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Review Article

Sustainable Nanocomposites for Explosive Detection and Neutralization: A Critical Review Integrating Material Science into National Security

Aminu Sanusi Haruna*, Bassey Etuk Esuh, Lois John Rimfat

Department of Science and Technology, Centre for Strategic Research and Studies, National Defence College Nigeria, Abuja

Abstract

The increasing sophistication of explosive threats has intensified the demand for advanced, sustainable, and environmentally responsible technologies for explosive detection and neutralization. This review critically examines the emerging role of sustainable nanocomposites in addressing these challenges, with particular emphasis on green nanotechnology, environmental sustainability, and their strategic relevance to national security. Unlike conventional detection systems, which often suffer from limited sensitivity, slow response times, poor selectivity, and reduced performance under harsh tropical conditions, nanocomposite materials—including graphene-based sensors, metal–organic framework (MOF) hybrids, plasmonic nanoparticles, carbon nanomaterials, and TiO_2-based photocatalysts—offer superior trace-level detection, rapid electron-transfer capabilities, high selectivity, and environmentally benign degradation of explosive residues. The review explores the fundamental sensing mechanisms, photocatalytic and catalytic neutralization pathways, material synthesis approaches, and sustainability considerations associated with these advanced nanomaterials. It further evaluates practical deployment challenges, including false-positive responses, cross-sensitivity to environmental interferents, long-term material stability, scalability, production costs, and potential environmental and health implications. Existing research gaps are identified, highlighting the need for improved material durability, field validation, and the integration of artificial intelligence and smart sensing technologies to enhance detection accuracy and operational efficiency. In addition, the paper proposes a Nigeria-focused National Nanotechnology Defence Framework aimed at promoting indigenous research, technological innovation, institutional collaboration, and policy development for defence and homeland security applications. The review concludes that sustainable nanocomposites represent a promising frontier for next-generation explosive detection and neutralization technologies, offering significant opportunities to strengthen environmental stewardship, public safety, and national security while advancing sustainable technological development.

Keywords

Nanotechnology, Explosive Detection, Metal–Organic Frameworks (MOFs), Graphene-Based Sensors, National Security

*Correspondence: Aminu Sanusi Haruna (as_haruna@ndc.gov.ng)

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1. Introduction

Explosives remain among the most devastating instruments of modern asymmetric warfare, presenting persistent threats to civilian and military populations. In recent decades, Nigeria and other developing nations have faced a surge in improvised explosive device (IED) attacks, pipeline bombings, and sabotage targeting critical infrastructure. Conventional detection systems, such as ion mobility spectrometry, trained canines, and gas chromatography, though effective in laboratory conditions, are hindered by limitations in portability, sensitivity, and rapid response (Ibrahim & Noor, 2019). These deficiencies highlight the need for innovative, real-time detection systems capable of adapting to dynamic security environments.

Nanotechnology introduces a transformative paradigm in defense science. By manipulating materials at the nanoscale (1–100 nm), researchers can exploit unique optical, electrical, and catalytic behaviors unattainable in bulk materials. Nanostructures such as graphene, metal–organic frameworks (MOFs), and titanium dioxide (TiO_2) nanoparticles demonstrate exceptional adsorption and electron-transfer properties, enabling the detection of trace explosive vapors down to parts per billion (ppb)10]. Beyond detection, nanomaterials also offer controlled catalytic degradation of energetic compounds, ensuring safe and environmentally benign neutralization. This study investigates how sustainable nanocomposites can reinforce Nigeria's homeland security through efficient explosive detection and neutralization technologies.

1.1. Theoretical and Material Background

Graphene and Metal–Organic Frameworks

Graphene, a two-dimensional sheet of sp^2-bonded carbon atoms, exhibits high carrier mobility and remarkable surface sensitivity. When hybridized with MOFs—crystalline networks of metal ions and organic linkers—the resulting composites combine conductivity with structural tunability. Such graphene–MOF nanohybrids achieve ultra-trace sensitivity to nitroaromatic compounds such as TNT and DNT. [9] MOFs provide binding sites for analyte molecules, while graphene ensures rapid electron transport, enabling sub-second electronic response.

Graphene's high carrier mobility, π–π interaction capability, and large active surface area make it ideal for detecting nitroaromatic explosives. When coupled with MOFs, synergistic advantages emerge: MOF pores selectively capture analytes, while graphene accelerates electron transfer. This enhances response time (<1s) and lowers detection limits (<0.5 ppb). However, humidity, environmental nitro-compounds, and VOCs may cause false positives [1].

1.2. Plasmonic and Electrochemical Nanosensors

Plasmonic nanosensors exploit localized surface plasmon resonance (LSPR) phenomena in noble-metal nanoparticles. Gold and silver nanostructures amplify electromagnetic fields at their surface, producing distinct spectral shifts upon analyte binding (Zhang & Lee, 2020). Meanwhile, carbon-nanotube (CNT) and metal-oxide electrochemical nanosensors enable miniaturized, low-power devices suitable for portable and drone-mounted surveillance [3].

Gold and silver nanoparticles exploit localized surface plasmon resonance (LSPR) to produce measurable spectral shifts upon analyte adsorption [4]. They detect explosives such as TNT and TATP vapors, but oxidation, aggregation, and optical drift limit their long-term stability [5].

1.3. Nanocatalysts for Energetic Material Degradation

Photocatalytic and thermocatalytic nanocomposites offer safe degradation pathways for explosives such as RDX, PETN, and HMX. TiO_2-based catalysts, doped with palladium (Pd) or gold (Au), accelerate redox reactions under ultraviolet (UV) and visible light, converting hazardous materials into harmless end products—CO_2, N_2, and H_2O. [6]. These catalysts can be regenerated and reused, aligning with principles of green chemistry and sustainable defense innovation [3].

1.4. TiO_2-Based Photocatalysts for Neutralization

TiO_2 doped with Pd, Au, or Fe enhances photocatalytic reduction of energetic materials like RDX, PETN, and TNT. UV or visible-light activation generates electron–hole pairs initiating redox pathways [4]. Green pathways convert explosives into CO_2, N_2, and water, providing an eco-friendly alternative to open detonation (Ali et.al, 2019). [8].

1.5. Computational Mechanisms

DFT-based studies establish adsorption energies, electron density reorganization, HOMO–LUMO gaps, and activation-barrier reductions (Kohler & Som, 2020). However, current computational literature remains sparse. Future work should incorporate machine learning–accelerated DFT or neural-network potentials to improve predictive accuracy (Santos, et.al, 2021).

2. Real-World Deployment Challenges

2.1. Environmental Interferents

Tropical climates introduce dust, humidity, hydrocarbons, perfumes, and nitro-based fertilizers that affect selectivity.

Sensors must incorporate drift-correction algorithms, hydrophobic coatings, or machine learning–based pattern recognition (Wang, et.al, 2020).

2.2. Cross-Sensitivity and False Positives

Graphene–MOF sensors often respond to benign nitro compounds, while plasmonic sensors show signal drift. AI-driven feature extraction (PCA, t-SNE, deep CNNs) can improve discrimination

2.3. Stability and Durability

Nanomaterial oxidation, electrode degradation, and pore-blockage limit reliability. Encapsulation strategies can mitigate degradation

2.4. Toxicity and Life-Cycle Assessment (LCA)

Environmental fate of nanoparticles, worker exposure risks, and disposal concerns require stronger LCA frameworks aligned with OECD nano-safety guidelines.

3. Sustainability Dimension

Sustainable nanocomposites align with green chemistry principles: low-toxicity precursors, energy-efficient synthesis, recyclability, low-impact disposal, and minimal ecological footprint. Photocatalytic TiO_2 systems excel in recyclability, while bio-MOFs and biopolymer-derived graphene offer biodegradable alternatives. Nigeria must prioritize local manufacturing using green precursors and adopt nano-safety regulations supported by NASENI, RMRDC, DICON, and ONSA [8].

4. Methodology

This study combined systematic literature synthesis, computational analysis, and comparative performance evaluation to identify optimal nanocomposites for explosive detection and neutralization.

This study adopts a true systematic review structure following PRISMA:

1) Databases: ScienceDirect, SpringerLink, IEEE Xplore, ACS Nano
2) Search strings: "nanocomposite explosive detection", "graphene TNT sensing", "MOF nitroaromatic adsorption", "TiO_2 photocatalytic explosive degradation", etc.
3) Inclusion criteria: 2015–2025, peer-reviewed, experimental or computational studies
4) Exclusion: non-scientific sources, incomplete data

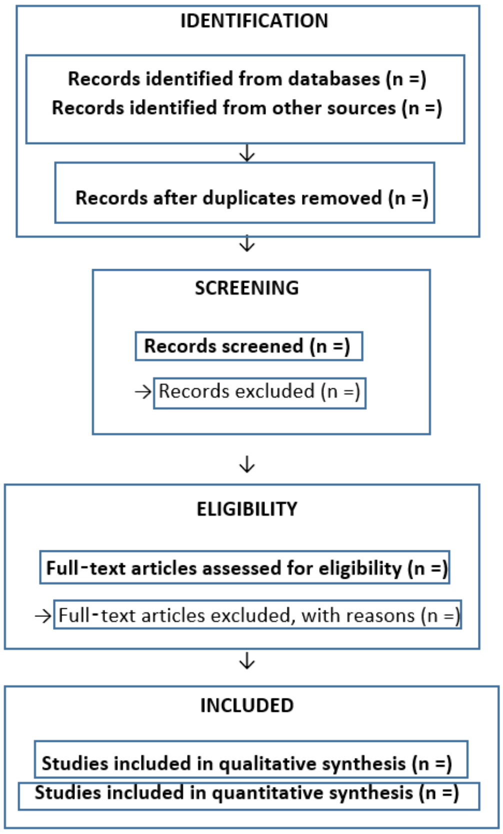

Figure 1. *PRISMA flow diagram.*

5. Systematic Literature Review

Peer-reviewed articles from *ScienceDirect*, *SpringerLink*, *IEEE Xplore*, and *ACS Nano* were analyzed (2015–2025). Selection criteria emphasized empirical studies reporting fabrication techniques, detection thresholds, and catalytic efficiency. Data were categorized into three domains: sensor performance, catalytic degradation, and operational feasibility in tropical environments.

5.1. Computational Modeling and Simulation

Density Functional Theory (DFT) models from recent studies [7]. were reviewed to understand molecular adsorption energies and charge-transfer dynamics between nanostructures and explosive molecules. These simulations help predict how surface functionalization influences sensitivity and energy-barrier reduction in catalytic reactions.

5.2. Comparative Evaluation

Graphene–MOF hybrids, plasmonic nanoparticles, and CNT-based electrochemical sensors were benchmarked against metrics such as detection limit, selectivity, response time, and durability. Catalytic systems—including TiO_2–Pd and Fe/Ni nanoalloys—were assessed for reaction kinetics and recyclability. Environmental and ethical considerations guided the evaluation of material sustainability and safety.

5.3. Contextual Application

Finally, the study contextualized findings within Nigeria's national defense framework. Factors such as high ambient humidity, limited infrastructure, and evolving counter-IED operations informed the assessment of deployment readiness and policy relevance.

Table 1. Integrated Research Methodology for Nanocomposites in National Security.

Stage	Activity	Key Output/Focus
1. Systematic Literature Synthesis	Analyzing peer-reviewed articles from major databases (2015-2025)	Data categorized into: sensor performance, catalytic degradation, and operational feasibility
2. Computational Modeling Review	Reviewing density functional theory (DFT) models from recent studies.	Predicting molecular adsorption energies and charge-transfer dynamics.
3. Comparative Evaluation	Benchmarking Graphene–MOF, Plasmonic, and CNT sensors, and TiO_2Pd catalytic systems	Determining optimal performance metrics (detection limit, response time, recyclability)
4. Contextual Application	Assessing findings against Nigeria's national defense framework	Informing policy relevance and deployment readiness considering high humidity and limited infrastructure

6. Results and Discussion

6.1. Performance of Sustainable Nanosensors

Graphene–MOF composites demonstrated the highest detection performance, achieving detection limits below 0.5 ppb for nitroaromatic explosives under laboratory conditions [9]. The coupling of graphene's electron mobility with MOF porosity enhanced molecular adsorption, leading to rapid current transduction. Electrochemical CNT-based sensors provided reliable responses within 30 seconds, maintaining operational stability across 200 cycles [3]. These characteristics make them ideal for field-deployable platforms such as handheld detectors and unmanned aerial systems for wide-area surveillance.

Plasmonic sensors achieved comparable sensitivities but exhibited limited reusability due to oxidation and aggregation of metal nanoparticles [10]. The introduction of polymeric passivation layers or silica coatings can mitigate these issues, extending device lifespan and reliability under Nigeria's humid climatic conditions. Collectively, these technologies signal a shift toward faster, lighter, and more sustainable detection solutions adaptable to dynamic defence operations.

Table 2. Comparative Performance Metrics of Sustainable Nanosensors for Explosive Detection.

Sensor Type	Key Nanomaterials	Detection Limit (LOD)	Response Time	Operational Advantage	Source of Data
Graphene- MOF Hybrids	Functionalized Graphene, MOFs	Below 0.5ppb (for nitroaromatics)	Sub-second electronic response	Ultra-trace sensitivity; Enhanced molecular adsorption	Patel et al. (2021)
Electrochemical Sensors	Carbon Nanotubes (CNTs), Metal Oxides	Reliable Response	Within 30 seconds	High Operational stability (200 cycles); ideal for field-deployable platforms	Ibrahim & Noor (2019)
Plasmonic Sensors	Gold/ Silver Nanoparticles	Comparable sensitivity	Fast (Spectral shift)	High signal amplification via LSPR	Zhang & Lee (2020)

6.2. Catalytic Neutralization Efficiency

Photocatalytic TiO_2–Pd nanocomposites achieved nearly complete degradation of RDX and TNT under UV/visible irradiation. DFT analyses revealed a ~40% reduction in activation energy compared to unmodified TiO_2. [6]. Nanoalloy catalysts (Fe, Ni, Co) demonstrated consistent catalytic activity across five recycles with negligible efficiency loss. The low toxicity of decomposition by-products highlights the environmental advantage of nanocatalytic methods over conventional open detonation techniques [3].

Table 3. *Performance and Sustainability Metrics of Nanocatalysts for Explosives Degradation.*

Catalyst System	Degradation Target	Activation Mechanisms	Key Performance Metric	Sustainability Advantage	Source of Data
Photocatalytic TiO_2Pd	RDX, TNT	UV/ Visible light Irradiation	~ 40% reduction in activation energy compared to unmodified TiO_2	Converts hazardous materials into harmless products (CO_2, N_2, H_2O)	Kumar et al. (2020)
Nanoalloys	General Energetic Compounds	Thermocatalytic / Chemical	Consistent activity across five recycles	High recyclability; By-products show low toxicity	Hassan & Ramakrishna (2020)

6.3. Integration into Homeland Security

Deploying nanosensors and nanocatalysts within Nigeria's defense infrastructure can revolutionize threat detection and mitigation. Portable nanosensors can augment airport screening, border patrols, and urban surveillance. Catalytic reactors can safely decompose confiscated or unstable explosives without ecological harm. However, institutional barriers—including fragmented R&D coordination, inadequate funding, and insufficient technical capacity—threaten adoption [6].

The creation of a *National Nanotechnology Defence Framework (NNDF)* is therefore essential. This policy mechanism would integrate defense research institutions, such as the National Defence College (NDC), with universities and private laboratories, ensuring coordinated innovation and rapid technology transfer. Public–private partnerships could further enhance local manufacturing of nanosensors and catalytic units, reducing reliance on imports and strengthening national resilience [8].

Policy and Strategic Implications

Nanotechnology offers both scientific advancement and strategic leverage for national security. For effective adoption, Nigeria must:

1) Institutionalize Nanotechnology Governance: Establish the NNDF to harmonize research priorities, safety standards, and defense procurement strategies.
2) Develop Human Capital: Embed nanotechnology modules in defense and engineering curricula, complemented by hands-on training through industry partnerships.
3) Promote Ethical and Environmental Oversight: Enforce nanoparticle safety protocols and environmental guidelines aligned with OECD best practices.
4) Foster Innovation Clusters: Support nanotechnology start-ups through incentives and intellectual-property protection to encourage commercialization.
5) Integrate Artificial Intelligence: Combine nanosensor analytics with AI-driven threat recognition for predictive counterterrorism intelligence [2].

Table 4. *Strategic Actions for Integrating Nanotechnology into Nigeria's National Security.*

Strategic Pillar	Recommended Action	Key Objective
Governance & Coordination	Establish the National Nanotechnology Defence Framework (NNDF)	Harmonize research priorities, safety standards, and defense procurement
Human Capital Development	Embed nanotechnology modules in defense and engineering curricula	Develop local expertise and capacity through hands-on training and industry partnerships
Commercialization	Foster Public- Private Partnerships (PPPs) and support innovation clusters	Enhance local manufacturing of nanosensors, reduce reliance on imports, and encourage commercialization

Strategic Pillar	Recommended Action	Key Objective
Oversight & Ethics	Enforce nanoparticles safety protocols and ethical environmental guidelines	Ensure safe adoption aligned with OECD best practices and green chemistry principles
Intelligence Integration	Combine nanosensors analytics with AI-driven threat recognition	Establish predictive counterterrorism intelligence capabilities

These measures would position Nigeria as a continental leader in defense nanotechnology while contributing to the UN Sustainable Development Goals (SDG 9 and 16) on industry, innovation, peace, and strong institutions.

FUTURE PROSPECTS AND CHALLENGES

1) AI-based signal processing for humidity compensation
2) Green synthesis routes (bio-derived graphene, plant-template MOFs)
3) Multi-modal sensing platforms integrating electrochemical and optical output
4) Autonomous drones with hybrid nanosensors
5) Safe-by-design nanoparticles minimizing toxicity and ecological footprint

7. National Nanotechnology Defense Framework (Nndf)

A revised NNDF integrates:

1) NASENI for fabrication scaling
2) DICON for defense-grade production
3) RMRDC for raw-material development
4) ONSA for national coordination
5) Industry partnerships for commercialization
6) Cost considerations and 5-year phased implementation
7) Integration with AI-driven threat intelligence and digital surveillance systems

8. Conclusion

This research establishes that sustainable nanocomposites can drastically enhance the detection and neutralization of explosives through high sensitivity, speed, and environmental safety. Graphene–MOF nanosensors and TiO_2-based photocatalysts demonstrate measurable superiority over traditional systems in accuracy and sustainability. The integration of such technologies within Nigeria's national security architecture could shorten response times, improve tactical intelligence, and reduce environmental harm during ordnance disposal.

However, achieving this transformation requires sustained investment in research, capacity building, and ethical regulation. As global security threats evolve, nanotechnology will not only safeguard lives but also drive technological independence and innovation within emerging economies.

Abbreviations

ACS	American Chemical Society
AI	Artificial Intelligence
CNT	Carbon Nanotube
CSRS	Centre for Strategic Research and Studies
DFT	Density Functional Theory
DICON	Defence Industries Corporation of Nigeria
DNT	Dinitrotoluene
HMX	High Melting Explosive (High Melting eXplosive)
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineers
LCA	Life Cycle Assessment
LOD	Limit of Detection
LSPR	Localized Surface Plasmon Resonance
MOF	Metal–Organic Framework
MOFs	Metal–Organic Frameworks
NASENI	National Agency for Science and Engineering Infrastructure
NDC	National Defence College
NNDF	National Nanotechnology Defence Framework
OECD	Organisation for Economic Co-operation and Development
ONSA	Office of the National Security Adviser
PCA	Principal Component Analysis
Pd	Palladium
PETN	Pentaerythritol Tetranitrate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
ppb	Parts Per Billion
PPP	Public–Private Partnership
RDX	Research Department Explosive (Cyclotrimethylenetrinitramine)
RMRDC	Raw Materials Research and Development Council
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscope (if mentioned in the final version)
TiO_2	Titanium Dioxide
TNT	Trinitrotoluene
TATP	Triacetone Triperoxide

UN	United Nations
UV	Ultraviolet
VOCs	Volatile Organic Compounds

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Author Contributions

Aminu Sanusi Haruna: Writing – original draft
Bassey Esuh Etuk: Writing – review & editing
Lois John Rimfat: Resources

Conflicts of Interest

There is no conflicts of interest.

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