

REVIEW ARTICLE

Sustainable Approaches to Green Explosives: A Path Towards Environmental Responsibility

Ankit Singh¹, Gunjan Saxena², Namrata Singh³**How to cite this article:**

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ABSTRACT

The explosives industry has a crucial part in several industries, including mining, construction, and military applications, but traditional explosive materials often present significant environmental and safety challenges. In response, there is increasing interest in developing sustainable approaches to explosives, ultimately resulting in the creation of green explosives. Green explosives prioritize environmental responsibility by utilizing alternative raw materials, green manufacturing processes, and renewable energy integration while maintaining performance standards for various applications. This review provides a comprehensive overview of sustainable approaches to the evolution of green explosives, addressing environmental issues while maintaining performance standards. It discusses the use of biodegradable materials such as bio-based compounds and recycled materials in explosive formulations, as well as green manufacturing techniques that minimize energy consumption, waste generation, and environmental emissions. In addition, it examines the performance characteristics, safety aspects, and regulatory implications of green explosives, emphasizing the need for rigorous testing, certification, and compliance with industry standards. In conclusion, sustainable approaches to green explosives represent a promising route to environmental responsibility, safety, and sustainability in the explosives industry. By prioritizing environmental stewardship, resource efficiency, and social responsibility, green explosives offer a viable solution to mitigating environmental degradation, reducing health and safety risks, and promoting a more sustainable future for explosives technology and beyond.

KEYWORDS

• Environment • Explosive Technology • Formulations • Green Explosives • Sustainable

AUTHOR'S AFFILIATION:

¹ Assistant Professor, Department of Forensic Science, Galgotias University, Greater Noida, Uttar Pradesh. India.

² Student, Department of Forensic Science, Galgotias University, Greater Noida, Uttar Pradesh. India.

³ Assistant Professor, Department of Paramedical Sciences, Integral University, Lucknow, Uttar Pradesh. India.

CORRESPONDING AUTHOR:

Ankit Singh, Assistant Professor, Department of Forensic Science, Galgotias University, Greater Noida, Uttar Pradesh. India.

E-mail: ankit4n6@gmail.com

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INTRODUCTION

Green explosives are sustainable alternatives to traditional explosives, designed to reduce environmental and health hazards.¹ These explosives meet performance standards while minimizing pollution, resource depletion, and ecosystem disruption. Made from renewable or biodegradable materials using eco-friendly manufacturing processes, they are widely used in mining, construction, demolition, and military sectors.² Examples include EcoBlast™, Bio Blitz, nitrate-free explosives, green detonators, and biodegradable emulsion explosives. Their development supports Sustainable Development Goals by promoting resource conservation and reducing emissions and contamination risks.³

Advantages of Green Explosives

Green explosives offer several benefits:

- **Environmental Safety:** Made from biodegradable, non-toxic components, they reduce pollution, greenhouse gas emissions, and habitat destruction.⁴
- **Improved Safety:** Safer formulations lower the risk of accidents and health hazards.
- **Performance:** Innovations allow green explosives to match or exceed the detonation efficiency of conventional explosives.
- **Sustainability:** Align with global efforts to combat climate change and foster corporate responsibility.

Green Explosive Formulation

Green explosives refer to the composition of explosive materials that prioritize environmental sustainability and safety while maintaining or improving performance characteristics.⁵ These formulations typically use alternative raw materials and manufacturing processes to reduce the environmental impact and health hazards caused by traditional explosives. Green explosives represent a shift towards more environmentally friendly and sustainable substitutes in the explosives industry.⁶

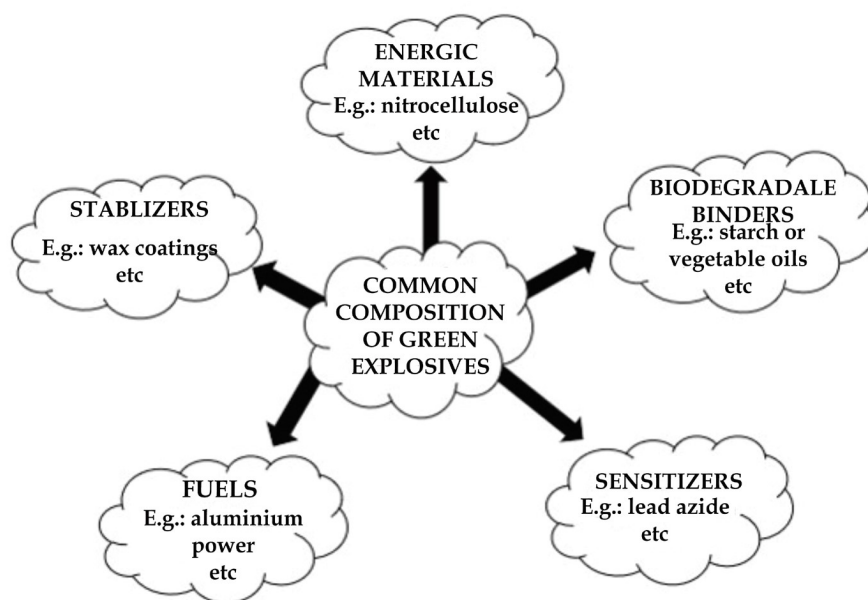


Figure 1: Common Composition of Green Explosives

- **Bio-based compounds:** Derived from renewable sources like plant sugars and cellulose, enhancing biodegradability.⁷
- **Recycled materials:** Utilize industrial waste or plastics to support circular economy practices.⁸
- **Non-toxic chemicals:** Replace harmful substances with safer alternatives like ammonium nitrate or nitrocellulose.⁹
- **Green manufacturing:** Employ energy efficient, low-waste processes such as solvent-free synthesis or microwave assisted reactions.

- **Energetic additives:** Use metal nanoparticles or energetic polymers to boost performance and safety.¹⁰
- **Renewable energy:** Integrate solar or wind energy into production to reduce the carbon footprint.¹¹

Biodegradability and Environmental Impacts

Biodegradability is central to green explosives, enabling them to break down into harmless substances, thus preventing long-term contamination of soil and water.¹² Their use of non-toxic materials and clean manufacturing processes further reduces emissions and environmental harm.¹³ Safer handling also minimizes risks to workers and communities. In conclusion, green explosives offer a viable, eco-friendly alternative to traditional explosives, enhancing sustainability, safety, and performance across multiple industries.¹⁴

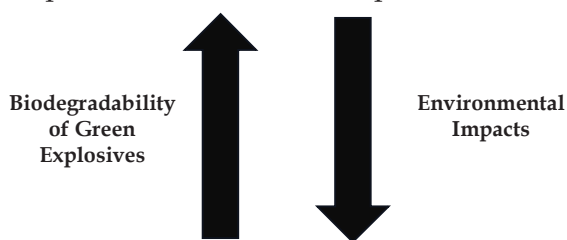


Figure 2: Relation between biodegradability and environmental impacts of green explosives

TOXICITY AND SAFETY ASPECTS

The toxicity of the components used in green explosives is a critical consideration to ensure their safety for the surroundings and human health. While green explosives favor the utilization of non-toxic and biodegradable materials compared to traditional explosives, it is essential to thoroughly assess the potential toxicity of individual components and their interactions within the formulation.¹⁵ One aspect of toxicity assessment involves examining the intrinsic properties of the raw materials and energetic compounds used in green explosives.¹⁶ For example, bio-based compounds derived from renewable sources may be inherently less toxic than synthetic chemicals or heavy metals commonly found in traditional explosives. In addition, recycled materials used in green explosives should undergo extensive testing to ensure they do not contain contaminants or impurities that could pose a danger to human health or the environment. By implementing

green chemistry principles and sustainable manufacturing practices, the overall toxicity of green explosives can be reduced, and safer handling and disposal practices can be promoted. Despite efforts to prioritize non-toxic ingredients and minimize environmental impact, comprehensive risk assessments of green explosives are essential to identify potential hazards and ensure regulatory compliance. Toxicity testing, including acute and chronic toxicity studies, ecological toxicity assessments, and exposure modeling, can help evaluate the potential hazards related to green explosive formulations throughout the course of their existence, from production to disposal. Manufacturing processes involved in the development of green explosives can affect the toxicity profile of the final product. Green manufacturing techniques aim to minimize the use of hazardous solvents, reduce energy consumption, and mitigate emissions of volatile organic compounds (VOCs) and other pollutants.¹⁷ While green explosives are generally designed to be less toxic than traditional explosives, some components may still pose environmental or health risks under certain conditions. Here are some factors to consider regarding the toxicity of green explosives:

Key Factors Influencing Toxicity:

- **Ingredient Selection:** Although green explosives use safer materials, some additives (e.g., energetic compounds or binders) may still pose toxicity risks and require careful selection and handling.¹⁸
- **Degradation Products:** Biodegradable components can produce by-products with potential environmental toxicity. It's crucial to evaluate their fate in soil, water, and ecosystems.¹⁹
- **Exposure Routes:** Human and wildlife exposure via inhalation, ingestion, or skin contact must be considered to assess real-world toxicity risks.
- **Energy Additives:** Components like metal nanoparticles may enhance performance but also carry toxicity concerns that require proper risk management.²⁰
- **Environmental Fate:** Factors like pH, temperature, and microbial activity can influence the transformation and toxicity of residues in the environment.

- **Manufacturing Processes:** Green production techniques aim to reduce emissions and hazardous waste, but potential by-products must still be monitored and controlled.
- **Regulatory Compliance:** Green explosives must meet legal safety and toxicity standards to ensure responsible use, handling, and disposal.

FORENSIC RELEVANCE OF GREEN EXPLOSIVES

Green explosives present emerging challenges and opportunities in the field of forensic science. As environmentally friendly alternatives to conventional explosives, their unique chemical compositions, degradation behaviours, and low-toxicity profiles demand updated forensic approaches for detection, analysis, and attribution.²¹

- **Novel Chemical Signatures:** Green explosives often contain bio-based or non-traditional materials, which produce different residue profiles compared to conventional explosives. This requires forensic analysts to develop new analytical techniques and databases for accurate identification and classification.²²
- **Residue Analysis and Detection Challenges:** Due to their biodegradable and low-toxicity nature, residues from green explosives may degrade rapidly in environmental conditions, complicating evidence collection. Forensic teams must act quickly and use sensitive, advanced instrumentation (e.g., GC-MS, LC-MS/MS, or portable sensors) to detect transient or trace-level residues.²³
- **Attribution and Source Determination:** Determining the origin or manufacturer of green explosives may be difficult, especially when they are custom-made or derived from renewable/recycled materials. However, advanced isotopic and chemical profiling can aid in source attribution and supply chain tracing.
- **Compatibility with Existing Explosive Databases:** Current explosive databases may lack reference data for green explosives, making comparative analysis harder. Forensic labs need to update repositories to include these newer compounds to improve investigative accuracy.

- **Implications for Crime Scene Investigation:** Green explosives may be used in criminal activities due to their perceived lower detectability. Their forensic invisibility poses a risk in forensic counterterrorism, bomb squad operations, and post-blast investigations, urging the need for updated training and tools.²⁴
- **Legal and Regulatory Considerations:** As green explosives gain industrial and commercial use, forensic experts must stay informed about legal classifications, usage licenses, and safety regulations to ensure compliance during forensic examination and courtroom presentation.

DETECTION TECHNIQUES

Green explosive detection technology plays an important role in ensuring safety and security in various environments, including transportation centers, public events, and military operations.²⁵ By combining multiple detection technologies and leveraging advances in sensor technology, data analytics, and machine learning, security personnel, and law enforcement agencies can increase their ability to identify and mitigate the risks associated with green explosives, thereby improving security and protect public safety.²⁶ Therefore, effective detection methods are necessary to identify and reduce these risks. Here are some common detection techniques used for green explosives.

- **Chemical Analysis:** Chemical analysis methods such as chromatography (eg gas chromatography-mass spectrometry, GC-MS), spectroscopy (eg infrared spectroscopy, Raman spectroscopy), and nuclear magnetic resonance (NMR) are used to identify and identify compounds.²⁷ Chemical Characteristics of Green Explosives These techniques provide high sensitivity and specificity for the detection of trace amounts of explosive residues in a variety of samples such as soil, air, and water.²⁸
- **Immunoassays:** Immunoassay-based techniques, such as enzyme-linked immunosorbent assay (ELISA) and lateral flow immunoassays, utilize antibodies

that selectively bind to target explosive compounds.²⁹ These assays are rapid, portable, and cost-effective, making them suitable for field detection of green explosives in diverse environments.

- **Ion Mobility Spectrometry (IMS):** IMS is a rapid and sensitive technique for the detection of explosive vapors or aerosols based on their ion mobility characteristics.³⁰ IMS devices can be handheld or stationary and are widely used for passenger and baggage screening at airports as well as military applications.
- **Electrochemical Sensors:** Electrochemical sensors, such as amperometry, potentiometric, and conductivity sensors, detect changes in electrical properties caused by the interaction between explosive molecules and the sensor surface.³¹ These sensors provide highly sensitive real-time detection and can be integrated into portable, low-cost devices for field deployment.
- **Mass spectrometry (MS):** mass spectrometry techniques such as time of flight (TOF), quadrupole, and ion trap MS allow analysis of the mass-to-charge ratio of ions produced by explosive molecules for precise identification and quantification. It will be possible. Several target compounds MS-based methods are highly sensitive and can detect a wide range of explosives with minimal sample preparation.³²
- **Dog detection:** Trained explosive detection dogs (EDD) are very effective in detecting explosives, including green explosives, because of their strong sense of smell and potential to identify various odors.³³ EDDs are frequently employed in security operations at airports, border crossings, and public events.
- **Nuclear Quadrupole Resonance (NQR):** NQR is a non-destructive technique that detects the unique nuclear quadrupole resonance frequencies of certain explosive compounds.³⁴ NQR devices are highly specific and can distinguish between different types of explosives, making them valuable tools for security screening and forensic analysis.

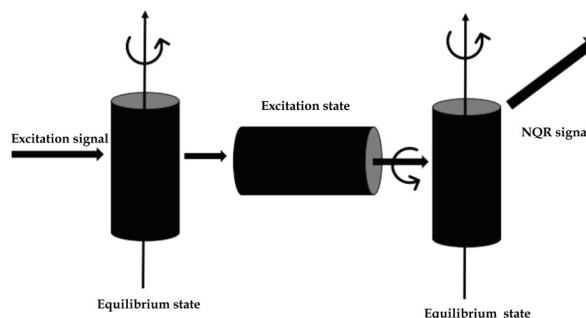


Figure 3: Schematic illustration of NQR

- **Acoustic detection:** Acoustic technologies, such as acoustic wave sensors and microphones, detect the characteristic sound waves produced by explosive detonation or mechanical disturbances caused by explosives.³⁵ These sensors can be deployed in urban areas, transportation networks, and critical infrastructure to detect and locate explosive threats.

CHALLENGES

The widespread introduction of green explosives confronts several challenges that must be addressed to utilize their full potential. To face these challenges, government agencies, industry stakeholders, research institutions, and civil society organizations need to put efforts together to overcome obstacles and advance green initiatives in promoting environmental sustainability, safety, and innovation in the explosives industry. The reasons of these challenges are:

- **Performance Considerations:** Green explosives must exhibit performance characteristics comparable to or better than conventional explosives to be accepted in numerous industries including mining, construction, and military applications³⁶. Ensuring that green explosives meet strict performance requirements while maintaining environmental sustainability is a significant challenge that requires ongoing research and development efforts.
- **Cost competitiveness:** The cost of producing green explosives can be higher compared to conventional explosives due to the use of alternative raw materials, environmentally friendly manufacturing processes, and strict

quality control measures.³⁷ Achieving cost competitiveness with conventional explosives without compromising safety and environmental standards is a key challenge that must be addressed to promote the widespread use of environmentally friendly explosives.

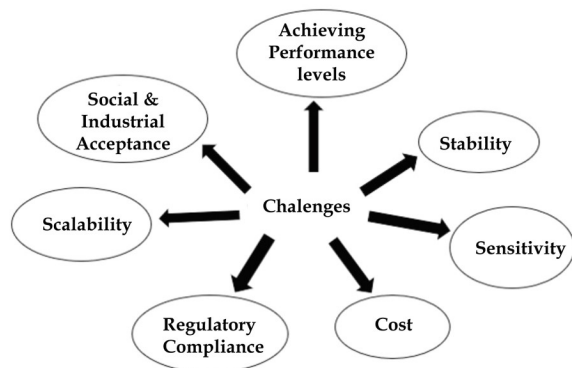


Figure 4: Challenges Associated with Green Explosives

- **Regulatory Barriers:** Regulatory frameworks governing the manufacture, transportation, and use of explosives vary by jurisdiction and may be a barrier to the widespread use of green explosives. To overcome the regulatory hurdles, it is required to provide supportive policies and incentives for sustainable explosive technologies and to guarantee adherence to current regulations and standards.³⁸
- **Technical limitations:** Green explosives can face technical limitations such as stability issues, sensitivity changes, and compatibility problems with existing explosive systems. Addressing these technical challenges through research, innovation, and collaboration with industry partners is critical to improving the reliability and performance of green explosives.³⁹
- **Industry resistance:** Incumbents in the explosives industry can be resistant to change and hesitant to adopt new technologies, especially if they perceive green explosives as disruptive to their existing business models. Overcoming industry resistance through education, benefit demonstrations and stakeholder engagement is critical to accelerating the transition to green explosives.
- **Infrastructure Requirements:** Widespread adoption of green explosives may require

significant investment in infrastructure, including manufacturing facilities, testing laboratories, and distribution networks. Securing funding and resources for infrastructure development and capacity building is critical to supporting the scale-up of production and deployment of green explosives.⁴⁰

- **Public perception and acceptance:** Public perception and acceptance of green explosives can affect their acceptance and market penetration. Educating stakeholders, including consumers, policymakers, and community members, about the environmental and safety benefits of green explosives is critical to building trust in these technologies.⁴¹
- **Supply Chain Considerations:** Ensuring a reliable and sustainable supply chain for raw materials and components for green explosives can be challenging, especially for bio-based or recycled materials that can be subject to availability, seasonality, and quality variability. Developing resilient supply chains and fostering supplier partnerships is critical to mitigating supply chain risks and ensuring the continuity of green explosives production.⁴²

FUTURE ASPECTS

The future of green explosives is driven by innovation, sustainability, and advanced technologies, aiming to enhance performance while minimizing environmental and health impacts.⁴³

Key Areas of Development:

- **Formulation Improvements:** Continued research will refine formulations to boost detonation performance, stability, and compatibility with existing systems while maintaining eco-friendliness.⁴⁴
- **Advanced Manufacturing:** Integration of automation, robotics, and new processing techniques will streamline production, reduce energy use, and lower waste, improving scalability and cost-efficiency.
- **Custom Applications:** Tailored green explosives will serve specific industry needs such as precision mining, urban demolition, and military operations with optimized environmental impact.⁴⁵

- **Digital Integration:** Technologies like IoT sensors and data analytics will enable real-time monitoring of blast performance, environmental impact, and safety, supporting smarter, safer operations.
- **Environmental Remediation:** Green explosives may assist in cleaning up contaminated sites by providing safer alternatives to traditional remediation methods.
- **Global Collaboration and Standards:** International cooperation will promote standardization, regulatory alignment, and knowledge sharing, accelerating global adoption.
- **Sustainability Certification:** Eco-labeling and sustainability certifications will build trust by highlighting environmental and social performance indicators.⁴⁶
- **Emerging Technology Integration:** Green explosives may be enhanced through 3D printing and nanotechnology, allowing precise customization for specific tasks.
- **Energy Efficiency:** Efforts will focus on reducing energy loss during detonation, increasing efficiency and lowering environmental impact.

CONCLUSION

In conclusion, a sustainable approach to green explosives represents a paradigm shift in the explosives industry towards more environmentally friendly, socially conscious, and economically viable practices. Through the adoption of alternative raw materials, environmentally friendly manufacturing processes, renewable energy integration, and life cycle assessment methods, green explosives aim to reduce environmental degradation, reduce health and safety risks, and promote sustainable development in various sectors. Adoption of green explosives offers numerous benefits including reduced pollution, resource conservation, and improved safety profile compared to conventional explosives. By prioritizing biodegradable materials, non-toxic chemicals, and efficient manufacturing techniques, green explosives minimize environmental impacts during their lifetime while meeting performance requirements for various applications. However, the widespread adoption of green explosives faces challenges,

including performance considerations, cost competitiveness, regulatory barriers, and industry resistance. Meeting these concerns requires collaborative efforts from stakeholders including governments, industry players, research institutions, and civil society organizations to promote innovation, develop supportive policies and promote market acceptance of sustainable explosives technologies. Looking ahead, future advances in green explosives will focus on optimizing formulations, enhancing manufacturing processes, tailoring applications, integrating digital technologies, and promoting global collaboration and standardization. These efforts will contribute to a more sustainable and resilient explosives industry, capable of meeting the growing demand for safe, environmentally friendly and socially responsible explosive materials in a rapidly changing world.

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