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Strategic Risk Assessment of Hazardous Energetic Chemicals in Defense Supply Chains: A Coupled Risk Framework for Ammonium Perchlorate (AP), RDX, and HMX

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ABSTRACT

Energetic materials such as ammonium perchlorate (AP), RDX, and HMX are essential in modern defense systems but pose multidimensional risks across industrial supply chains. This study presents a literature-based assessment integrating hazard profiling with node-based risk characteristics; RDX shows high acute process instability, AP poses environmental risks due to perchlorate mobility in groundwater, and HMX presents strategic coupling risk from production interdependence. A Coupled Risk Triangle Model is proposed, framing energetic chemical governance as a dynamic system linking reactive instability, environmental persistence, and strategic supply concentration. The findings indicate that risks extend beyond occupational safety to environmental regulation and national security resilience. Effective mitigation therefore requires lifecyle-integrated governance, supply diversification, and resilience-oriented industrial strategies.

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INTRODUCTION

Energetic chemicals such as ammonium perchlorate (AP), cyclotrimethylenetrinitramine (RDX), and cyclotetramethylenetetranitramine (HMX) constitute the chemical backbone of modern military propulsion and explosive systems. In solid rocket propellants, oxidizers account for 60–80% of total composition by weight, making oxidizer selection critical to ballistic performance, combustion stability, and operational reliability (Lynch et al., 2022). For over six decades, AP has remained the dominant oxidizer due to its high density, favorable thermal properties, and relatively low cost (Peng et al., 2004). Nitramine explosives such as RDX and HMX are widely applied in warheads, booster charges, plastic explosives, and high-performance munitions (Abdelaziz et al., 2024). HMX, often classified as a high-melting explosive, is used in systems requiring enhanced thermal stability (Li et al., 2023). Industrial production commonly generates RDX and HMX simultaneously, creating impurity cross-presence that introduces technological interdependence and extends risk beyond single-compound assessment (Li et al., 2023).

From a strategic perspective, these materials function as critical enablers of national defense capability. Historical HMX production has reached tens of millions of pounds annually (Abdelaziz et al., 2024), yet production capacity remains concentrated in a limited number of facilities (Li et al., 2023), increasing vulnerability to disruptions caused by industrial accidents, regulatory constraints, environmental liabilities, or geopolitical trade restrictions. Incident analyses indicate that relatively minor deviations in thermal control or impurity accumulation may trigger catastrophic accidents in energetic material facilities[20]. Risk profiles extend across the full lifecycle, including production, storage, transportation, deployment, and disposal. Environmental release pathways are well documented, particularly for nitramines. RDX and HMX may contaminate soil and groundwater from manufacturing facilities, ammunition depots, and training areas (OECD, 2025). Experimental studies show that nitramine dissolution rates increase with temperature and hydrological agitation, indicating that climatic conditions influence contaminant mobility (OECD, 2025). RDX exhibits measurable soil mobility and groundwater migration potential (New Jersey Dept. of Health, 2000), while HMX has been detected in groundwater and surface water near production sites (Li et al., 2023).

AP presents distinct environmental concerns due to the high solubility and persistence of perchlorate ions. Human exposure primarily occurs through drinking water and food ingestion (American Pacific, 2017). Perchlorate competitively inhibits iodine uptake in the thyroid gland, potentially causing hypothyroidism and developmental effects (Chen et al., 2020). Chronic low-dose exposure may also produce cumulative ecological and endocrine impacts(Lucas et al., 2024), indicating that environmental risk is structurally embedded in the lifecycle of energetic oxidizers. Process safety further intensifies the hazard landscape. Trace contaminants such as iron salts and residual acids may reduce HMX exothermic onset temperatures and alter decomposition kinetics (Galante et al., 2014). Similarly, nitration-based RDX synthesis is highly temperature-sensitive, where deviations in reaction control can accelerate reaction rates and increase explosion risk (Abadin & Liccione, 1997). Consequently, hazards arise not only from final energetic products but also during intermediate synthesis and processing stages.

Defense supply chains exhibit characteristics distinct from conventional industrial systems, including concentrated production nodes, strict regulatory oversight, export controls, and complex multi-tier supplier structures (Defense Business Board, 2025). Recent geopolitical tensions affecting critical raw materials have exposed structural vulnerabilities in strategic supply chains (PwC, 2025). For hazardous energetic chemicals, risks are amplified by limited global producers, stringent safety regulations, environmental compliance requirements, long lead times, and high capital investment barriers. Although supply chain resilience literature emphasizes redundancy, flexibility, and transparency as core resilience dimensions (Savard et al., 2007) Integration of chemical hazard science with supply chain risk modeling remains limited.

LITERATURE REVIEW

This gap is particularly significant for AP, RDX, and HMX, whose risk characteristics combine high energetic performance requirements, environmental persistence, process-safety sensitivity, and concentrated strategic production. Evaluating these materials solely through detonation or toxicological parameters may underestimate systemic cascading risks across defense industrial ecosystems. Therefore, this study presents an integrated strategic review of hazardous energetic chemicals within defense supply chains, focusing on AP, RDX, and HMX. By synthesizing toxicological, environmental, and process-safety evidence and mapping multidimensional risk across supply chain nodes, this research aims to bridge chemical hazard analysis with defense supply chain resilience frameworks to support industrial governance, environmental management, and strategic defense planning.

METHODOLOGY

Literature Review Strategy

This study employs a structured qualitative literature synthesis combined with analytical risk modeling. References were selected from peer-reviewed journals, governmental toxicological profiles, defense policy reports, and industrial safety documents published between 2000 and 2024. The literature selection followed three criteria;

- *Chemical Hazard Relevance:* Studies addressing toxicological, environmental, thermal, and reactive hazard characteristics of ammonium perchlorate (AP), RDX, and HMX
- *Process Safety and Manufacturing Risk:* Research describing nitration processes, incompatibility reactions, thermal decomposition behavior, and hazard analysis methodologies such as Hazard and disruption management.
- *Supply Chain and Strategic Risk Frameworks:* Policy reports and academic analyses on defense supply chain resilience, multi-tier supplier mapping, and disruption management.

Primary toxicological and environmental data were extracted from authoritative sources, including the ATSDR Toxicological Profile for HMX4, LANL RDX environmental characterization6, and state-level hazardous substance documentation for AP8. Quantitative exposure data (e.g., concentration ranges, chronic intake contributions) were incorporated where available. Rather than conducting a bibliometric meta-analysis, this study applies a thematic synthesis approach, categorizing findings into hazard domains and mapping them onto supply chain nodes.

Risk Matrix Development

An integrated risk matrix was constructed to quantify and compare risk across chemicals and supply chain nodes.

- *Hazard Identification:* Hazards were identified through cross-referencing toxicological data, process safety analyses, and environmental transport studies. Each identified hazard was categorized under process safety (PS), occupational health (OH), environmental impact (EI), and strategic disruption (SD)
- *Likelihood and Severity Scoring:*

  Risk scoring uses a semi-quantitative 5x5 matrix.

  Likelihood (L):

  1. Rare (historically limited occurrence)
  2. Unlikely
  3. Possible
  4. Likely
  5. Frequent or structurally probable

Likelihood assignment was informed by historical accident documentation and environmental detection frequency Severity (S):

  1. Minor operational disruption
  2. Localized injury/environmental effect
  3. Serious facility-level impact
  4. Major off-site impact
  5. Strategic-level disruption or long-term ecological damage

Severity scoring considered toxicological endpoints, contamination scale, and explosion consequences

- *Environmental Persistence Factor (E):* To reflect long-term ecological impact, an environmental persistence factor was introduced to reflect rapid degradation, moderate persistence, as well as high persistence and groundwater mobility. Data for persistence and mobility were derived from dissolution kinetics and environmental fate assessments.
- *Strategic Weight Factor (W)*

  Strategic weight accounts for supply chain criticality:

  1. Readily substitutable
  2. Limited substitutes
  3. Mission-critical with concentrated production

This weighting incorporates production interdependence and supply concentration, as well as resilience vulnerability frameworks.

- *Risk Score Equation:* The integrated risk score for each chemical-node combination was calculated as:

$$Risk\ Score = (L \times S) + (E + W)$$

This structure ensures that operational hazard and long=term strategic vulnerability are jointly reflected. Risk levels were categorized as low (1-8), moderate (9-16), high (17-24), and critical (>25).

Uncertainty Consideration

Recognizing data limitations in toxicological and environmental modeling, this study qualitatively incorporates uncertainty through documentation and data gaps, sensitivity reflection in environmental factor assignment, and comparative rather than absolute risk ranking. The objective is not deterministic prediction but structured prioritization of hazardous energetic chemicals across the defense supply chain.

RESULT AND DISCUSSION

Hazard Profile of Energetic Chemicals

Table 1. Comparative Hazard Synthesis

Dimension	AP	RDX	HMX
Primary Hazard	Strong oxidizer	High explosive	High melting explosive
Main Health Concern	Thyroid disruption	Neurotoxicity	Limited data; systemic
Environmental Mobility	High (water-soluble)	Moderate-high	Moderate
Process Sensitivity	Fire/explosion in mixing	Thermal runway	Contaminant-induced instability
Strategic Risk	High substitution barrier	Widely used	Production concentration risk

These findings confirm that energetic chemical risk cannot be assessed in isolation at the detonation stage. Instead, risk manifests differently across chemical identity, production process, environmental fate, and strategic supply configuration.

Ammonium Perchlorate (AP)

Ammonium perchlorate (AP) has been the dominant oxidizer in composite solid propellants for more than six decades due to its high density, favorable oxygen balance, and relatively stable thermal behavior (Lynch et al., 2022; Peng et al., 2004). Because oxidizers typically constitute 60–80% of propellant mass, AP functions as a mission-critical determinant of propulsion efficiency and ballistic reliability (Lynch et al., 2022). Although alternative oxidizers such as ammonium nitrate and hybrid systems have been investigated, performance limitations, hygroscopic instability, and reduced specific impulse have hindered large-scale substitution (Peng et al., 2004). This technological lock-in reinforces strong industrial dependence on AP within defense supply chains.

AP is classified as a Category 1 oxidizing solid capable of intensifying combustion when in contact with incompatible substances (Chen et al., 2020). Thermal decomposition above approximately 270 °C generates reactive chlorine species, nitrogen oxides, and hydrogen chloride (HCl), increasing risks of fire, explosion, corrosion, and toxic emissions (Chen et al., 2020). Compatibility management is therefore essential, particularly in propellant mixtures containing aluminum powder, which enhances energetic performance but also increases thermal sensitivity. As a result, hazard exposure extends across synthesis, blending, storage, and transportation stages.

The primary toxicological concern related to AP derives from the perchlorate anion, which inhibits iodine uptake in the thyroid gland and may induce hypothyroidism and endocrine disruption(Chen et al., 2020). Exposure occurs predominantly through ingestion of contaminated water and food, accounting for more than 90% of total intake in certain regions[7]. Regulatory standards remain inconsistent across jurisdictions, creating governance challenges in transnational supply networks (Chen et al., 2020). Environmentally, perchlorate exhibits high solubility and mobility in groundwater, enabling persistence unless degraded under specialized anoxic conditions. Combustion emissions of HCl and chlorinated species may further contribute to atmospheric acidification and ozone depletion(Peng et al., 2004). Collectively, AP risk encompasses oxidizer-induced explosion hazards, endocrine toxicity, environmental persistence, and strategic supply dependence.

RDX (Cyclotrimethylenetrinitramine)

RDX is one of the most widely used secondary high explosives in military systems, applied in warheads, booster charges, shaped munitions, and propellant formulations (Abdelaziz et al., 2024). Industrial production typically involves nitration of hexamethylenetetramine under strongly acidic conditions, a process highly sensitive to temperature variations. Deviations exceeding approximately 15 °C during critical reaction stages significantly accelerate reaction kinetics and increase internal pressure, elevating the risk of runaway reactions in large-scale batch operations (Abadin & Liccione, 1997).

HAZOP studies identify critical risk nodes in reactor systems, heat exchangers, filtration units, and emergency discharge mechanisms. Excess temperature, cooling failure, pressure accumulation, and nitric acid mismanagement may trigger vessel rupture or uncontrolled side reactions (Abadin & Liccione, 1997). These hazards require advanced process control systems, including PLC monitoring, redundant cooling loops, and emergency quench mechanisms to ensure operational stability.

RDX also exhibits moderate solubility and mobility in soil and groundwater systems. Field investigations confirm migration from contaminated soils into aquifers near legacy defense sites (New Jersey Dept. of Health, 2000), while experimental studies show increased dissolution rates under higher temperature and hydrodynamic conditions (OECD, 2025). Although short-term exposure risks may remain limited at regulated concentrations (New Jersey Dept. of Health, 2000), long-term ecological persistence remains a concern. Toxicologically, RDX is associated primarily with neurotoxic effects, including seizure activity, as well as potential impacts on liver and bone marrow under elevated exposure conditions (Abdelaziz et al., 2024; *OECD, 2025)*. However, uncertainties remain regarding chronic low-dose exposure pathways, complicating long-term environmental risk assessment (Li et al., 2023).

HMX (Cyclotetramethylenetetranitramine)

HMX is a high-performance nitramine explosive characterized by high detonation velocity and thermal stability. Industrially, it is commonly produced as a co-product of RDX synthesis, creating interdependence within nitramine supply chains (Li et al., 2023). Historical production volumes approaching 30 million pounds annually highlight its strategic importance (Abdelaziz et al., 2024), while the concentration of manufacturing capacity in limited facilities increases vulnerability to supply disruption (Li et al., 2023). Despite relative thermal stability, HMX exhibits sensitivity to contamination. Differential scanning calorimetry studies show that trace iron salts or residual acids can reduce exothermic onset temperatures by 50–90 °C, altering decomposition pathways and increasing the probability of secondary explosions (Galante et al., 2014). These findings emphasize the importance of strict purity control and corrosion management across the supply chain.

Environmentally, HMX demonstrates lower solubility than RDX but remains persistent in soil and groundwater systems. Detection in environmental monitoring near ammunition facilities indicates long-term mobility potential, with limited volatilization and weak soil adsorption. Photolysis may contribute to partial degradation in surface water, although persistence remains significant. Toxicological data for long-term human exposure remain limited, creating uncertainty in regulatory benchmarking and chronic risk prioritization (Li et al., 2023). Consequently, HMX represents a material characterized by production interdependence, contamination-sensitive instability, environmental persistence, and incomplete toxicological characterization.

Supply Chain Risk Exposure Across Lifecycle Nodes

The supply chain of energetic chemicals such as ammonium perchlorate (AP), RDX, and HMX spans multiple lifecycle stages, from precursor procurement to disposal or demilitarization. Unlike conventional industrial chemicals, energetic materials operate within tightly regulated and security-sensitive production systems, where environmental monitoring has confirmed persistent nitramine residues in former manufacturing and training sites(MacDonald, 2009). Upstream risks originate from raw material dependence: RDX and HMX production rely on nitration chemistry involving nitric acid and hexamethylenetetramine (Abadin & Liccione, 1997), while AP production depends on perchlorate pathways associated with chlorine-based industrial processes (Chen et al., 2020; Peng et al., 2004). These dependencies create exposure to regulatory constraints, environmental compliance pressures, and geopolitical supply disruptions.

The synthesis stage represents the most critical process safety node. Studies on nitration systems show that temperature deviations significantly accelerate reaction kinetics and increase internal pressure, thereby elevating runaway reaction probability (Abadin & Liccione, 1997). Similarly, HMX contamination with metallic impurities may substantially reduce exothermic onset temperatures, increasing instability under non-ideal handling conditions (Galante et al., 2014). During formulation, energetic compounds are combined with metallic fuels, binders, and stabilizers; for example, AP–aluminium mixtures enhance combustion performance but also increase ignition sensitivity (Peng et al., 2004). Industrial concentration in limited nitration and crystallization facilities further constrains surge production capacity and amplifies supply vulnerability (EPA Federal Facilities Restoration & Office, 2014). Downstream stages introduce environmental persistence risks. RDX and HMX exhibit mobility in soil and groundwater systems (New Jersey Dept. of Health, 2000), while perchlorate residues from demilitarization and incomplete combustion processes may extend long-term contamination pathways (Li et al., 2023). Overall, risk distribution across the energetic material supply chain is heterogeneous: upstream and synthesis stages are dominated by acute process safety hazards, whereas downstream stages are characterized by environmental persistence and regulatory exposure.

Integrated Risk Assessment and Comparative Matrix

To consolidate hazard characteristics across lifecycle stages, a qualitative comparative matrix was constructed, integrating four analytical dimensions: probability of occurrence, consequence severity, environmental persistence, and strategic supply impact. This framework enables cross-material comparison beyond explosive performance or toxicological classification, positioning energetic chemicals within a systemic supply chain risk context. The assessment reveals differentiated dominance patterns among AP, RDX, and HMX. RDX demonstrates elevated acute process risk at the synthesis stage due to nitration sensitivity and potential runaway reactions (abadin & Liccione, 1997). Ammonium perchlorate exhibits higher long-term environmental persistence driven by perchlorate mobility in groundwater systems (American Pasific, 2017), while also presenting substitution barriers in solid propellant systems (Peng et al., 2004). HMX shows moderate process instability but introduces structural coupling risk because of its production interdependence with RDX (Li et al., 2023).

Comparative Node-Based Risk Assessment of Energetic Chemicals

Table 2. Ammonium Perchlorate (AP)

Node	Probability	Severity	Environmental Persistence	Strategic Impact	Overall Risk
Raw Material Procurement	2	2	3	3	High
Synthesis & Processing	2	3	2	3	High
Formulation & Integration	3	3	2	3	Very High
Storage & Transportation	2	3	3	2	High
Disposal & Demilitarization	2	2	3	2	Medium-High

Table 3. RDX

Node	Probability	Severity	Environmental Persistence	Strategic Impact	Overall Risk
Raw Material Procurement	2	2	2	3	Medium-High
Synthesis & Processing	3	3	2	3	Very High
Formulation & Integration	2	3	2	2	High
Storage & Transportation	2	3	2	2	Medium-High
Disposal & Demilitarization	2	2	3	2	Medium

Table 4. HMX

Node	Probability	Severity	Environmental Persistence	Strategic Impact	Overall Risk
Raw Material Procurement	2	2	2	3	High
Synthesis (Co-production)	2	3	2	3	High
Formulation & Integration	2	3	2	2	Medium-High
Storage & Transportation	2	3	2	2	Medium-High
Disposal & Demilitarization	1	2	2	2	Medium

The matrix highlights several structural patterns. First, synthesis nodes consistently represent the highest severity category, particularly for RDX (Abadin & Liccione, 1997). Second, environmental persistence scores are comparatively elevated for ammonium perchlorate due to perchlorate mobility (American Pasific, 2017). Third, strategic impact values reflect limited substitution capacity and concentrated production networks (Abdelaziz et al., 2024; Li et al., 2023). By integrating environmental, process, and strategic dimensions into a unified comparative structure, the matrix reveals that energetic chemical vulnerability is heterogeneous and node-dependent rather than uniform across the supply chain. This multidimensional assessment provides the analytical bridge toward the proposed Coupled Risk Triangle Model.

Conceptual Model: Energetic Chemical Risk as a Coupled Security Environmental System

Analysis of ammonium perchlorate (AP), RDX, and HMX across lifecycle nodes indicates that energetic chemical risk cannot be adequately described using linear hazard models. Instead, these materials operate within a coupled security–environment system, where chemical reactivity, industrial structure, and strategic dependency interact dynamically. Conventional risk frameworks often separate occupational safety, environmental toxicity, and supply chain management into distinct domains, yet energetic materials inherently link these dimensions. For instance, thermal instability in RDX nitration processes(Abadin & Liccione, 1997) represents not only a reactor-level hazard but also a potential disruption node capable of affecting production continuity. Similarly, the environmental persistence of perchlorate and nitramines in groundwater systems (Chen et al., 2020; New Jersey Dept. of Health, 2000) may trigger regulatory constraints that indirectly influence defense readiness and industrial output.

This interdependence can be conceptualized as a triangular risk coupling model consisting of three mutually reinforcing dimensions: (1) reactive instability driven by physicochemical sensitivity and contamination effects (Galante et al., 2014; Abadin & Liccione, 1997)(2) environmental persistence characterized by solubility, mobility, and long-term degradation behavior (New Jersey Dept. of Heath, 2000; American Pasific, 2017)(3) and strategic concentration defined by production centralization, substitution barriers, and geopolitical exposure (Abdelaziz et al., 2024; Li et al., 2023). Disruption in one dimension may propagate to others, as process accidents can lead to environmental release, regulatory restrictions may constrain supply continuity, and production concentration may increase operational risk pressure. Consequently, energetic chemical risk behaves as a feedback-amplified system rather than an isolated hazard category.

Within this framework, mitigation strategies should extend beyond node-level hazard control toward system-level resilience engineering. Reducing interdependence between risk dimensions may involve diversification of precursor sourcing, decentralization of production capacity, lifecycle environmental monitoring, and integration of chemical risk assessment into national defense planning. Framing energetic materials as components of a coupled security–environment system highlights that their primary vulnerability lies not only in explosive potential but also in structural interdependencies across defense industrial ecosystems. Integrated systemic risk modeling further demonstrates the importance of linking chemical hazard severity with supply chain centrality metrics to prevent cascading failure effects(Ekström, 2025).

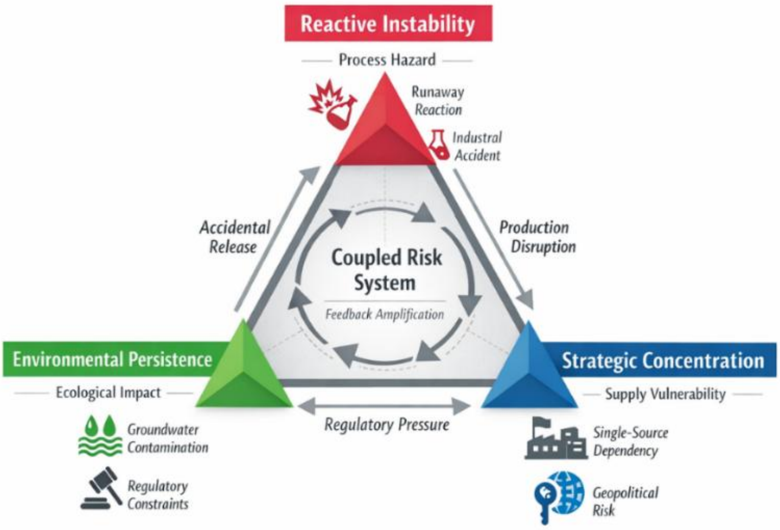

Figure 1. Energetic Chemical Coupled Risk Triangle Model

Strategic Governance and Supply Chain Resilience Implications.

1. *Policy Implications and Strategic Risk Governance*

The risk matrix indicates that energetic chemicals such as ammonium perchlorate (AP), RDX, and HMX represent structurally embedded risk vectors within defense supply chains rather than isolated industrial hazards. Their multidimensional risk profile spans process instability, environmental persistence, and strategic production dependency. Nitration-based synthesis of RDX exhibits intrinsic thermal sensitivity, where temperature deviations significantly increase runaway reaction probability (Abadin & Liccione, 1997), potentially propagating disruption across downstream weapon integration stages. In contrast, ammonium perchlorate presents long-term environmental vulnerability due to high solubility and perchlorate mobility in groundwater systems (Chen et al., 2020; American Pasific, 2017), creating persistent liabilities beyond production sites.

Regulatory asymmetry across exposure thresholds and lifecycle governance (Chen et al., 2020; Li et al., 2023) further amplifies systemic risk. Digital supply chain illumination and multi-tier mapping have been identified as key tools for strengthening defense supply resilience (Robidoux et al., 2003). When safety standards, environmental monitoring, and industrial policy operate in parallel rather than in an integrated framework, energetic materials become nodes of governance fragmentation. Increasing regulatory controls on perchlorate discharge and energetic waste disposal have raised compliance costs within defense manufacturing sectors (Sowik & Ruzik, 2025). Consequently, risk mitigation must extend beyond technical safeguards toward coordinated regulatory architectures linking safety engineering, environmental oversight, and strategic supply management.

2. *Strategic Mitigation Architecture*

Rather than treating energetic chemical risk as an isolated occupational safety issue, the findings highlight the need for layered governance across the supply chain lifecycle. Strategic stockpiling has historically been used to buffer volatility in defense-critical materials. At the production stage, process intensification and reactor automation reduce runaway reaction probability in nitration-based RDX synthesis (Abadin & Liccione, 1997). Redundant cooling systems, corrosion-resistant materials, and strict contamination control are particularly important for HMX, where metallic impurities can significantly lower decomposition onset temperatures (Galante et al., 2014). Remediation technologies for perchlorate and nitramine-contaminated groundwater show partial effectiveness but require long-term monitoring and high operational costs (LANL, 2000).

Environmental mitigation must address perchlorate mobility and nitramine persistence through continuous groundwater monitoring near production and storage facilities, reflecting documented subsurface migration of RDX and perchlorate species (American Pacific, 2017; New Jersey Dept. of Health, 2000). Long-term containment and biological remediation approaches may reduce ecological accumulation risks (Chen et al., 2020), although sustained regulatory oversight remains necessary. From a strategic perspective, supply diversification is critical to reduce single-point vulnerabilities arising from concentrated production capacity and limited substitution options, particularly for AP-based oxidizer systems (Peng et al., 2004). Industrial redundancy, stockpiling, and domestic production strengthening should therefore be integrated into national defense planning. Overall, mitigation strategies should shift from compliance-based control toward resilience-oriented governance embedded within broader defense industrial systems.

3. *Defense Industrial Resilience and Chemical Risk*

The integration of energetic materials into modern defense systems creates a structural paradox: these compounds enable propulsion efficiency and detonation reliability, yet their physicochemical properties simultaneously introduce environmental and process instability risks. Comparative analysis indicates that RDX presents the highest acute process hazard due to nitration sensitivity (Abadin & Liccione, 1997), while ammonium perchlorate poses the greatest environmental persistence risk because of perchlorate mobility in groundwater systems (American Pasific, 2017). HMX contributes strategic coupling risk through its production interdependence with RDX manufacturing pathways (Li et al., 2023).

These differentiated risk profiles suggest that policy responses must be material-specific rather than generic. Disruptions in chemical production, whether caused by industrial accidents, environmental litigation, or regulatory shutdown, may propagate into downstream capability gaps. Consequently, energetic chemical governance should be considered a national security variable, not solely a chemical safety issue. Defense supply chain resilience depends not only on platform manufacturing capacity but also on stable access to critical energetic precursors. Failure to integrate chemical risk assessment into defense acquisition and industrial policy planning may create hidden fragilities within deterrence infrastructure. Effective governance, therefore, requires coordination among environmental authorities, defense institutions, and industrial regulators (Qian et al., 2023).

CONCLUSION AND RECOMMENDATION

This study examined the strategic role and multidimensional risk profile of three critical energetic chemicals, ammonium perchlorate (AP), RDX, and HMX, within the defense industrial supply chain. Through a literature-based hazard synthesis and node-oriented risk matrix analysis, the findings demonstrate that energetic chemical risk extends beyond conventional safety and toxicological considerations. RDX presents the highest acute process hazard due to nitration instability and thermal runaway sensitivity, whereas ammonium perchlorate exhibits the most significant long-term environmental risk due to perchlorate mobility in groundwater systems. HMX, although less frequently emphasized, introduces structural coupling risk due to its production interdependence with RDX processes.

The proposed Coupled Risk Triangle Model reframes energetic chemical governance as an interconnected system linking reactive instability, environmental persistence, and strategic supply concentration. Within this coupled system, disruption at one vertex may propagate across environmental, industrial, and defense readiness domains. Accordingly, risk management must evolve from isolated compliance-based approaches toward integrated resilience-oriented governance that incorporates process safety reinforcement, lifecycle environmental monitoring, and supply chain diversification strategies. Energetic chemicals are therefore not only operational enablers of defense capability but also structural determinants of industrial vulnerability. Recognizing and managing this duality is essential for sustaining long-term defense supply chain resilience.

FURTHER RESEARCH

This study is subject to several limitations. The analysis relies on secondary literature, which introduces variability in experimental conditions, reporting standards, and data comparability. The proposed *Coupled Risk Triangle* framework remains conceptual and has not yet been validated through quantitative probabilistic modeling of reaction kinetics, environmental transport, or supply chain dynamics. In addition, the focus on ammonium perchlorate (AP), RDX, and HMX may limit generalization to other emerging energetic materials. Future research should integrate probabilistic risk assessment, system dynamics modeling, and network-based supply chain analysis to strengthen empirical validation of interdependent risk dimensions. Experimental studies on thermal stability, contamination sensitivity, and environmentally sustainable oxidizer alternatives are also needed to improve hazard characterization and support resilience-oriented governance of energetic material supply chains.

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