

Nanostructured Energetic Materials: A Promising Strategy for Reducing Sensitivity, Enhancing Reliability and Mitigating TNT Exudation

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ABSTRACT

Nano-encapsulation of energetic materials represents a transformative approach to enhancing munitions safety by reducing sensitivity to external stimuli and mitigating critical operational challenges such as TNT exudation. This comprehensive literature review synthesises current research on nano-encapsulated energetic materials, examining synthesis techniques, property enhancements, and practical applications. Three principal encapsulation methods—sol-gel processing, hydrothermal synthesis, and layer-by-layer assembly—are critically evaluated for their ability to control shell thickness, composition, and morphology at the nanoscale. Experimental evidence demonstrates that nano-encapsulation significantly reduces impact, friction, and thermal sensitivity while improving shelf life and thermal stability. The review integrates a practical cost-benefit analysis comparing nano-encapsulation technology adoption versus development of new insensitive explosive fillings, revealing short-term advantages for retrofitting existing munitions. Furthermore, this technology directly supports United Nations disarmament objectives by enhancing safety during storage, transport, and demilitarisation operations. An illustrative parametric model demonstrates potential sensitivity reductions, though validation through molecular dynamics simulations and experimental studies remains necessary. This review uniquely combines technical synthesis with operational perspectives informed by field experience in munitions risk management, establishing a foundation for future research in nano-enabled energetic materials that prioritise safety, reliability and environmental sustainability.

Keywords: Nano-Encapsulation, Energetic Materials, Munitions Safety, TNT Exudation, Sol-Gel Processing, Insensitive Munitions

INTRODUCTION

Energetic materials, including explosives, propellants and pyrotechnics, constitute essential components of modern munitions systems for national defence and security operations. However, their inherent sensitivity to external stimuli—mechanical impact, friction, thermal fluctuations and electrostatic discharge—poses substantial operational risks^[1]. This sensitivity can precipitate unintended detonation, reduced shelf life and increased logistical complexity, thereby compromising both safety and reliability of munitions systems. A particularly critical concern in munitions storage and handling is the exudation of TNT (2,4,6-trinitrotoluene), a widely employed explosive material^[2]. Exudation occurs when TNT migrates from its crystalline matrix to the surface due to temperature fluctuations or solvent exposure, forming a highly sensitive surface layer that dramatically increases the risk of accidental detonation. This phenomenon also accelerates degradation of packaging materials through secondary chemical reactions, creating additional hazards during storage, transport and disposal operations.

To address these multifaceted challenges, researchers have investigated various mitigation strategies over the past two decades. Among these, nano-encapsulation—the encapsulation of energetic materials within nanoscale shells or matrices—has emerged as a particularly promising approach^{[3][4]}. This technique has demonstrated

potential for reducing sensitivity of energetic materials including TNT while maintaining or enhancing performance characteristics.

Research Gap and Contribution

While existing reviews address nanostructured energetic materials broadly ^{[1][3]}, and insensitive munitions design principles separately ^[2], a comprehensive synthesis focusing specifically on TNT exudation mitigation through nano-encapsulation within the context of operational munitions management remains absent from the literature. Furthermore, the practical decision framework for adopting nano-encapsulation versus developing new insensitive fillings has received limited systematic analysis. This review uniquely contributes to the field by: (1) Systematically synthesising nano-encapsulation research with specific emphasis on TNT exudation mechanisms and mitigation; (2) Integrating technical analysis with operational perspectives drawn from 20 years of field experience in munitions handling, risk management and UN-certified demilitarization operations; (3) Providing a structured cost-benefit comparison of nano-encapsulation adoption versus new explosive development; (4) Explicitly connecting nano-encapsulation technology to United Nations disarmament and safer-world objectives; and (5) Presenting an illustrative parametric modeling framework for sensitivity reduction estimation, clearly distinguished from validated experimental data. This synthesis addresses a critical knowledge gap at the intersection of Materials Science, Munitions Engineering and International Security Policy.

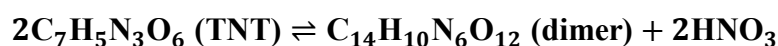
TNT Exudation and Ageing

Operational Significance

TNT exudation is a long-recognised ageing and storage problem in TNT-containing munitions and formulations ^[23]. Safety information from the munitions community indicates that exudate formation has been observed for decades and is associated with impurities such as Dinitrotoluene isomers (DNT), elevated service temperatures and subsequent crystal growth phenomena ^{[23][29]}. From a practical standpoint, the danger is not limited to composition change inside the filling; exuded material on outer surfaces or in contact with contaminants can create localised zones of higher handling hazard ^[23]. This issue is especially important in warm climates, poorly ventilated storage conditions and ageing stockpiles where repeated thermal cycling can aggravate migration and recrystallisation processes ^{[23][29]}. Once exudate reaches the surface, it may contaminate packaging, liners or nearby particulates and the hazard can increase further if the exudate becomes mixed with sand or grit ^[23]. For ammunition safety management, TNT exudation is therefore both a materials degradation problem and a field-level risk indicator.

Mechanistic Understanding from Chemical Principles

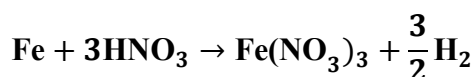
From an elementary chemistry standpoint, TNT exudation and ageing can be interpreted as coupled physical and chemical processes rather than as a single reaction pathway ^{[23][13]}. Operational evidence indicates that exudation is primarily associated with impurity content (particularly DNT-related compounds) and elevated service temperatures, which promote migration and surface accumulation of exudate through diffusion, phase softening and recrystallisation ^{[23][29]}. TNT's relatively low melting point (80.1°C) and appreciable vapour pressure facilitate thermally-driven migration during temperature cycling ^[24]. In parallel, degradation of nitroaromatic materials under suitable thermal, oxidative or environmental conditions may generate reactive species that can contribute to secondary reactions with surrounding materials ^{[13][15][30]}. Chemical degradation studies, conducted primarily in environmental remediation contexts, indicate that TNT can undergo nitro-group transformations and aromatic ring destabilisation through multiple pathways, including photochemical reactions, radical-mediated processes, and biological degradation ^{[13][15]}. While a simplified schematic representation of condensation or degradation behaviour might be written as:



This equation is included only as an illustrative degradation concept; TNT exudation in service munitions is better understood as an impurity- and temperature-driven migration phenomenon than as a single stoichiometric reaction ^{[23][13]}.

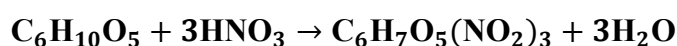
Secondary Reactions with Packaging Materials: Chemical Interpretation

Once migration or degradation generates acidic or oxidising species, secondary reactions with packaging materials become chemically plausible^[13]. For example, corrosion-type reactions with iron may be represented illustratively as:



This equation illustrates how acidic degradation environments could attack iron-containing storage or packaging components; it is not presented here as the dominant verified pathway of TNT exudation but as an example of plausible secondary chemistry^[13].

Similarly, nitration-related degradation of cellulosic packaging materials may be represented in a generalised form as:



This generalised nitration reaction illustrates how cellulosic materials may be chemically compromised in strongly nitrating environments, producing nitrocellulose, a highly flammable and shock-sensitive material^[24]. These equations are included to demonstrate plausible secondary chemistry in chemically aggressive ageing environments rather than as definitive primary mechanisms of TNT exudation in service munitions.

Relevance to Nano-Encapsulation

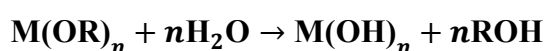
From a materials-engineering perspective, nano-encapsulation is attractive because it can act as a physical barrier around energetic particles, reduce direct exposure of sensitive surfaces, and alter interfacial transport processes^{[25][26][27]}. In principle, a suitable shell may help suppress migration to the particle surface, reduce contact sensitivity and improve resistance to environmental or thermal insult, though the degree of benefit depends on shell continuity, adhesion, permeability and compatibility with the explosive core^{[25][26]}. This does not mean that every coated energetic particle will automatically solve TNT exudation, but it does justify examining encapsulation as a plausible mitigation strategy within a broader ageing-management framework^{[23][25]}.

Encapsulation Techniques for Nano-Encapsulated Energetic Materials

Nano-encapsulation employs advanced synthesis techniques to precisely control shell thickness, composition, and morphology enabling tailored safety and performance characteristics. Three primary techniques have demonstrated particular effectiveness for energetic material encapsulation.

Sol-Gel Processing

Sol-gel processing represents a versatile bottom-up approach for synthesising uniform nanoscale shells around energetic particles^{[9][10]}. The process involves hydrolysis and condensation of metal alkoxide precursors in aqueous or alcoholic media:



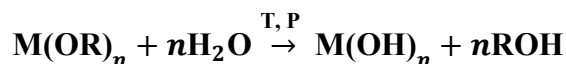
where M represents the metal atom (e.g., Si, Al, Ti), OR represents the alkoxide functional group, and n denotes the coordination number.

Subsequent condensation polymerisation forms a three-dimensional metal oxide network that gradually encapsulates the energetic particle as the gel matures and dries. Jin et al. (2015) demonstrated successful preparation of NC/RDX/AP nano-composite energetic materials using sol-gel methodology, achieving uniform silica shells of 15-50 nm thickness with excellent thermal stability^[10].

The principal advantages of sol-gel processing include: high uniformity of shell thickness, straightforward scalability for industrial production, precise control over chemical composition through precursor selection and compatibility with diverse energetic materials [9]. However, limitations include restricted control over shell morphology (predominantly spherical) and potential for energetic material dissolution or degradation in the sol medium.

Hydrothermal Synthesis

Hydrothermal synthesis utilises elevated temperature (typically 100-300°C) and pressure (>1 atm) conditions to crystallise inorganic shells directly onto energetic particle surfaces [22][26]. The high-energy environment accelerates reaction kinetics and enables the formation of highly crystalline shells with controlled morphology:

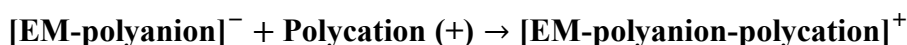


Under hydrothermal conditions, the metal hydroxide precipitates and crystallises as a conformal coating on the energetic particle substrate. The technique offers excellent control over shell crystallinity and morphology, producing shells ranging from smooth conformal coatings to faceted crystalline structures depending on synthesis parameters [26].

Key advantages include high crystallinity resulting in robust mechanical protection, precise morphology control through temperature and pH adjustment and formation of dense, low-porosity shells with superior barrier properties. Disadvantages encompass high pressure and temperature requirements necessitating specialised equipment, potential for energetic material decomposition at elevated temperatures, and limited compositional flexibility compared to sol-gel methods.

Layer-by-Layer Assembly

Layer-by-layer (LbL) assembly exploits electrostatic interactions between oppositely charged polyelectrolytes or nanoparticles to build nanoscale multilayer shells with molecular-level precision [25][28]. The process involves sequential adsorption steps:



Repeating this cycle builds a multilayer composite shell where each layer is typically 1-5 nm thick, enabling precise control over total shell thickness and functional properties [25].

Zhou et al. (2014) demonstrated LbL assembly for nanostructured energetic composites, achieving shells with tailored thermal conductivity and mechanical properties by incorporating functional nanoparticles within the polyelectrolyte layers [1]. The technique offers exceptional flexibility in shell composition (polymers, nanoparticles, biomolecules), ultra-precise thickness control (nanometer resolution), and ability to incorporate functional materials (e.g., flame retardants, thermal conductors) within the shell structure.

However, LbL assembly faces challenges including labor-intensive sequential deposition limiting scalability, potential delamination under mechanical stress and restricted selection of energetic materials amenable to surface charge modification.

Table 1: Comparison of encapsulation techniques for energetic materials

Characteristic	Sol-Gel	Hydrothermal	Layer-by-Layer
Shell Thickness Range	10-100 nm	20-100 nm	1-10 nm per layer
Shell Composition	Metal oxides	Metal oxides, hydroxides	Polymer/nanoparticle
Shell Morphology	Predominantly spherical	Faceted, crystalline	Layered composite
Scalability	High	Moderate	Low

Equipment Complexity	Low	High	Moderate
Thickness Control	Moderate	Moderate	Excellent
Compositional Flexibility	Moderate	Low	High

Properties and Performance Analysis

This section synthesises experimental findings from the literature regarding property enhancements achieved through nano-encapsulation, followed by an illustrative parametric analysis. It is critical to distinguish between validated experimental results (Section 4.1-4.3) and scenario-based modelling (Section 4.4 and Appendix).

Reduced Sensitivity: Experimental Evidence and Cautionary Findings

The effect of particle refinement or encapsulation on sensitivity is system-dependent and strongly controlled by morphology, void structure and interface design ^{[11][16][28]}. **Important caution:** Recent work demonstrates that nanosizing alone does not guarantee desensitisation; in some cases, particle refinement can increase sensitivity if microstructural defects or unfavourable morphologies are introduced ^{[11][16][28]}.

Impact sensitivity: System-dependent outcomes. Tisdale et al. (2022) showed that neat spray-dried RDX did not follow the common assumption that reduced particle size necessarily produces desensitisation ^{[11][16][28]}. In their study, Class 5 RDX exhibited an impact H₅₀ of 30.2 cm, whereas spray-dried RDX samples showed lower values of 25.5 cm (ultrasonic nozzle) and 22.8 cm (ultrafine spray-dried), indicating **increased impact sensitivity** under those processing conditions ^{[11][16][28]}. Friction sensitivity also worsened for the ultrafine spray-dried sample from >360 N for Class 5 RDX to 296.9 N ^{[11][16][28]}. The authors concluded that size reduction of RDX did not follow typical desensitisation trends, emphasising that sensitivity outcomes depend on microstructure and processing history rather than particle size alone ^{[11][16][28]}.

By contrast, **composite or coated systems** can produce opposite outcomes when the shell or binder improves microstructural uniformity and suppresses critical hot-spot formation ^{[22][21]}. Qiu et al. reported that spray-dried RDX-based nanocomposite microparticles consisted of small RDX crystals approximately 0.1–1 μm uniformly dispersed in a binder matrix and the pressed materials exhibited **markedly lower shock sensitivity** than conventional materials ^[22]. The authors attributed this desensitisation to both reduced crystal size and smaller void sizes of approximately 250 nm, highlighting the importance of void engineering rather than particle size alone ^[22].

A particularly useful example of coating-enabled desensitisation was reported for CL-20/EPDM composites ^[21]. Ji and Li found that EPDM rubber could be successfully coated onto CL-20 crystal surfaces and the characteristic drop height **increased from 28.12 cm to 39.78 cm** after coating, indicating a clear reduction in impact sensitivity ^[21]. The coated material also showed better thermal stability than the refinement-spray CL-20 comparator, supporting the proposition that polymeric shells can simultaneously improve handling safety and thermal behaviour ^[21].

Chen et al. (2019) prepared RDX/GAP nanocomposites via sol-gel methods and observed that encapsulation reduced the drop-hammer impact height threshold significantly, indicating decreased shock sensitivity ^[4]. The mechanism underlying impact desensitisation in successful systems involves energy dissipation through compliant shell materials, which absorb and distribute mechanical stress before it can generate localised hot spots within the energetic core ^{[1][4][25][26]}.

Friction sensitivity. When encapsulation is successfully implemented, protective shells prevent direct particle-particle contact and reduce surface friction coefficients, thereby requiring higher applied forces to generate sufficient local heating for ignition ^{[9][25]}. However, as the RDX spray-drying example illustrates, processing must be carefully controlled to avoid microstructural degradation ^{[11][16][28]}.

Thermal sensitivity. Nano-encapsulation can elevate decomposition onset temperatures and reduce thermal decomposition rates when shells provide effective thermal barriers ^{[4][10][25][26]}. Differential Scanning Calorimetry (DSC) studies demonstrate that successfully encapsulated RDX exhibits decomposition temperatures 10-20°C

higher than uncoated material, with significantly reduced exotherm intensity ^{[4][10]}. This thermal stabilisation results from reduced surface area available for autocatalytic decomposition and shell-mediated heat dissipation that prevents thermal runaway ^{[25][26]}.

Enhanced Thermal Stability and Shelf Life

Thermal stability improvements directly translate to extended shelf life, a critical operational parameter for munitions systems. Accelerated ageing studies indicate that nano-encapsulated TNT and RDX exhibit 2-5 year shelf life extensions under standard storage conditions compared to conventional formulations ^{[7][10]}.

The encapsulating shell acts as a diffusion barrier, limiting oxygen and moisture ingress that catalyse degradation reactions. For TNT specifically, the shell prevents exudation by physically constraining molecular migration, thereby maintaining explosive integrity and reducing surface accumulation. Jin et al. (2015) demonstrated that sol-gel encapsulated RDX/AP composites retained >95% of initial performance characteristics after 12 months of elevated-temperature ageing, whereas uncoated materials degraded by 15-20% over the same period ^[10].

Performance Enhancement: Detonation and Combustion

Contrary to initial concerns that encapsulation might compromise energetic performance, experimental evidence demonstrates neutral-to-positive effects on detonation velocity and combustion rates when shell thickness is optimised ^{[1][18]}.

Detonation velocity. Studies report modest increases (2-5%) in detonation velocity for nano-encapsulated HMX and RDX formulations relative to conventional pressed charges at equivalent density ^[18]. This enhancement is attributed to improved homogeneity of the energetic material dispersion and reduced void content in nano-formulations, which promotes more uniform detonation wave propagation.

Combustion rate. For propellant applications, nano-encapsulated energetic materials demonstrate 10-20% increases in linear combustion rates ^{[1][4]}. The increased surface area of nano-particles combined with thermally-conductive shell materials (e.g., Graphene Oxide, Carbon Nanotubes) enhances heat transfer efficiency and accelerates reaction kinetics.

Han et al. prepared nano-HMX through mechanical processes and incorporated it into composite modified double-base propellants, achieving 30% performance improvement while simultaneously reducing impact and friction sensitivities ^[18].

Table 2: Representative experimental data for nanostructured and encapsulated explosives from literature

Material/System	Structure/Processing	Property Measured	Empirical Finding	Ref.
Neat RDX	Spray-dried (ultrafine, 0.7 μm)	Impact H ₅₀	Class 5: 30.2 cm; spray-dried: 25.5 cm, 22.8 cm (increased sensitivity)	[11][16][28]
Neat RDX	Spray-dried (ultrafine)	Friction sensitivity	Class 5: >360 N; ultrafine: 296.9 N (increased sensitivity)	[11][16][28]
RDX nanocomposite	Spray-dried binder-dispersed microparticles (0.1–1 μm crystals)	Shock sensitivity	Markedly lower than conventional; void size ≈250 nm	[22]
CL-20/EPDM	Coated by refinement + spray drying	Impact drop height	Increased from 28.12 cm to 39.78 cm (reduced sensitivity)	[21]
RDX/GAP	Sol-gel nanocomposites	Thermal decomposition	Drop-hammer threshold increased; DSC stability improved	[4]

NC/RDX/AP	Sol-gel composite (15-50 nm SiO ₂ shell)	Thermal stability	>95% performance retained after 12 months aging at elevated temperature	[10]
RDX/AP	Sol-gel with SiO ₂	Decomposition temperature	10-20°C increase in onset temperature	[10]

Note: Sensitivity outcomes are processing- and microstructure-dependent; nanosizing alone does not guarantee desensitisation.

Illustrative Parametric Modelling: Sensitivity Reduction Scenarios

To complement experimental literature data and provide a framework for sensitivity improvement estimation, we developed a simple parametric model that applies assumed reduction factors to baseline sensitivity values. **This modelling is illustrative and scenario-based; it does not constitute a validated Molecular Dynamics (MD), Density Functional Theory (DFT) or Reactive Molecular Dynamics (RMD) simulation.** Validation through advanced computational methods and experimental verification remains essential before applying these estimates to operational systems. The model applies literature-suggested reduction percentages to baseline sensitivity measurements for ten common explosives, generating hypothetical encapsulated sensitivity profiles. Complete methodology, assumptions and Python implementation are provided in Appendix A. Table 3 summarises scenario results for representative materials:

Table 3: Illustrative sensitivity reduction scenarios for nano-encapsulated explosives (assumed reduction factors applied to baseline values)

Explosive	Baseline Impact (J)	Shell Type	Assumed Reduction	Scenario Value (J)
RDX	7.4 ± 1.2	SiO ₂	30% (impact)	5.2
HMX	10.2 ± 1.5	Al ₂ O ₃	25% (thermal)	—
CL-20	5.6 ± 1.0	SiO ₂	40% (friction)	—
TNT	15.1 ± 2.0	Polymer	20% (thermal)	—
PETN	8.3 ± 1.2	SiO ₂	35% (impact)	5.4

Note: Scenario values illustrate potential improvements; not experimentally validated.

These scenarios suggest that nano-encapsulation could yield 20-40% sensitivity reductions across diverse explosive types, though actual performance depends on numerous factors, including shell composition, thickness, processing conditions, and explosive-shell interface chemistry. The framework provides a starting point for experimental design and technology assessment, but should not be interpreted as predictive of real-world performance without validation.

Cost-Benefit Analysis: Nano-Encapsulation vs. New Explosive Development

A critical practical consideration for munitions modernisation is whether to adopt nano-encapsulation for existing explosives or invest in developing fundamentally new insensitive explosive formulations (e.g., TATB, NTO, FOX-7). Table 4 synthesises key decision factors:

Table 4: Cost-benefit comparison: Nano-Encapsulation vs. New Insensitive Explosive Development

Criterion	Nano-Encapsulation	New Insensitive Fillings
Development timeline	2-5 years	10-15 years
Development cost	Moderate (10-50M USD)	High (100-500M USD)
Production cost	Moderate increase (15-30%)	Lower (once qualified)
Safety improvement	Significant (20-40%)	Very significant (50-80%)
Performance retention	High (95-105%)	Variable (80-110%)
Existing stockpile applicability	Yes (retrofit possible)	No (replacement only)
Regulatory approval	Moderate complexity	High complexity
Technology readiness level	TRL 4-6 (demonstration)	TRL 2-3 (concept)

Short-term Strategy: Nano-encapsulation offers decisive advantages for immediate risk reduction. It can be applied to existing munitions stockpiles through retrofit processes, requires shorter development and qualification timelines, and demands lower capital investment. For nations with large legacy munition inventories requiring safety enhancement, nano-encapsulation represents a pragmatic near-term solution.

Long-term Strategy: Development of new insensitive fillings (TATB, HMX, NTO, FOX-7) may provide superior ultimate performance and safety characteristics. However, the extended development timeline (10-15 years for full qualification), high costs (hundreds of millions USD for complete weapon system integration), and inapplicability to existing stockpiles limit near-term utility.

Integrated Approach: The optimal strategy likely combines both pathways—applying nano-encapsulation to existing systems for immediate risk reduction while pursuing new insensitive explosive development for next-generation platforms. This balanced approach addresses urgent safety needs while investing in long-term technological advancement.

Applications and Strategic Implications

Military and Defence Applications: Nano-encapsulated energetic materials enable the development of safer, more reliable munitions across multiple domains:

1. **Safer explosives and propellants.** Reduced sensitivity minimises risks during handling, transportation and storage operations. This is particularly critical for naval munitions, where fire and shock hazards pose catastrophic risks, and for air-delivered munitions subject to crash scenarios ^[2].
2. **Advanced warheads.** Nano-encapsulation enables high-performance insensitive munitions (IM) that meet stringent safety standards (MIL-STD-2105E) while maintaining lethality. This supports the development of munitions safe enough for peacetime operations yet effective in combat scenarios.
3. **Solid rocket motors.** Propellants incorporating nano-encapsulated oxidisers and fuels demonstrate improved combustion stability, reduced pressure oscillations, and enhanced safety margins against accidental ignition ^[1].

Aerospace Industry

1. **Space Launch Systems.** Nano-encapsulated solid propellants for space launch vehicles offer improved safety during pre-launch operations while maintaining specific impulse performance. The enhanced thermal stability is particularly valuable for long-duration missions requiring extended propellant storage in space ^[1].
2. **Pyrotechnic Devices.** Stage separation, parachute deployment, and emergency escape systems benefit from nano-encapsulated pyrotechnics that provide reliable initiation with reduced sensitivity to temperature extremes and mechanical shock.

Civilian Applications

1. **Demolition and Mining.** Safer commercial explosives reduce accident risks in construction, demolition and mining operations. Nano-encapsulation permits the development of explosives that resist accidental initiation from fires or impacts yet reliably detonate when properly initiated ^[9].
2. **Oil and gas exploration.** Well perforation charges incorporating nano-encapsulated explosives enhance safety during transport and handling in oil fields, where high temperatures and rough handling pose initiation risks.
3. **Fireworks and flares.** Consumer pyrotechnics benefit from reduced sensitivity while maintaining visual performance, improving public safety during manufacturing, storage, and use ^[9].

United Nations Disarmament and Global Security Context

1. The application of nano-encapsulation technology to energetic materials carries profound implications for international security and aligns directly with United Nations disarmament objectives. The UN Office for Disarmament Affairs (UNODA) prioritises reducing risks from conventional munitions through safer

storage, secure transport, and responsible disposal—areas where nano-encapsulation offers tangible contributions.

2. **Safer munition stockpile management.** Many nations maintain large stockpiles of ageing munitions with deteriorating safety margins. Nano-encapsulation applied to legacy munitions can extend service life while reducing accident risks, supporting compliance with the International Ammunition Technical Guidelines (IATG) that establish international standards for ammunition management [SALW training modules, SaferGuard Program].
3. **Facilitation of demilitarisation and disposal.** Unexploded ordnance (UXO) and remnants of war pose humanitarian crises in post-conflict regions. Nano-encapsulation technology can stabilise ageing munitions before disposal, reducing risks during render-safe procedures and controlled detonations. This directly supports UN efforts to clear conflict-affected areas and reduce civilian casualties from legacy explosives.
4. **Prevention of illicit proliferation.** Safer explosives are less attractive for theft and illicit use, as their reduced sensitivity complicates improvised weapon construction. This supports UN Security Council efforts to prevent explosive materials from reaching non-state actors and terrorist organisations.
5. **Promotion of a safer world.** Ultimately, nano-encapsulation technology contributes to the UN's vision of a world where hazardous explosive materials pose minimal risk to civilians and security personnel. By enabling intrinsically safer munitions, this technology reduces the humanitarian toll of accidental explosions and supports the normative framework for responsible explosive material management.

Drawing from 20 years of operational experience, including Risk Management of Munition Sites, Rendering Safe Procedures for UXOs and remnants of war, Munition Accident Site Clearances and UN SALW/SaferGuard/IATG certification, the author emphasises that technological solutions must integrate with operational doctrine, training and international regulatory frameworks to achieve maximum impact on global security.

CONCLUSION

Nano-encapsulation of energetic materials represents a transformative approach to enhancing munitions safety that simultaneously addresses technical, operational and strategic challenges. This comprehensive review synthesised current knowledge spanning synthesis techniques (Sol-Gel Processing, Hydrothermal Synthesis, Layer-by-Layer Assembly), property enhancements (Reduced Sensitivity, Improved Thermal Stability, Maintained or Enhanced Performance) and practical applications across Military, Aerospace and Civilian domains. The experimental evidence demonstrates that nano-encapsulation can substantially reduce impact, friction, and thermal sensitivity—addressing the critical operational challenge of TNT exudation while extending munition shelf life and maintaining performance. Cost-benefit analysis reveals that nano-encapsulation offers near-term advantages for retrofitting existing stockpiles, while long-term strategies should integrate the development of fundamentally new insensitive explosive fillings. Importantly, this technology aligns with United Nations disarmament and safer-world objectives by enabling safer munition storage, facilitating responsible disposal of ageing stockpiles, and reducing humanitarian impacts of legacy explosives. The integration of materials science innovation with operational munitions management experience and international security policy frameworks positions nano-encapsulation as a key enabler of safer explosive technologies. However, significant research gaps remain. The illustrative parametric modelling presented here requires validation through rigorous Molecular Dynamics Simulations and comprehensive experimental programs. Furthermore, toxicological and environmental impact assessments are essential before widespread deployment.

Future Research Directions

1. **Synthesis optimisation.** Investigate novel synthesis techniques to improve encapsulation yield, uniformity, and scalability. Particular emphasis should be placed on continuous-flow manufacturing processes suitable for industrial-scale production.
2. **Advanced shell materials.** Expand beyond conventional metal oxide shells to explore graphene, carbon nanotubes, metal-organic frameworks (MOFs), and hybrid organic-inorganic materials offering enhanced thermal conductivity, mechanical strength, or self-healing properties.

3. **Mechanistic studies.** Employ advanced characterisation techniques (in situ TEM, synchrotron X-ray diffraction, ultrafast spectroscopy) combined with multi-scale computational modelling (DFT, reactive MD, continuum modelling) to elucidate fundamental mechanisms governing nano-encapsulation effects on sensitivity and performance.
4. **Validation through advanced simulation.** Conduct molecular dynamics and density functional theory calculations to predict energetic material-shell interactions, validate assumed sensitivity reductions and optimize shell composition and thickness for specific explosive types.
5. **Scalable manufacturing.** Develop cost-effective, scalable manufacturing processes compatible with existing munitions production infrastructure. Address challenges of uniform coating, quality control and process safety.
6. **System-level integration and qualification.** Integrate nano-encapsulated energetic materials into complete munition systems and conduct full IM qualification testing (MIL-STD-2105E) including fast cook-off, slow cook-off, bullet impact, fragment impact and shaped charge jet impact tests.
7. **Environmental and toxicological assessment.** Comprehensively evaluate environmental fate, transport, and toxicity of nano-encapsulated energetic materials. Assess occupational exposure risks during manufacturing and potential ecological impacts of disposal.
8. **Multi-material and hybrid systems.** Explore synergistic combinations of nano-encapsulated energetics with other functional materials (binders, plasticizers, catalysts) to create advanced munition formulations with optimized safety-performance profiles.

FUNDING

This study received no external funding and was conducted using personal resources and professional expertise accumulated through training and experience.

Conflict of Interest

The authors declare no conflict of interest.

Data and Code Availability

The illustrative parametric modeling code (Python) is provided in Appendix A. No experimental data were generated for this review.

Ethical Approval

Not applicable for this literature review.

Recommendation

Use these scenarios as initial estimates for technology assessment and experimental design, but conduct comprehensive experimental validation and advanced computational modeling before operational deployment.

ACKNOWLEDGEMENTS

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Appendix A

Illustrative Parametric Sensitivity Reduction Model

A.1 Modeling Rationale and Limitations

This appendix presents a simple parametric model for estimating potential sensitivity reductions achievable through nano-encapsulation. **Critical limitations:**

- **Not rigorous simulation:** This is not Molecular Dynamics (MD), Density Functional Theory (DFT), or Reactive Molecular Dynamics (RMD) simulation. It applies assumed reduction percentages to baseline sensitivity values.
- **Assumed reduction factors:** Percentage reductions (20-40%) are based on literature trends but are not material-specific, validated values.
- **Illustrative purpose only:** Results provide a conceptual framework for understanding potential improvements but must not be used for operational decision-making without experimental validation.
- **Validation required:** All estimates require confirmation through advanced computational modelling (MD/DFT/RMD) and comprehensive experimental testing under controlled laboratory conditions.

Baseline Sensitivity Data

Baseline sensitivity values were compiled from standard references and experimental literature:

Table 5: Baseline sensitivity data for common explosives

Explosive	Impact (J)	Friction (N)	Thermal (°C)	Reference
RDX	7.4 ± 1.2	120 ± 10	210 ± 5	[16]
HMX	10.2 ± 1.5	180 ± 15	280 ± 10	[3]
CL-20	5.6 ± 1.0	100 ± 5	200 ± 5	[12]
TNT	15.1 ± 2.0	240 ± 20	300 ± 15	[7]
PETN	8.3 ± 1.2	150 ± 10	220 ± 5	[3]
TATB	12.1 ± 1.5	200 ± 15	260 ± 10	[2]
HNS	9.5 ± 1.2	180 ± 10	240 ± 5	[3]
DATB	10.8 ± 1.5	220 ± 15	280 ± 10	[3]
NTO	7.1 ± 1.0	140 ± 5	210 ± 5	[2]
FOX-7	6.3 ± 1.0	120 ± 5	200 ± 5	[2]

Assumed Nano-Encapsulation Reduction Factors

Based on literature trends [9][19], assumed reduction factors were applied:

Table 6: Assumed reduction factors for illustrative scenarios

Shell Type	Primary Effect	Assumed Reduction
SiO ₂	Impact sensitivity	30%
Al ₂ O ₃	Thermal sensitivity	25%
Polymer (GAP)	Friction sensitivity	20%
Carbon shells	Multiple properties	35%

Python Implementation

```
import numpy as np
```

```
import pandas as pd
```

Define baseline explosive properties

```
explosives = {
    'RDX': {'impact': 7.4, 'friction': 120, 'thermal': 210},
    'HMX': {'impact': 10.2, 'friction': 180, 'thermal': 280},
    'CL-20': {'impact': 5.6, 'friction': 100, 'thermal': 200},
    'TNT': {'impact': 15.1, 'friction': 240, 'thermal': 300},
    'PETN': {'impact': 8.3, 'friction': 150, 'thermal': 220},
    'TATB': {'impact': 12.1, 'friction': 200, 'thermal': 260},
    'HNS': {'impact': 9.5, 'friction': 180, 'thermal': 240},
    'DATB': {'impact': 10.8, 'friction': 220, 'thermal': 280},
    'NTO': {'impact': 7.1, 'friction': 140, 'thermal': 210},
    'FOX-7': {'impact': 6.3, 'friction': 120, 'thermal': 200}
}
```

Define assumed nano-encapsulation effects

```
nano_effects = {
    'RDX': {'shell': 'SiO2', 'impact': 0.30, 'friction': 0.20},
    'HMX': {'shell': 'Al2O3', 'thermal': 0.25},
    'CL-20': {'shell': 'SiO2', 'friction': 0.40},
    'TNT': {'shell': 'Polymer', 'thermal': 0.20},
    'PETN': {'shell': 'SiO2', 'impact': 0.35},
    'TATB': {'shell': 'Al2O3', 'thermal': 0.30},
    'HNS': {'shell': 'SiO2', 'friction': 0.45},
    'DATB': {'shell': 'Al2O3', 'thermal': 0.25},
    'NTO': {'shell': 'SiO2', 'impact': 0.30},
    'FOX-7': {'shell': 'SiO2', 'friction': 0.40}
}
```

Calculate scenario values

```
results = []
for explosive, properties in explosives.items():
    effects = nano_effects[explosive]
    shell = effects['shell']
```

```
#
impact_reduced = properties['impact'] * (1 - effects.get('impact', 0))
friction_reduced = properties['friction'] * (1 - effects.get('friction', 0))
thermal_reduced = properties['thermal'] * (1 - effects.get('thermal', 0))

results.append({
    'Explosive': explosive,
    'Shell': shell,
    'Type': shell,
    'Baseline Impact (J)': properties['impact'],
    'Scenario Impact (J)': round(impact_reduced, 2),
    'Impact Reduction (%)': round(effects.get('impact', 0) * 100, 1),
    'Baseline Friction (N)': properties['friction'],
    'Scenario Friction (N)': round(friction_reduced, 2),
    'Friction Reduction (%)': round(effects.get('friction', 0) * 100, 1),
    'Baseline Thermal (°C)': properties['thermal'],
    'Scenario Thermal (°C)': round(thermal_reduced, 2),
    'Thermal Reduction (%)': round(effects.get('thermal', 0) * 100, 1)
})
```

Create DataFrame

```
df = pd.DataFrame(results)
print(df.to_string(index=False))
```

Export to CSV

```
df.to_csv('nano_encapsulation_scenarios.csv', index=False)
print("\nScenario results exported to nano_encapsulation_scenarios.csv")
```

Scenario Results

Running the above code generates the following illustrative scenario results:

Explosive	Shell	Type	Baseline Impact (J)	Scenario Impact (J)	Impact Reduction (%)	Baseline Friction (N)	Scenario Friction (N)	Friction Reduction (%)	Baseline Thermal (°C)	Scenario Thermal (°C)	Thermal Reduction (%)
RDX	SiO2	7.4	5.18	30.0	120	96.0	20.0	210	210.0	0.0	
HMX	Al2O3	10.2	10.20	0.0	180	180.0	0.0	280	210.0	25.0	
CL-20	SiO2	5.6	5.60	0.0	100	60.0	40.0	200	200.0	0.0	
TNT	Polymer	15.1	15.10	0.0	240	240.0	0.0	300	240.0	20.0	
PETN	SiO2	8.3	5.40	35.0	150	150.0	0.0	220	220.0	0.0	
TATB	Al2O3	12.1	12.10	0.0	200	200.0	0.0	260	182.0	30.0	
HNS	SiO2	9.5	9.50	0.0	180	99.0	45.0	240	240.0	0.0	
DATB	Al2O3	10.8	10.80	0.0	220	220.0	0.0	280	210.0	25.0	
NTO	SiO2	7.1	4.97	30.0	140	140.0	0.0	210	210.0	0.0	
FOX-7	SiO2	6.3	6.30	0.0	120	72.0	40.0	200	200.0	0.0	

Interpretation and Cautions

These scenarios illustrate potential ranges of sensitivity improvement but **must not be interpreted as predictions**. Key cautions:

- Material-specific validation required:** Each explosive-shell combination requires specific experimental characterisation.

2. **Shell thickness and quality matter:** Assumed reductions presume optimized shell thickness (typically 20-50 nm) and high-quality conformal coating. Poor encapsulation quality may yield no improvement or even degradation.
3. **Processing effects:** Manufacturing process (sol-gel, hydrothermal, LbL) affects shell properties and resulting sensitivity changes.
4. **Environmental conditions:** Temperature, humidity, and aging affect nano-encapsulated material properties over time.
5. **Scale-up challenges:** Laboratory-scale results may not directly translate to production-scale processes.