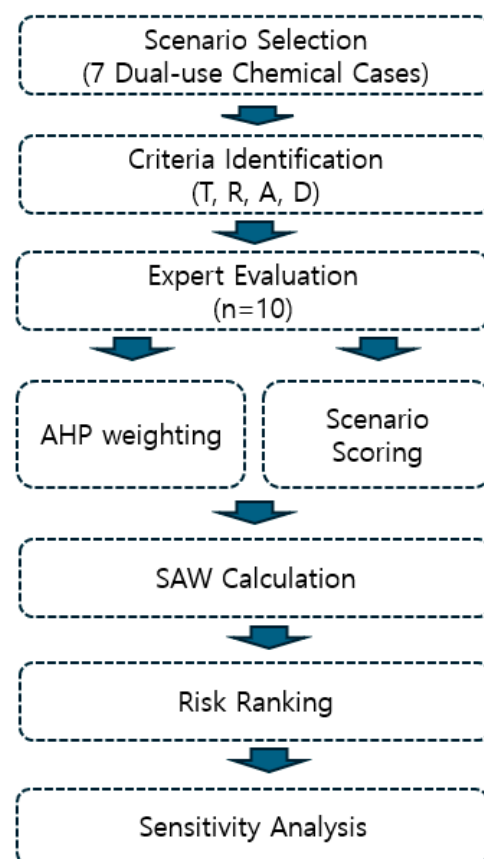


Figure 1. Proposed Framework for the risk assessment of dual-use chemical scenarios.

Beyond its application as a screening-level risk assessment tool, the proposed framework may also support emergency preparedness training and exercise planning. Because dual-use chemical incidents often involve uncertainty regarding substance identification, intent, and operational consequences, emergency responders require training scenarios that reflect both intrinsic hazard characteristics and practical response challenges. By systematically prioritizing representative dual-use chemical scenarios, the framework can assist agencies in selecting realistic training priorities, designing tabletop exercises, improving inter-agency coordination, and allocating preparedness resources more effectively. In this regard, the proposed approach contributes not only to risk assessment but also to the enhancement of operational readiness for emerging CBRN chemical threats.

2. Literature Review

2.1. CBRN and Chemical Emergency Preparedness

Recent studies have highlighted the structural limitations of current response systems in addressing dual-use chemical threats, particularly in terms of detection, regulation, and inter-agency coordination [7]. CBRN incidents have been widely recognized as high-impact, low-probability events that require coordinated and rapid response across multiple agencies. Previous studies have emphasized the importance of integrated response systems, risk communication, and decision-making under uncertainty in managing such incidents [5,8]. Incident-management standards further emphasize the need for clearly defined roles and responsibilities, resource coordination, and joint cooperation among multiple organizations during emergency response [9]. These requirements are particularly important for chemical incidents because early protective actions often must be taken before the causative agent, release mechanism, and intent of the event are fully confirmed [6,10].

From an emergency preparedness perspective, CBRN incidents differ from routine hazardous-material events in that they may involve deliberate intent, uncertain agent identity, public anxiety, and rapidly evolving operational conditions. These characteristics place significant pressure on responders to make timely decisions regarding scene isolation, evacuation or shelter-in-place orders, decontamination, medical triage, risk communication, and inter-agency notification. Frameworks based on risk governance and emergency management have therefore highlighted the need for structured coordination among law enforcement, fire services, emergency medical teams, public health authorities, and regulatory agencies [2,5,8,9,11]. The vulnerability of chemical infrastructure to deliberate attack or disruption has also been emphasized, particularly because chemical facilities, storage systems, and transportation networks may generate large-scale consequences if hazardous materials are intentionally released or misused [12].

Recent research has further emphasized that CBRN preparedness remains an active and unresolved research area. A recent systematic review of CBRN emergency preparedness strategies identified the need for continuous training, realistic exercises, inter-agency coordination, and structured response planning [13]. Similarly, a Delphi-based study of CBRN preparedness and response strategies highlighted the importance of expert-informed operational protocols, scenario-based planning, and coordinated decision-making across health and emergency systems [14]. Hospital-focused reviews and empirical studies have also shown that preparedness gaps remain in staff training, decontamination capacity, CBRNE-specific protocols, surge readiness, and inter-organizational coordination [15,16].

Despite these advancements, several studies have pointed out limitations in the initial response phase, particularly in identifying the nature of hazardous events [10]. In many real-world cases, chemical incidents are initially treated as industrial accidents rather than intentional attacks [3]. This ambiguity can lead to delayed situational awareness and suboptimal deployment of response resources, ultimately increasing the scale of damage. The vulnerability of chemical infrastructure to deliberate disruption has also been emphasized in prior studies, which note that the consequences of intentional chemical incidents may resemble severe industrial accidents while creating additional challenges related to attribution, public communication, and security response [12]. These observations support the need for scenario-based preparedness tools that can help agencies prioritize plausible dual-use chemical threats before an incident occurs.

2.2. Risk Assessment Approaches for Hazardous Chemicals

Risk assessment methodologies for hazardous chemicals have traditionally focused on industrial safety, process safety, occupational health, and environmental protection. Quantitative Risk Assessment (QRA), Hazard and Operability Study (HAZOP), and Layer

of Protection Analysis (LOPA) are among the widely used approaches for identifying hazards, estimating accident likelihood, evaluating consequences, and assessing safeguards in chemical process industries [17–21]. More broadly, ISO 31000 provides a general risk-management framework for identifying, analyzing, evaluating, treating, monitoring, and communicating risk, whereas IEC 31010 provides guidance on the selection and application of risk assessment techniques under uncertainty [22,23]. These approaches have contributed significantly to improving safety in industrial settings by supporting systematic hazard identification, process review, scenario development, and risk reduction.

Conventional chemical risk assessment methods typically consider factors such as toxicity, flammability, reactivity, exposure pathways, initiating events, and the availability of engineered or procedural safeguards. HAZOP is particularly useful for identifying deviations from intended process operation, QRA provides a quantitative structure for estimating likelihood and consequence, and LOPA supports semi-quantitative evaluation of protection layers between hazardous initiating events and undesired consequences [17–21,24]. These methods are therefore well suited to industrial facilities where process conditions, chemical inventories, operating parameters, and safety systems are known or can be reasonably defined.

Recent studies confirm that hazardous-chemical risk assessment is moving toward more integrated, dynamic, and uncertainty-aware approaches. Peron et al. reviewed available methodologies and research streams for hazardous-substance risk assessment in European industry, showing that the field increasingly combines technical hazard analysis with organizational and regulatory considerations [25]. Ab Rahim et al. provided a recent literature review of risk assessment methods for process safety, process security, and resilience in the chemical process industry, emphasizing the need to consider security and resilience in addition to conventional safety [26]. Dynamic approaches based on bow-tie analysis and Bayesian networks have also been proposed to update risk estimates under changing process conditions and uncertain accident pathways [27,28].

However, their applicability to CBRN terrorism or intentional misuse scenarios remains limited. Conventional methods are primarily designed for controlled environments with known processes and materials [24]. In CBRN preparedness contexts, the assessment problem is not limited to estimating the consequence of a known substance under predefined process conditions. It also involves uncertainty regarding material acquisition, intentional diversion, agent combination, delayed recognition, field detectability, and operational response constraints [29,30]. Therefore, while traditional process-safety methodologies remain essential for industrial hazard management, complementary screening-level decision-support approaches are needed to prioritize ambiguous or intentional dual-use chemical scenarios using both chemical hazard properties and response-relevant operational criteria.

2.3. Dual-Use Chemical Agents and Emerging Threats

As previously noted, the dual-use nature of certain chemicals presents a significant challenge to global security due to their legitimate industrial applications, wide distribution, and potential for diversion. The Chemical Weapons Convention recognizes that toxic chemicals and precursors may have both prohibited and legitimate purposes, and OPCW chemical schedules include substances that are relevant to chemical-weapons control while also appearing in industrial or commercial contexts [1,31]. The increasing availability and distribution of such chemicals have raised concerns regarding their potential misuse in terrorist activities [32,33]. Unlike highly regulated chemical warfare agents, many dual-use substances are embedded in ordinary industrial supply chains and may therefore be more accessible to non-state actors or malicious insiders [12,34].

A critical challenge associated with dual-use chemicals is their combinatorial potential. Individually, these substances may exhibit relatively low or manageable hazard levels under normal industrial use; however, when diverted, combined, concentrated, or chemically transformed, they can generate highly toxic, reactive, explosive, or otherwise hazardous outcomes. This characteristic significantly complicates detection, regulation, and response strategies. A substance may be legally available or routinely used in industry, yet become operationally significant when misused in a densely occupied or environmentally vulnerable setting. Conversely, a highly hazardous substance may present different preparedness implications depending on whether it is difficult to acquire, difficult to detect after release, or likely to be confused with an ordinary industrial accident.

Recent studies indicate that chemical terrorism and CBRN misuse remain contemporary threats rather than historical concerns. Tin and Ciottone argued that the use of chemical agents in terrorist events requires enhanced civilian preparedness, particularly because response systems may not be adequately equipped for rapid recognition and management of chemical casualties [35]. A subsequent descriptive analysis of CBRN weapon use by violent non-state actors found that chemical events accounted for a major proportion of recorded CBRN incidents and produced substantial fatalities and injuries [36]. More recent analysis of chemical terrorism patterns from 1970 to 2021 further suggests that the threat landscape is evolving and that preparedness systems must adapt to changing agent types, attack modes, and operational contexts [37]. In addition, research on toxic industrial chemicals and chemical warfare agent simulants shows that the boundary between industrial chemicals, hazardous materials, and warfare-related agents remains important for decontamination, detection, and response planning [38].

The dual-use problem is therefore both a material-control issue and an emergency-response issue. Existing studies have made important contributions to chemical terrorism, chemical security, and hazardous-materials management, but much of the literature remains focused on single-agent hazards, industrial accident scenarios, or regulatory control of specific substances [12,29–38]. Less attention has been given to the comparative prioritization of representative dual-use chemical scenarios that combine intrinsic hazard characteristics with operational factors such as accessibility and detection difficulty. This gap is important because emergency preparedness agencies require not only substance-specific hazard information but also a practical basis for selecting training scenarios, allocating detection resources, and planning inter-agency response exercises.

2.4. Multi-Criteria Decision-Making Approaches in CBRN and Chemical Risk Assessment

In recent years, Multi-Criteria Decision-Making (MCDM) techniques have been increasingly applied to complex risk assessment problems involving multiple and often conflicting evaluation criteria. MCDM is particularly relevant to CBRN and chemical emergency preparedness because such problems require the simultaneous consideration of heterogeneous criteria, including chemical severity, operational feasibility, detectability, response constraints, and environmental vulnerability [39–45]. Among these techniques, the Analytic Hierarchy Process (AHP) has been widely used to derive criterion weights from structured expert judgment, while the Simple Additive Weighting (SAW) method has been employed to aggregate weighted scores and rank alternatives [39,40,43,44,46,47].

Recent studies further demonstrate the value of MCDM and hybrid decision-support methods in disaster risk, emergency management, and resilience contexts. Keisler et al. developed a multicriteria decision analytic approach to systems resilience, demonstrating how decision analysis can support prioritization when systems are exposed to complex and uncertain disruptions [48]. Wang et al. applied an AHP–TOPSIS model to evaluate emergency management capacity in resilient communities, showing the relevance of MCDM

for preparedness and response-capability assessment [49]. Ortiz-Barrios et al. proposed a fuzzy hybrid decision-making framework for improving hospital disaster preparedness, highlighting the usefulness of hybrid MCDM models when preparedness indicators include both quantitative and qualitative factors [50]. A recent bibliometric analysis also confirmed the growing application of MCDM techniques in disaster management and emergency transportation research [51].

AHP is suitable for risk-prioritization problems in which empirical incident data are limited or uncertain but expert knowledge is available. Through pairwise comparisons, AHP allows experts to express the relative importance of criteria and provides a consistency check for evaluating the logical coherence of judgments [43,46,47]. SAW, in contrast, provides a transparent and computationally simple aggregation procedure in which normalized criterion scores are multiplied by criterion weights and summed to generate an overall priority score [40,44]. This simplicity is advantageous in screening-level emergency preparedness applications because decision-makers can easily trace how individual criteria contribute to the final ranking.

Despite the growing application of MCDM techniques in safety and risk management, limited research has applied AHP–SAW-based frameworks specifically to dual-use chemical scenarios within CBRN emergency preparedness contexts. Existing applications have primarily focused on industrial safety, environmental hazards, infrastructure systems, or transportation-related risks, leaving a gap in the systematic prioritization of dual-use chemical threats that incorporate both intrinsic hazard characteristics and operational response considerations. In particular, few studies have integrated toxicity, reactivity, accessibility, and detection difficulty into a single screening-level prioritization framework while treating environmental vulnerability as a separate contextual planning layer.

The methodological rationale for adopting a hybrid AHP–SAW framework in this study is based on the complementary strengths of the two techniques. AHP provides a systematic mechanism for deriving criterion weights from expert judgment, whereas SAW enables transparent aggregation and prioritization of alternative scenarios. Consequently, the combined AHP–SAW approach is particularly suitable for screening-level risk assessment problems involving multiple qualitative and quantitative criteria under uncertainty.

2.5. Synthesis of Research Gaps and Problem Definition

The review of existing literature reveals a critical gap in the systematic assessment of dual-use chemical risks within CBRN terrorism and emergency preparedness contexts. Current risk assessment models do not adequately incorporate the combined effects, accessibility, and detectability challenges associated with dual-use chemical scenarios [29]. Furthermore, there is a distinct lack of screening-level decision-support frameworks that integrate real-world response considerations into the formal evaluation process [30].

Recent studies have advanced CBRN decision support, medical response simulation, and AI-based preparedness analysis. Kegyes et al. proposed a machine learning-based decision-support framework for CBRN protection, demonstrating the increasing role of computational tools in CBRN preparedness [52]. De Rouck et al. developed computer simulation approaches for nerve-agent mass-casualty response and realistic victim profiles, showing how simulation can improve medical response planning for high-consequence CBRN events [53,54]. Farhat et al. also applied artificial intelligence techniques to examine CBRN preparedness perspectives and expert feedback in the Middle East and North Africa region [55]. These studies show that CBRN preparedness research is becoming increasingly data-driven, simulation-based, and decision-support oriented.

Nevertheless, three limitations remain unresolved. First, conventional hazardous-chemical risk assessment methods are primarily designed for known industrial processes

rather than intentional or ambiguous dual-use scenarios. Second, CBRN preparedness studies emphasize uncertainty, inter-agency coordination, medical readiness, and public communication, but often do not provide a transparent quantitative structure for comparing chemical scenarios before an incident occurs. Third, recent decision-support and simulation studies improve preparedness planning, but they generally focus on system-level readiness, medical response, or computational protection support rather than the relative prioritization of dual-use chemical scenarios based on intrinsic hazard and operational response criteria [52–56].

The present study addresses these limitations by proposing a screening-level AHP–SAW framework that integrates intrinsic hazard criteria, including toxicity and reactivity, with operational response criteria, including accessibility and detection difficulty. Unlike studies that focus mainly on preparedness capacity, medical simulation, or conventional process-safety analysis, this study explicitly prioritizes representative dual-use chemical scenarios for emergency preparedness planning. In addition, environmental vulnerability is treated separately from the composite chemical risk score, allowing decision-makers to interpret how built-environment conditions may affect exposure potential, evacuation difficulty, and response complexity without double-counting contextual factors. Therefore, the proposed framework is intended to complement, rather than replace, detailed QRA, HAZOP, LOPA, dispersion modeling, or medical-response simulation. Its primary contribution is to provide a transparent and reproducible screening structure for early-stage scenario prioritization, training scenario selection, inter-agency preparedness planning, and resource allocation for emerging CBRN chemical threats.

3. Methodology

This study developed a screening-level, scenario-based multi-criteria decision framework to prioritize dual-use hazardous chemical scenarios for CBRN emergency response planning. The framework was designed to support relative risk prioritization rather than deterministic consequence prediction. Accordingly, it combines ordinal scoring, expert-based weighting, and scenario interpretation to identify combinations that may require elevated preparedness and response attention.

A key methodological principle was to separate the chemical risk priority score from the contextual vulnerability of the incident environment. The composite score was calculated only from the four AHP-weighted criteria: toxicity, reactivity, accessibility, and detection difficulty, following the AHP-based weighted aggregation approach [39,40,44,46,47]. Environmental vulnerability was assessed separately to interpret how built-environment conditions may amplify exposure potential, evacuation difficulty, and operational complexity.

3.1. Assessment Framework and Workflow

The proposed risk assessment framework is structured around four primary criteria—toxicity, reactivity, accessibility, and detection difficulty—to capture the full spectrum of dual-use chemical threats. These criteria were selected by synthesizing classical industrial hazard metrics [17,18,57] with operational security considerations identified in recent CBRN response studies. The criteria were grouped into two functional dimensions. Toxicity and reactivity represent intrinsic hazard potential, because they evaluate the inherent capacity of a chemical combination to cause severe health effects, mass-casualty potential, or physical destruction. Accessibility and detection difficulty represent extrinsic operational factors; however, they refer to different phases of the threat timeline and different stakeholder perspectives.

To avoid conceptual overlap, accessibility was defined as a pre-incident, prevention-oriented criterion assessed from the perspective of potential acquisition or diversion. It reflects the extent to which chemicals or precursors can be obtained through legitimate industrial distribution networks, routine commercial markets, or weakly controlled supply chains, considering regulatory restrictions and licensing requirements. Detection difficulty, in contrast, was defined as an early incident-response criterion assessed from the perspective of frontline responders. It reflects the difficulty of recognizing, screening, and confirming the agent in the field after a release has begun, including limitations associated with sensory cues, portable detection equipment, false alarms, and the need for advanced confirmation. Thus, accessibility concerns how readily the material can be obtained before an incident, whereas detection difficulty concerns how difficult it is to identify the agent during the initial response phase. This chronological and operational separation prevents regulatory or supply-chain availability from being conflated with field-level detection limitations.

The assessment process consists of five stages: scenario definition, criterion selection, expert-based weighting, composite scoring, and strategic ranking. This structure links intrinsic hazard properties with operational feasibility factors while preserving a transparent distinction between material-related risk priority and contextual response complexity.

Seven representative scenarios were evaluated using four risk criteria. Criterion weights were derived using the Analytic Hierarchy Process (AHP), while scenario scores were obtained from expert evaluations. The weighted scores were aggregated using the Simple Additive Weighting (SAW) method and subsequently validated through sensitivity analyses.

3.2. Scenario Definition and Environmental Vulnerability Classification

To reflect realistic threat environments, representative scenarios were developed for high-risk public locations, including transportation hubs, urban crowded areas, semi-enclosed commercial facilities, and industrial or storage-related areas. Each scenario was characterized not only by chemical risk attributes but also by contextual environmental vulnerability factors, including population density, ventilation conditions, response time, evacuation constraints, and potential exposure pathways [22]. These environmental factors were used to support scenario interpretation rather than to serve as additional weighted criteria in the composite risk score. This scenario-based approach has been widely adopted in chemical safety and emergency response studies to address complex and uncertain environments [22,30,58].

The scoring of scenario-specific environmental conditions (on a scale of 1–5) was not determined solely by the nominal classification of facilities (e.g., “multi-use facilities” or “transportation hubs”) but rather based on a set of operationally relevant exposure and dispersion factors. Specifically, the scoring framework incorporates: (i) the average number of occupants and temporal crowd density, (ii) population density per unit area, (iii) enclosure characteristics and ventilation conditions (natural vs. mechanical ventilation), (iv) the complexity of evacuation and access control, and (v) the potential for secondary spread through interconnected spaces.

Accordingly, facilities with similar functional labels may receive different scores depending on their structural and operational characteristics. For instance, open-air or well-ventilated environments with low occupancy are assigned lower scores, whereas enclosed or semi-enclosed environments with high population density and centralized ventilation systems—such as underground stations, airport terminals, and large shopping complexes—are assigned higher scores due to their elevated potential for mass exposure and rapid contaminant propagation. Therefore, facility types were treated as contextual

descriptors rather than direct determinants of risk scores, ensuring that the scoring system reflects realistic hazard propagation dynamics and response constraints. Accordingly, the environmental score was not directly included in the weighted-sum risk equation; instead, it was used to contextualize the operational severity and response complexity of each scenario.

Each scenario was assigned an environmental score (1–5) based on the criteria presented in Table 1. High scores (4–5) were typically assigned to multi-use facilities and transportation hubs due to their high occupancy turnover, enclosed spatial configurations, and interconnected infrastructure, which collectively increase the likelihood of rapid contaminant dissemination and complicate initial response operations.

Table 1. Environmental scoring criteria for scenario assessment.

Score	Criteria Description
1	Low occupancy; open or outdoor environment with natural ventilation; easy access control and evacuation; minimal risk of contaminant accumulation.
2	Relatively low population density with partial enclosure; limited potential for localized exposure and moderate control feasibility.
3	Moderate occupancy and density; standard ventilation systems; potential for confined exposure within a limited area.
4	High population density in enclosed or semi-enclosed structures; mechanical ventilation; increased evacuation difficulty and higher potential for contaminant spread.
5	Extremely high population density in enclosed and spatially connected environments, such as underground networks or transit hubs; delayed evacuation and high likelihood of secondary propagation across multiple zones.

Based on these criteria, representative built-environment settings were assigned to each dual-use chemical scenario to evaluate its contextual vulnerability. The resulting environmental vulnerability scores were used to interpret how the same or similar chemical risk scores may lead to different response implications depending on the spatial and operational conditions of the incident location. Therefore, the environmental vulnerability score should be interpreted as a contextual classification variable rather than as an additional component of the AHP-weighted composite risk score.

Operationally, the framework is intended to be used in a two-step manner. First, the AHP-weighted composite score establishes the baseline priority of each chemical scenario. Second, the environmental vulnerability class is overlaid as a decision-support flag to translate that priority into site-specific preparedness actions, such as evacuation planning, ventilation control, decontamination staging, responder access routing, and allocation of training resources. This overlay does not change the numerical composite score; rather, it indicates where a chemically high-priority scenario may require more intensive operational planning because of the built environment.

3.3. Risk Criteria and Scoring Rubric

Four criteria were used to evaluate each scenario. Toxicity and reactivity represent intrinsic hazard potential, whereas accessibility and detection difficulty represent operational feasibility and response challenges. Each criterion was scored from 1 to 5. For accessibility, higher scores indicate lower acquisition barriers and broader availability through legitimate commercial or industrial channels. For detection difficulty, higher scores indicate lower field detectability during the early response phase and greater reliance on specialized equipment or laboratory-grade confirmation. These two criteria were intentionally

scored independently: a chemical may be widely accessible but readily detectable, or less accessible but difficult to identify once released.

To ensure consistency in expert evaluations, explicit scoring definitions were developed for each criterion. For example, a toxicity score of 1 represented negligible health effects, whereas a score of 5 represented severe or potentially lethal consequences. Similarly, an accessibility score of 1 indicated highly restricted substances, whereas a score of 5 represented materials that are routinely available for legitimate industrial or commercial use. Furthermore, to distinguish accessibility from detection difficulty, the latter was operationalized from the perspective of frontline responders during the incident phase; a detection difficulty score of 1 indicated agents instantly identifiable via standard field screening kits, while a score of 5 represented agents requiring advanced laboratory-grade verification due to high false-alarm rates. This conceptual separation ensures that pre-incident regulatory availability is not conflated with real-time operational detection challenges. Detailed scoring definitions are presented in Table 2.

Table 2. Risk assessment criteria and scoring rubric.

Criterion	1	2	3	4	5
Toxicity	Negligible	Mild reversible	Serious treatable	Life-threatening	Severe/lethal
Reactivity	Stable	Low	Conditional hazard	Rapid release	Violent/energetic
Accessibility—pre-incident acquisition/diversion barrier	Highly restricted	Specialized access	Licensed industrial	Common industrial	Routine use
Detection difficulty—early incident field identification	Obvious	Routine screening	Specialized tools	Advanced confirmation	Delayed recognition

3.4. Expert Elicitation and AHP-Based Criterion Weighting

This study employed an expert-based evaluation to determine the relative importance of the selected risk criteria. The expert panel consisted of 10 professionals with direct experience in CBRN response, hazardous-materials management, or related emergency operations as shown in Table 3. Experts were selected through purposive sampling from organizations directly involved in CBRN preparedness and response activities, based on their operational experience and professional expertise in hazardous-materials management, emergency response, and inter-agency coordination.

Table 3. Composition of the expert panel.

Professional Field	Number of Experts	Experience Range
Police EOD/CBRN	2	10–11 years
Military CBRN	2	12–13 years
Fire services	2	14–15 years
Ministry of Environment	2	10–11 years
Airport CBRN operations	2	12–13 years
Total	10	10–15 years

The panel was deliberately structured to ensure multidisciplinary representation across operational, regulatory, and infrastructure-related domains. Specifically, it included two experts from police Explosive Ordnance Disposal (EOD)/CBRN units, two from military CBRN units, two from fire services, two from the Ministry of Environment, and two from airport CBRN operations. All experts had at least 10 years of professional experience, ranging from 10 to 15 years, with an average of 12.1 years. To protect respondent confidentiality, participants were coded by number, and no personally identifying information was used in the analysis. This multidisciplinary composition helped the weighting process reflect both chemical hazard knowledge and practical response considerations, including field detection, access control, evacuation, and inter-agency coordination. Furthermore, the inclusion of experts from multiple response agencies helped reduce the potential for organizational bias and improved the practical relevance.

AHP was used to derive the relative importance weights of the four evaluation criteria. The AHP procedure consisted of five steps. First, the decision hierarchy was defined with the overall goal of prioritizing dual-use chemical scenarios, the four evaluation criteria, and the representative scenarios. Second, each expert compared the four criteria pairwise using Saaty's 1–9 scale, where higher values indicate stronger relative importance of one criterion over another. Third, the ten individual pairwise comparison matrices were aggregated into a single group-level comparison matrix using the element-wise geometric mean method. This aggregation method was used because AHP pairwise comparison values are ratio-scale judgments and the geometric mean preserves the reciprocal structure of the comparison matrix [59,60]. Fourth, the aggregated comparison matrix was normalized to derive the AHP criterion weights. Fifth, the consistency of the aggregated judgment matrix was evaluated using the consistency index (CI) and consistency ratio (CR), with a CR value below 0.10 considered acceptable according to the standard AHP procedure [46,47].

3.5. SAW-Based Composite Risk Priority Score

After the AHP-derived criterion weights were obtained, the Simple Additive Weighting (SAW) method was used to calculate the composite risk priority score for each scenario. SAW was selected because it provides a transparent and interpretable weighted-sum aggregation procedure for comparing alternatives evaluated across multiple criteria [39,40,44,46,47]. In this study, all four criteria were scored on the same 1–5 risk-oriented scale, where a higher score indicates greater risk or operational concern. Therefore, additional direction conversion was not required before aggregation.

For each scenario, the composite risk priority score was calculated by multiplying each criterion score by its corresponding AHP-derived weight and summing the weighted values across the four criteria:

$$R_s = \sum_{i=1}^4 w_i x_{si}$$

where R_s is the composite risk priority score for scenario s , w_i is the AHP-derived weight of criterion i , and x_{si} is the integer score assigned to scenario s for criterion i . Because the criterion weights sum to one, the resulting score remains on the same 1–5 scale as the original criterion scores.

The four criteria included in the SAW aggregation were toxicity, reactivity, accessibility, and detection difficulty. Environmental vulnerability was not included in the SAW equation; instead, it was treated as a separate contextual interpretation layer for assessing how built-environment conditions may affect exposure potential, evacuation difficulty, and response complexity. This separation prevents double-counting of contextual vulnerability factors while preserving the composite score as a chemical scenario priority index.

For practical decision-making, the two outputs should therefore be interpreted sequentially rather than merged through an additional equation. Scenarios with high composite scores remain the primary chemical-risk priorities, while high environmental vulnerability is used to escalate preparedness attention within those priorities or to flag moderate-score scenarios that may become operationally demanding in enclosed, crowded, or difficult-to-evacuate settings. This rule preserves the mathematical independence of the composite score and avoids double-counting exposure-related factors.

3.6. Sensitivity Analysis

A sensitivity analysis was conducted to examine the robustness of the AHP-based weighted-sum results. Because the composite risk priority score depends on expert-derived weights and ordinal 1–5 criterion scores, three complementary checks were applied: one-at-a-time weight sensitivity analysis, Monte Carlo simulation, and a non-compensatory threshold check.

First, each AHP-derived weight was varied by $\pm 10\%$ and $\pm 20\%$ while the remaining weights were proportionally rescaled so that the total weight remained equal to one. For each perturbation case, the composite score and scenario ranking were recalculated.

Second, Monte Carlo simulation was conducted to reflect uncertainty in both weights and ordinal scores. In each run, the four criterion weights were randomly sampled within $\pm 20\%$ of their baseline AHP values and normalized to sum to one. Because the expert-derived ordinal scores were considered relatively stable but still subject to judgment uncertainty, a simple discrete perturbation distribution ($-1, 0, +1$) with probabilities of 0.20, 0.60, and 0.20 was adopted to represent moderate scoring variability. Scenario scores were then perturbed accordingly while remaining within the valid 1–5 range. A total of 100,000 simulations were performed. In each simulation run, composite scores were recalculated, scenario rankings were recorded, and the probabilities of being ranked first and remaining within the top-three group were estimated.

Third, a non-compensatory threshold check was applied because the weighted-sum model is compensatory. Under this rule, scenarios were flagged as critical if they had toxicity = 5, reactivity = 5, or both toxicity and reactivity ≥ 4 . This rule was used as an additional safety-oriented screening step to prevent high-toxicity or high-reactivity scenarios from being downgraded solely because of lower accessibility or detection difficulty scores.

The threshold values were selected to represent high-consequence hazard conditions commonly emphasized in chemical emergency management, where extreme toxicity or reactivity may warrant priority attention regardless of composite ranking.

4. Results

4.1. AHP-Derived Criterion Weights and Consistency Analysis

The relative importance of the four risk criteria—toxicity, reactivity, accessibility, and detection difficulty—was determined using the AHP based on expert pairwise comparison judgments. As described in Section 3.4, the ten individual expert matrices were first aggregated using the element-wise geometric mean method to construct the group-level pairwise comparison matrix shown in Table 4.

The matrix indicates that toxicity was assigned greater relative importance than the other criteria, followed by reactivity. Accessibility and detection difficulty were evaluated as having similar levels of relative importance, reflecting their comparable roles in prevention-oriented assessment and initial response challenges.

The criterion weights were then calculated from Table 4 using the standard AHP normalization procedure. Each column of the aggregated comparison matrix was summed, and each matrix element was divided by its corresponding column sum. The priority

weight for each criterion was obtained by averaging the normalized values across the corresponding row. The resulting normalized matrix and AHP criterion weights are presented in Table 5.

Table 4. Aggregated pairwise comparison matrix for AHP-based weighting.

Criteria	Toxicity	Reactivity	Accessibility	Detection Difficulty
Toxicity	1.000	1.335	1.835	1.835
Reactivity	0.749	1.000	1.149	1.231
Accessibility	0.545	0.871	1.000	1.000
Detection difficulty	0.545	0.812	1.000	1.000

Table 5. Column-normalized AHP matrix and derived criterion weights.

Criteria	Toxicity	Reactivity	Accessibility	Detection Difficulty	AHP Weight	Rank
Toxicity	0.352	0.332	0.368	0.362	0.354	1
Reactivity	0.264	0.249	0.231	0.243	0.247	2
Accessibility	0.192	0.217	0.201	0.197	0.202	3
Detection difficulty	0.192	0.202	0.201	0.197	0.198	4

As shown in Table 5, toxicity received the highest weight (0.354), followed by reactivity (0.246), accessibility (0.202), and detection difficulty (0.198). These results indicate that toxicity was considered the most critical factor in evaluating the risk of dual-use chemical scenarios, while reactivity was also assigned substantial importance because of its potential to amplify incident consequences. Although accessibility and detection difficulty received slightly lower weights, they showed comparable levels of importance and together accounted for approximately 40% of the composite score. This distribution suggests that intrinsic hazard factors, namely toxicity and reactivity, were dominant in the expert-based prioritization, while operational feasibility factors, including accessibility and detection difficulty, also played a significant role in prevention and emergency response considerations.

As shown in Table 6, the logical consistency of the aggregated AHP comparison matrix was then evaluated using the Consistency Index (CI) and Consistency Ratio (CR). The CI was calculated from the maximum eigenvalue of the judgment matrix and the number of criteria, and the CR was obtained by dividing the CI by the Random Index (RI). To verify consistency, the weighted-sum vector was calculated by multiplying the aggregated comparison matrix by the derived weight vector. Each element of the weighted-sum vector was then divided by the corresponding criterion weight to estimate the consistency vector, and the average of this vector was used as $\lambda_{\max}$. For four criteria, the RI value is 0.900. The maximum eigenvalue ($\lambda_{\max}$) was 4.003, resulting in a CI value of 0.001. The resulting CR was also 0.001, which is substantially below the commonly accepted threshold of 0.10 [46,47]. Therefore, the aggregated expert judgments were considered logically consistent and suitable for deriving AHP-based criterion weights.

Table 6. Consistency test results for the AHP comparison matrix.

Consistency Metric	Value
$\lambda_{\max}$	4.003

Table 6. *Cont.*

Consistency Metric	Value
CI	0.001
RI	0.900
CR	0.001

4.2. Scenario-Level Criterion Scores

Seven representative dual-use chemical scenarios were evaluated using the four criteria and the 1–5 scoring rubric described in Section 3.3. The evaluation was conducted independently by ten experts with professional experience in CBRN response, emergency management, and chemical safety. For each scenario–criterion combination, the ten individual expert ratings were aggregated using the arithmetic mean to obtain a representative group score.

The resulting arithmetic mean values were rounded to the nearest integer to maintain consistency with the 1–5 ordinal scoring rubric used in the framework. Thus, all criterion scores reported in Table 7 are integer values derived from the rounded mean scores of the ten expert evaluations. These rounded integer scores were subsequently used as input values for the SAW-based composite risk ranking process. Because abbreviated scenario labels can appear broad when presented alone, Table 7 also provides expanded operational definitions for the seven representative scenarios. These definitions clarify each scenario by linking the shorthand label to a chemical scenario category, a representative built-environment setting, and a response-relevant exposure context. This approach improves interpretability while preserving the screening-level purpose of the framework and avoiding excessive site-specific assumptions, quantities, or deterministic incident mechanics.

As shown in Table 7, TATP received the highest scores for reactivity and accessibility, indicating that it was evaluated as both highly reactive and comparatively accessible within the screening framework. VX binary and sarin precursor scenarios received the highest toxicity scores, reflecting their severe health-impact potential. H₂O₂ mixture and ammonia-oxidizer scenarios were characterized by high accessibility, but their toxicity scores were lower than those of VX binary and sarin precursor scenarios. Chlorine and industrial solvent scenarios showed comparatively lower toxicity and reactivity profiles, although their accessibility and detection-difficulty scores indicate that they remain relevant for emergency preparedness screening. These criterion-level scores provide the direct input values for the SAW-based weighted aggregation and composite risk ranking presented in the following section.

Table 7. Expanded operational definitions and aggregated criterion scores of dual-use chemical scenarios.

Scenario	Expanded Operational Scenario Definition	Toxicity	Reactivity	Accessibility	Detection Difficulty
TATP	TATP-related energetic-material scenario in a densely occupied underground transit environment	4	5	5	4
VX binary	Binary nerve-agent scenario in an enclosed public-use facility	5	4	3	4
Sarin precursor	Nerve-agent precursor-related scenario in a semi-enclosed transit environment	5	4	3	3

Table 7. *Cont.*

Scenario	Expanded Operational Scenario Definition	Toxicity	Reactivity	Accessibility	Detection Difficulty
H ₂ O ₂ mixture	Oxidizer-mixture scenario in a semi-enclosed commercial environment	3	4	5	3
Ammonia-oxidizer	Industrial chemical reaction or release scenario in a storage-related environment	3	3	5	3
Chlorine	Chlorine-related storage or facility-release scenario in an indoor pool or storage-related facility	3	3	4	3
Industrial solvent	Volatile solvent exposure scenario in an industrial or commercial workspace	2	3	4	3

Note: Each score represents the rounded arithmetic mean of ten expert ratings for the corresponding scenario-criterion combination. All aggregated mean values were rounded to the nearest integer before the SAW-based composite score calculation.

4.3. Composite Risk Priority Scores and Ranking

The weighted contribution of each criterion and the resulting composite risk priority scores are presented in Table 8. The ranking demonstrates that the highest-priority scenario was not determined by toxicity alone, but by the combined effects of intrinsic hazard and operational feasibility factors. Although the VX binary and sarin precursor scenarios showed the highest toxicity contributions and were strongly influenced by reactivity, their relatively lower accessibility contributions reduced their overall scores compared with the TATP scenario. In contrast, TATP combined high reactivity, high accessibility, and substantial detection difficulty, which substantially increased its total score and produced the highest overall risk priority. Moderate risk levels were identified for H₂O₂ mixture (3.65) and ammonia-oxidizer combinations (3.40). These scenarios were characterized by relatively high accessibility, but their lower toxicity contributions kept their total scores below those of the highest-ranked scenarios. Chlorine-based scenarios (3.20) and industrial solvent combinations (2.85) showed comparatively lower composite scores; however, their potential for large-scale impacts in confined or poorly ventilated environments remains notable. Overall, these findings illustrate why dual-use chemical scenarios require a multi-criteria, scenario-based assessment approach rather than a single-agent toxicity hierarchy.

Table 8. Criterion-level contribution to weighted risk scores.

Scenario	Toxicity	Reactivity	Accessibility	Detection Difficulty	Total
TATP	1.42	1.23	1.01	0.79	4.45
VX binary	1.77	0.98	0.61	0.79	4.15
Sarin precursor	1.77	0.98	0.61	0.59	3.95
H ₂ O ₂ mixture	1.06	0.98	1.01	0.59	3.65
Ammonia-oxidizer	1.06	0.74	1.01	0.59	3.40
Chlorine	1.06	0.74	0.81	0.59	3.20
Industrial solvent	0.71	0.74	0.81	0.59	2.85

4.4. Environmental Vulnerability Interpretation

In addition to the composite risk scores and criterion-level contributions, environmental vulnerability was separately classified for each representative scenario to provide an additional contextual layer for interpreting emergency response implications. As shown in Table 9, the classification includes the assumed built-environment setting, environmental vulnerability score, and contextual interpretation for each scenario. These scores were not incorporated into the numerical aggregation of the composite chemical risk score; rather, they were used to interpret how site-specific built-environment conditions may amplify exposure potential, delay evacuation, and increase response complexity. Scenarios located in enclosed, densely occupied, and spatially interconnected environments were assigned higher vulnerability scores because such settings can increase contaminant accumulation, complicate evacuation routes, delay incident recognition, and hinder incident command and inter-agency coordination. The classification further indicates that scenarios occurring in these environments may require higher response priority even when their composite chemical risk scores are similar to those of other scenarios. For example, the TATP and VX binary scenarios received the highest environmental vulnerability scores because they were assumed to occur in an underground transit hub or enclosed public facility, where high crowd density, enclosure, delayed recognition, and evacuation complexity can substantially increase operational severity. In contrast, ammonia–oxidizer and industrial solvent scenarios received moderate vulnerability scores because they were associated with industrial, storage, or commercial workspaces, where access control, localized response, and operational containment may be relatively more feasible. Therefore, environmental vulnerability does not alter the numerical composite risk score, but it changes how that score should be interpreted for preparedness planning, emergency response prioritization, and resource allocation.

Accordingly, decision-makers can combine the two results as an operational matrix: high composite score with high environmental vulnerability indicates the highest preparedness priority; high composite score with moderate or low environmental vulnerability indicates agent-specific preparedness priority; moderate composite score with high environmental vulnerability indicates a need for site-specific mitigation planning despite its lower chemical-priority rank; and low scores in both dimensions indicate routine monitoring. This interpretation explains, for example, why the TATP and VX binary scenarios should receive immediate training and resource-allocation attention, whereas H₂O₂, despite lower composite priority than nerve-agent-related scenarios, still warrant evacuation and ventilation planning in crowded or semi-enclosed facilities.

Table 9. Scenario-specific environmental vulnerability classification and contextual interpretation.

Scenario	Representative Setting	Environmental Vulnerability Score	Contextual Interpretation
TATP	Underground transit hub	5	High crowd density, enclosed structure, complex evacuation
VX binary	Enclosed public facility	5	High exposure severity and delayed recognition
Sarin precursor	Semi-enclosed transit space	4	High exposure potential and response difficulty
H ₂ O ₂ mixture	Semi-enclosed commercial area	4	Localized but potentially severe exposure

Table 9. Cont.

Scenario	Representative Setting	Environmental Vulnerability Score	Contextual Interpretation
Ammonia–oxidizer	Industrial/storage area	3	Moderate occupancy and partial control feasibility
Chlorine	Indoor pool or storage-related facility	4	Ventilation-dependent spread and evacuation concern
Industrial solvent	Industrial/commercial workspace	3	Moderate exposure potential under standard ventilation

4.5. Sensitivity Analysis Results

The one-at-a-time (OAT) weight sensitivity analysis showed that the ranking remained stable under all $\pm 10\%$ and $\pm 20\%$ weight perturbation cases. Across the 16 perturbation conditions, the rank order was unchanged: TATP, VX binary, sarin precursor, H_2O_2 mixture, ammonia–oxidizer, chlorine, and industrial solvent. This indicates that the baseline ranking was not highly sensitive to moderate changes in any single AHP-derived criterion weight.

The Monte Carlo simulation provided a more conservative robustness test by incorporating simultaneous uncertainty in both weights and ordinal scenario scores. As shown in Table 10, TATP had the highest probability of being ranked first, followed by VX binary and sarin precursor scenarios. Although the exact first-ranked scenario varied across simulation runs, the upper risk tier remained stable. TATP, VX binary, and sarin precursor scenarios showed the highest probabilities of remaining within the top-three group, indicating that the principal prioritization result was robust under the assumed uncertainty ranges.

The non-compensatory threshold check identified TATP, VX binary, and sarin precursor scenarios as critical cases. TATP was flagged because of its maximum reactivity score and high combined toxicity–reactivity profile. VX binary and sarin precursor scenarios were flagged because of their maximum toxicity scores and high reactivity scores. These results indicate that high intrinsic hazard scenarios remain in the high-priority review tier even when the compensatory weighted-sum model might otherwise allow lower accessibility or detection difficulty scores to reduce the total score.

Table 10. Sensitivity analysis and rank acceptability results.

Scenario	Baseline Score	OAT Score Range	P (Rank 1)	P (Top 3)	Threshold Flag
TATP	4.45	4.40–4.50	70.6%	98.1%	Yes
VX binary	4.15	4.06–4.24	21.3%	88.8%	Yes
Sarin precursor	3.95	3.84–4.07	6.5%	71.1%	Yes
H_2O_2 mixture	3.65	3.58–3.72	1.5%	29.1%	No
Ammonia–oxidizer	3.40	3.32–3.48	0.2%	8.8%	No
Chlorine	3.20	3.16–3.24	0.1%	3.8%	No
Industrial solvent	2.85	2.76–2.94	0.0%	0.3%	No

Note: The probabilities reported in Table 10 are rank-acceptability indicators under the assumed uncertainty ranges and should not be interpreted as probabilities of incident occurrence.

Overall, the sensitivity analysis supports the robustness of the proposed screening framework. The deterministic ranking was stable under weight perturbation, the Monte Carlo simulation confirmed that the three highest-priority scenarios consistently formed the upper risk tier, and the threshold check strengthened the safety interpretation of the

model by reducing the possibility that extreme toxicity or reactivity would be masked by compensatory aggregation.

5. Discussion

5.1. Principal Findings: Beyond Toxicity-Centered Prioritization

The results of this study show that the risk priority of dual-use chemical scenarios in CBRN emergency preparedness cannot be adequately explained by toxicity alone. Although toxicity received the highest weight in the expert-based AHP analysis, accessibility and detection difficulty together accounted for approximately 40% of the composite score. This distribution is important because dual-use chemical threats are shaped not only by intrinsic hazard severity, but also by whether materials can be legally obtained or routinely accessed, whether hazardous reactions or transformations can occur rapidly, and whether early recognition by responders is difficult.

The scenario ranking further demonstrates that different dual-use chemical scenarios are driven by different combinations of risk criteria. VX binary and sarin precursor scenarios were primarily driven by toxicity and reactivity, reflecting their severe intrinsic hazard potential. By contrast, the TATP-related scenario achieved the highest composite risk priority not because of toxicity alone, but because high reactivity and high accessibility were combined with substantial detection difficulty. This finding highlights a key limitation of traditional single-agent or toxicity-centered CBRN risk assessment approaches, which may underestimate scenarios involving accessible materials that become operationally significant through reactivity, field-detection difficulty, or delayed recognition.

Overall, the findings support a shift from substance-centric hazard assessment toward scenario-based multi-criteria risk prioritization. In the context of dual-use chemicals, the most operationally challenging scenarios are not necessarily those with the highest toxicity score, but those in which intrinsic hazard, accessibility, and detection difficulty converge. This is particularly relevant for screening-level preparedness planning, where decision-makers need to identify which scenarios require further monitoring, training, or detailed consequence modeling before an actual incident occurs.

5.2. Scenario-Specific Risk Profiles and Criterion-Level Interpretation

The criterion-level contribution analysis provides a more detailed explanation of why the scenarios were ranked differently. As shown in Table 8, the TATP-related scenario received the highest overall score because its high reactivity and accessibility contributions substantially increased its composite risk priority. This indicates that operational feasibility factors can increase the priority of a scenario even when its toxicity score is lower than that of nerve-agent-related scenarios.

VX binary and sarin precursor scenarios showed high toxicity and reactivity contributions, but their relatively lower accessibility contributions reduced their total scores compared with the TATP-related scenario. This does not imply that nerve-agent-related scenarios are less hazardous in absolute terms. Rather, it shows that a screening-level prioritization model must distinguish between intrinsic severity and operational feasibility. Highly toxic scenarios may rank below more accessible and reactive dual-use scenarios when the objective is to identify relative emergency preparedness priorities across representative scenarios.

Moderate risk levels were identified for H₂O₂ mixture and ammonia–oxidizer scenarios. These scenarios were characterized by relatively high accessibility, but their lower toxicity contributions kept their composite scores below those of the highest-ranked scenarios. Chlorine and industrial solvent scenarios showed comparatively lower composite scores; however, their criterion profiles indicate that they remain relevant for emergency

preparedness screening, particularly when accessibility, detection difficulty, or contextual environmental conditions are considered. These results demonstrate why dual-use chemical threats require a multi-criteria, scenario-based assessment approach rather than a simple hierarchy based on individual-agent toxicity.

5.3. Environmental Vulnerability and Emergency Response Implications

The environmental vulnerability classification provides an additional contextual layer for interpreting the emergency response implications of each scenario. Importantly, environmental vulnerability was not incorporated into the numerical aggregation of the composite chemical risk score. Instead, it was used to assess how site-specific built-environment conditions may amplify exposure potential, delay evacuation, and increase response complexity. Thus, the composite score provides the baseline chemical scenario priority, whereas environmental vulnerability helps translate this priority into site-specific preparedness and response implications.

As shown in Table 9, scenarios located in enclosed, densely occupied, and spatially interconnected environments received higher environmental vulnerability scores. Such settings can increase contaminant accumulation, restrict evacuation routes, delay incident recognition, and complicate incident command and inter-agency coordination. Therefore, scenarios with similar composite chemical risk scores may require different preparedness and response priorities depending on where they occur.

For example, the TATP-related and VX binary scenarios received the highest environmental vulnerability scores because they were assumed to occur in an underground transit hub or enclosed public facility. These environments are characterized by high crowd density, enclosure, complex evacuation pathways, and the possibility of delayed recognition. These factors can substantially increase operational severity even when the chemical risk score itself remains unchanged. In contrast, ammonia-oxidizer and industrial solvent scenarios received moderate vulnerability scores because they were associated with industrial, storage, or commercial workspaces where access control, localized response, and operational containment may be more feasible.

This finding suggests that emergency response planning should consider both composite chemical risk and site-specific vulnerability. In high-vulnerability environments, response priorities may need to emphasize rapid isolation, evacuation support, ventilation management, medical triage capacity, and coordinated communication among police, fire services, environmental authorities, medical responders, infrastructure operators, and security personnel.

5.4. Implications for Decision Support, Preparedness, and Regulation

The findings have practical implications for the initial phase of CBRN emergency response. In real incidents, responders may not immediately know whether an event is accidental, criminal, or terrorist in nature. Many dual-use chemical scenarios may initially appear to be industrial accidents or ordinary hazardous-material incidents, which can delay escalation, protective action, and specialized CBRN response. A structured screening model can help responders and planners identify scenarios that deserve heightened attention because they combine high hazard potential, accessibility, and detection difficulty.

The results also suggest implications for chemical security and preparedness planning. Current chemical control systems often focus on highly controlled or highly toxic substances. While such controls remain necessary, they may overlook risk pathways associated with combinations of more accessible dual-use materials. These findings suggest that risk-based chemical security and preparedness planning may benefit from considering precursor accessibility, distribution patterns, detection constraints, and scenario-specific exposure

contexts. This does not mean that all accessible chemicals should be treated as high-risk substances. Rather, the framework can help identify combinations and settings where additional monitoring, awareness training, detection planning, or preparedness measures may be justified.

For emergency preparedness, the proposed framework can support the selection of scenarios for training exercises, tabletop drills, and inter-agency planning. Because the scoring structure is transparent, it can also help different agencies understand why particular scenarios are prioritized. This is especially important for CBRN incidents, where response responsibilities often overlap across law enforcement, fire services, environmental authorities, medical responders, infrastructure operators, and security personnel.

5.5. Methodological Contribution and Interpretability

The main methodological contribution of this study is the integration of expert-based AHP weighting, scenario-level criterion scoring, and SAW-based composite ranking while maintaining a clear separation between composite chemical risk priority and environmental vulnerability. This separation reduces the risk of double-counting contextual factors and allows the same chemical scenario to be interpreted differently across different locations. The approach is therefore suitable for screening-level prioritization, where decision-makers need a transparent and repeatable method for comparing scenarios before conducting more resource-intensive dispersion, exposure, or consequence modeling.

The criterion-level contribution analysis also improves the interpretability of the results. Rather than reporting only total scores, the model decomposes each scenario into toxicity, reactivity, accessibility, and detection-difficulty contributions. This allows decision-makers to identify which factor drives each scenario's priority. For example, scenarios driven primarily by accessibility may require supply-chain monitoring, awareness training, and regulatory attention, whereas scenarios driven by detection difficulty may require improved field detection protocols, early-warning procedures, information sharing, and responder training.

The use of a multidisciplinary expert panel further strengthens the practical relevance of the framework. By incorporating perspectives from law enforcement, fire services, military CBRN units, environmental authorities, and airport CBRN operations, the weighting process reflects both technical hazard knowledge and operational response considerations. This supports the development of more realistic and response-oriented CBRN risk assessment tools.

The sensitivity analysis improves the interpretability and defensibility of the proposed framework. The one-at-a-time weight perturbation confirmed that the ranking was not strongly affected by moderate changes in AHP-derived weights. The Monte Carlo simulation further showed that, although the exact first-ranked scenario may vary under simultaneous weight and score uncertainty, the upper-tier grouping remained stable. In addition, the non-compensatory threshold check addressed a key limitation of weighted-sum MCDM models by ensuring that scenarios with extreme toxicity or reactivity were not downgraded solely through compensation by lower operational feasibility scores.

5.6. Limitations

This study has several limitations. First, the proposed framework is based on expert judgment and ordinal screening-level scoring rather than experimentally measured toxicity, dispersion behavior, exposure-dose relationships, or probabilistic attack likelihood. Therefore, the resulting scores should be interpreted as relative priorities for preparedness and screening, not as deterministic estimates of casualties, physical damage, or incident probability.

Second, the expert panel was multidisciplinary but limited in size. The criterion weights and scenario scores may therefore be influenced by the disciplinary composition, institutional background, and operational experience of the participating experts. In addition, the conversion of arithmetic mean scores into integer values improved consistency with the 1–5 scoring rubric but may have reduced some scoring granularity. Future studies should examine whether larger expert panels, alternative aggregation rules, or fuzzy scoring approaches produce similar prioritization results.

Third, the environmental vulnerability classification was based on representative built-environment settings rather than site-specific measurements. Variables such as occupancy level, ventilation rate, evacuation time, access control, emergency response access, and spatial connectivity may vary substantially across facilities. Therefore, future research should refine the vulnerability classification using facility-specific data, evacuation simulation, ventilation analysis, and dispersion or exposure modeling.

Fourth, the scenario set used in this study was illustrative rather than exhaustive. The selected scenarios were intended to demonstrate the applicability of the framework, but they do not cover all possible dual-use chemical combinations, precursor pathways, or operational environments. Future studies should expand the scenario database and examine the sensitivity of the ranking results to changes in scenario selection, scoring assumptions, and AHP-derived criterion weights.

Although this study incorporated weight sensitivity analysis, Monte Carlo score perturbation, rank-acceptability analysis, and a non-compensatory threshold check, the uncertainty ranges were designed for screening-level robustness testing rather than probabilistic consequence estimation. Future research should validate these assumptions using larger expert panels, field exercise data, detection-performance data, and facility-specific exposure or evacuation models. Additional work is also needed to refine threshold rules for different operational environments and response contexts.

6. Summary and Conclusions

This study developed a screening-level, semi-quantitative decision-support framework for the relative prioritization of dual-use chemical scenarios in CBRN emergency preparedness. The purpose of the study was to address the limitations of conventional single-agent or toxicity-centered assessment approaches by integrating intrinsic hazard factors and operational feasibility factors within a scenario-based multi-criteria model.

The proposed framework evaluated representative dual-use chemical scenarios using four AHP-weighted criteria: toxicity, reactivity, accessibility, and detection difficulty. Expert judgment was incorporated through the Analytic Hierarchy Process to derive relative criterion weights, and the resulting weights were applied to scenario-level scores through SAW-based aggregation to calculate composite chemical risk priorities. Environmental vulnerability was classified separately as a contextual interpretation layer to examine how built-environment conditions, such as enclosure, crowd density, ventilation constraints, and evacuation complexity, may affect preparedness and response implications without being mathematically incorporated into the composite score.

The results showed that toxicity remained the most influential criterion, but accessibility and detection difficulty also played a substantial role in shaping the final ranking. The TATP-related scenario received the highest composite risk priority because high reactivity and accessibility, combined with detection difficulty, outweighed its lower toxicity relative to nerve-agent-related scenarios. VX binary and sarin precursor scenarios were strongly driven by toxicity and reactivity, whereas H₂O₂ mixture, ammonia–oxidizer, chlorine, and industrial solvent scenarios showed different profiles depending on their criterion-level contributions. The sensitivity analysis further supported the robustness of the ranking

by showing that the upper-priority group remained stable under weight perturbation, simulation-based uncertainty, and non-compensatory threshold screening.

6.1. Contributions

This study contributes to CBRN risk assessment and emergency preparedness research in three main ways. First, it demonstrates the importance of moving beyond substance-centric hazard ranking toward scenario-based multi-criteria prioritization. The findings show that dual-use chemical risks cannot be fully understood through toxicity evaluation alone. Instead, operational factors such as accessibility, detection difficulty, and response context should also be considered when identifying scenarios that may pose significant challenges for emergency responders.

Second, the study provides a transparent AHP-SAW-based screening framework that integrates expert-derived criterion weights with scenario-level risk scoring. This structure allows decision-makers to compare representative dual-use chemical scenarios in a systematic and reproducible manner. The criterion-level contribution analysis also improves interpretability by showing whether each scenario is primarily driven by toxicity, reactivity, accessibility, or detection difficulty.

Third, the study clarifies the relationship between composite chemical risk priority and environmental vulnerability. By treating environmental vulnerability as a separate contextual layer rather than as an additional component of the composite score, the framework avoids double-counting while still allowing decision-makers to consider how site-specific conditions may influence exposure potential, evacuation difficulty, contaminant propagation, and operational response complexity. This distinction is useful for planning responses in high-vulnerability settings such as underground transit hubs, enclosed public facilities, commercial complexes, and industrial storage areas.

From a practical perspective, the framework can support scenario selection for training exercises, tabletop drills, inter-agency coordination, and preparedness resource allocation. Because the scoring structure is transparent, it can help different agencies understand why particular scenarios are prioritized and how different risk criteria contribute to the final ranking. The framework may also inform prevention-oriented chemical security planning by highlighting combinations of accessible materials, detection limitations, and scenario-specific exposure contexts that warrant additional monitoring, awareness training, or field detection planning.

6.2. Concluding Remarks

In conclusion, this study demonstrates that the evolving risk of dual-use chemical agents requires an integrated, semi-quantitative, and scenario-based approach to CBRN preparedness. The findings show that high-priority scenarios may emerge not only from highly toxic substances, but also from combinations of accessibility, reactivity, and detection difficulty, while environmental vulnerability further shapes how these priorities should be interpreted for preparedness planning. By providing a transparent screening-level framework, this study offers a practical basis for improving emergency response planning, strengthening inter-agency coordination, informing adaptive chemical security policy, and enhancing preparedness for complex dual-use chemical threats.

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