

RECENT ADVANCES IN EXPLOSIVE DETECTION TECHNIQUES IN INDIAN FORENSIC SCIENCE: CHALLENGES AND PROSPECTS

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Abstract

The detection of explosive substances plays a crucial role in forensic science, aiding criminal investigations and national security. Indian forensic laboratories have evolved from rudimentary chemical tests to advanced spectrometric, biosensor-based, and AI-driven technologies. This review critically examines the progression of explosive detection techniques from conventional colorimetric assays to state-of-the-art instrumental methods in Indian forensic science. The study also highlights the persistent challenges in explosive forensic investigations and provides insights into future advancements required to enhance detection capabilities.

The study also highlights the persistent challenges in explosive forensic investigations, discusses global trends, and explores future directions including policy frameworks and ethical considerations. By bridging traditional practices with cutting-edge developments, this review aims to enhance forensic reliability and national preparedness.

Keywords: Explosives residues; AI in forensics; Biosensors; Indian forensic infrastructure

INTRODUCTION

Explosives have been widely used in criminal activities, terrorism, and industrial sabotage, necessitating precise and rapid detection techniques. The increasing prevalence of improvised explosive devices (IEDs) and other energetic materials in crimes has led to a growing demand for reliable forensic methodologies. Accurate identification of explosive residues plays a crucial role in linking suspects, reconstructing crime scenes, and ensuring legal admissibility of forensic evidence. Over the years, Indian forensic science laboratories have evolved from relying on rudimentary qualitative tests to sophisticated, high-throughput analytical techniques.

Historically, forensic explosive detection in India was limited to wet chemical tests, which, though effective for preliminary analysis, lacked specificity and sensitivity. Early forensic reports emphasized the limitations of classical methods in differentiating between explosive residues and naturally occurring compounds (Reddy *et al.*, 1987). As forensic science progressed, researchers recognized the need for instrumental techniques to improve detection reliability. Thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) introduced in the late 20th century enhanced analytical capabilities but were still constrained by the requirement of laboratory-based processing (Gupta & Mehta, 1999).

With the advent of mass spectrometry and spectroscopic techniques, forensic investigations witnessed a paradigm shift. The use of gas chromatography-mass spectrometry (GC-MS) and Fourier transform infrared spectroscopy (FTIR) significantly improved detection limits and specificity in explosive analysis (Patil & Verma, 2010). These advancements allowed forensic experts to detect trace levels of explosive residues with high confidence, leading to more accurate forensic conclusions. However, accessibility to such sophisticated instruments remained limited to well-established forensic laboratories, posing logistical challenges in field investigations (Rao *et al.*, 2015).

Recent developments in forensic technology have introduced portable detection devices such as ion mobility spectrometry (IMS) and biosensor-based detection, revolutionizing on-site forensic applications (Mishra *et al.*, 2018). More recently, biosensor technologies using enzyme-based and immunochemical techniques have been deployed. The integration of artificial intelligence (AI) and machine learning in forensic investigations has further enhanced data processing, allowing real-time analysis and reducing human error (Malhotra & Sen, 2023). These novel approaches offer promising solutions to address the growing complexity of explosive-related crimes in India.

This review explores the advancements in explosive detection techniques used in Indian forensic laboratories, progressing from traditional chemical-based tests to contemporary high-throughput analytical methods. By critically analyzing these methodologies, we aim to provide insights into the strengths, limitations, and future prospects of explosive forensic investigations in India. The given Figure 1 represents a journey of **early chemical tests to advance detection techniques in forensic explosive detections**.

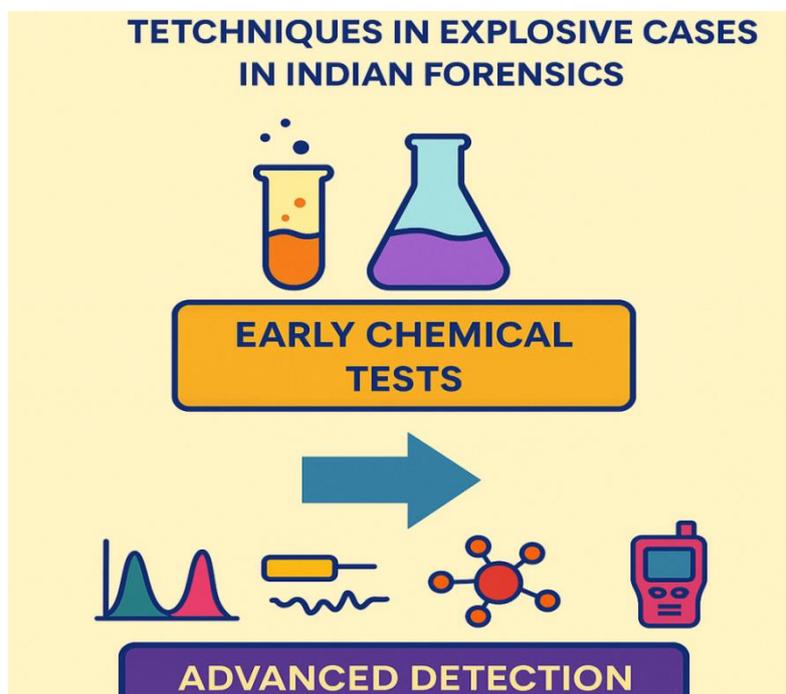


Figure: 1 A pictorial journey of early chemical tests (colorimetric tests) to advance detection techniques (GC-MS, HPLC, Ion chromatography, handheld sensor devices etc.) in forensic explosive detections.

1. Early Chemical Tests to Advance Detection Techniques in Explosive cases in the Indian Forensics:

2.1 Early Wet Chemical and Spot Tests:

Initial forensic investigations in India relied on qualitative chemical tests for detecting nitro-aromatic, nitrate, and peroxide-based explosives. Techniques such as Colorimetric assays using diphenylamine, Griess reagent, and paraffin tests were commonly employed (Reddy *et al.*, 1987). Although simple and cost-effective, these tests often yielded false positives and lacked specificity. Spot tests for nitrate-based explosives were limited in their ability to differentiate between explosive residues and environmental nitrates (Sharma *et al.*, 1992).

2.2 Advent of Chromatographic Techniques:

To overcome the limitations of spot tests, Thin-Layer Chromatography (TLC) and later High-Performance Liquid Chromatography (HPLC) were introduced, enhancing both sensitivity and specificity in explosive residue detection (Gupta & Mehta, 1999). TLC provided a rapid screening method, while HPLC allowed for quantification of nitro-aromatic and peroxide explosives (Kumar *et al.*, 2004). However, the limitations of chromatographic techniques included prolonged sample preparation times and difficulties in on-site application.

2.3 The Rise of Mass Spectrometry and Spectroscopy:

The integration of Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Mass Spectrometry (LC-MS) revolutionized forensic explosive detection in India (Patil & Verma, 2010). These techniques offered high sensitivity and specificity in identifying trace levels of explosive residues. Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy further contributed to forensic investigations by enabling rapid and non-destructive analysis of explosives (Rao *et al.*, 2015). Although effective, these methods required well-equipped forensic laboratories and skilled personnel, limiting their widespread implementation.

2.4 Portable and On-Site Detection:

The adoption of Ion Mobility Spectrometry (IMS) provided a breakthrough in on-site forensic detection of explosives (Mishra *et al.*, 2018). IMS-based portable detectors enhanced the efficiency of security forces by enabling rapid screening at crime scenes. Additionally, Surface-Enhanced Raman Spectroscopy (SERS) improved the trace detection of energetic materials, significantly increasing forensic detection limits (Shankar *et al.*, 2020).

2.5 Emerging Frontiers: Biosensors and AI:

Recent developments in biosensors have introduced enzyme-based and immunochemical methods for detecting explosive residues with high selectivity (Raj *et al.*, 2021). The emergence of artificial intelligence (AI) and machine learning in forensic analysis has optimized data processing, enhancing the accuracy and efficiency of explosive detection in complex matrices (Malhotra & Sen, 2023). AI-driven predictive analytics combined with forensic databases now offer real-time profiling of explosive substances, aiding national security measures.

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Forensic science practitioners often face challenges in analyzing post-blast residues due to environmental contamination, the minimal quantity of explosive material remaining after detonation, and the degradation of key chemical signatures.

CASE STUDIES IN THE INDIAN CONTEXT

Forensic science has played a pivotal role in investigating and solving acts of terrorism in India. Two of the most significant incidents underscoring this role are the **2008 Mumbai terror attacks** and the **2019 Pulwama bombing**. These events catalyzed the advancement and deployment of cutting-edge forensic technologies, especially in explosive detection and residue analysis. Forensic teams used **Gas Chromatography-Mass Spectrometry (GC-MS)** and **Ion Mobility Spectrometry (IMS)** to detect traces of RDX and PETN, common high explosives used in the improvised explosive devices (IEDs) found at the sites (Sharma *et al.*, 2010). The forensic findings helped link the attackers' equipment and explosives to specific manufacturing sources and provided critical inputs for intelligence operations. The explosive used in this attack was later confirmed to be a mixture containing **ammonium nitrate, RDX (Research Department Explosive), and possibly TNT**, based on chemical residue analysis conducted by forensic experts.

The **Central Forensic Science Laboratory (CFSL)** and the **National Bomb Data Centre (NBDC)** deployed field-portable analytical technologies to rapidly identify explosive residues. Instruments like IMS, which allows the real-time detection of nitro-aromatic compounds, and GC-MS, capable of precise molecular identification, were instrumental in confirming the nature of the explosives (Kumar *et al.*, 2020). These tools helped establish the source routes for the explosive materials, supporting claims of cross-border material and logistical support.

3.1 Forensic Technology Advancement Post-Incidents:

In response to these high-profile attacks, India has significantly strengthened its forensic infrastructure. Portable detection kits such as **handheld IMS detectors, portable GC-MS units, and Raman spectrometers** have been introduced in regional forensic science laboratories (FSLs) for rapid on-site analysis (Bhatnagar *et al.*, 2021). The enhanced capacity for **trace evidence detection and scene-of-crime analysis** ensures that forensic teams can respond more quickly and accurately in both urban and remote areas.

These events highlighted the importance of integrating **forensic intelligence** with national security frameworks. By identifying explosive signatures and sourcing materials, forensic science not only helps in legal prosecution but also supports counter-terrorism efforts by mapping supply chains and modus operandi. The comparative analysis Table 1 summarizes the methods, their sensitivity and portability of different techniques.

Table 1: A concise table comparing traditional and advanced techniques on different parameters

Method	Sensitivity	Portability	Cost	Field Application
Colorimetric	Low	High	Very low	Yes
GC-MS	Very High	Low	High	No
IMS	Moderate	High	Moderate	Yes
Biosensors	High	High	Moderate	Emerging

GLOBAL TRENDS AND DEVELOPMENTS IN EXPLOSIVES TESTING

Beveridge; 1992; Yinon and Zitrin; 1993 and McCord *et al.*; 1994 reported the traditional methods of explosive residue detection. Those methods subsequently focus on the integration of multiple analytical techniques to systematically examine and accurately identify residues from improvised explosive devices (IEDs), hand swabs collected from individuals suspected of handling explosives, and organic gunshot residue (OGSR). Caygill *et al.*; (2012) provided a comprehensive overview of a wide range of techniques for the detection of explosives. The study systematically discussed spectroscopic, electrochemical, and biochemical methods, emphasizing their underlying principles and applications. Additionally, the authors presented an overview of nanomaterials and their impact on enhancing detection capabilities. Key performance parameters such as sensitivity, specificity, cost-effectiveness, ease of use, and the potential for miniaturization of these detection techniques were also critically addressed, offering valuable insights into the practical applicability of these methodologies in real-world forensic and security settings. Researchers (Ling Bai *et al.*; 2017) at Indiana University have determined that the sensitivity of Gas Chromatography–Vacuum Ultraviolet Spectroscopy (GC-VUV) varies depending on the analyte and experimental conditions. In general, certain compounds can be detected at picogram (10^{-12} g) levels, meeting their respective detection limits. For explosive materials, the technique demonstrates the capability to detect concentrations in the low parts-per-million (ppm) range (0.0001%). Cruse and Goodpaster (2019) demonstrated that the temperature of the flow cell significantly influences the VUV spectra of certain explosives, resulting in complex and highly specific spectral patterns. Additionally, Reavis and Goodpaster (2020; 2022) successfully identified and quantified intact smokeless powder particles from pipe bomb debris using this analytical approach.

These factors constrain the applicability of analytical techniques. Currently, no standardized method exists for linking an explosive charge to its manufacturing source based solely on the chemical signatures detected in post-blast trace residues. An interesting and critical study reported by researchers at the Massachusetts Institute of

Technology Lincoln Laboratory collaborated with statisticians at South Dakota State University in 2022 to determine the extent to which isotopic and chemical signatures capable of linking explosive materials to their manufacturing sources remain preserved post-detonation remains an area of investigation. This includes determining whether forensic analysts can successfully recover these materials from a blast site, detect them at measurable concentrations, and correlate them with pre-detonation signatures. A recent study was reported by Tanapornraweekit *et al*; 2023 to evaluate the reliability of current forensic methodologies for analyzing explosion events. It aims to integrate forensic engineering techniques with computational models for blast fragment simulation and blast pressure analysis to estimate the explosive charge used in a bombing incident. Furthermore, the study seeks to predict the lethal radius resulting from blast pressure and the lethal zone caused by fragment impact.

Klapec *et al*. (2023) published an insightful and scientifically valuable study titled “*Interpol Review of the Analysis and Detection of Explosives and Explosive Residues.*” In this comprehensive review, the authors highlighted numerous applications of explosives analysis across diverse fields relevant to forensic laboratory operations. While the article offers an extensive overview of international research contributions (reviewed about 1004 bibliography), it notably lacks adequate representation of literature from Indian authors. This underrepresentation of Indian research in the domain of explosives detection is a significant limitation and underscores the need for increased visibility and documentation of indigenous advancements in this critical forensic field.

CHALLENGES AND FUTURE PERSPECTIVES

Regional laboratories face significant challenges due to inadequate infrastructure, which contributes to delays in report generation and creates case backlogs. In rural areas, the lack of real-time portable detection kits further hampers timely investigation and evidence collection. Compounding these issues is the absence of a centralized forensic explosives database, which limits information sharing and coordination across agencies. Additionally, law enforcement personnel often receive insufficient training on newer technologies, reducing their effectiveness in handling modern forensic challenges. These Challenges raises the following questions:

- Are all Indian labs (state and central) using the *same manual books/standard operating procedures (SOP)* for testing explosives?
- Do we have *enough skilled people* to run all this sophisticated/costly equipment and where are experts learning these skills (universities, special training centres)?
- How do the different teams (police, forensic labs, intelligence) *work together* on bomb cases?
- How does India's progress in explosive detection *stack up against other countries*?

To address these challenges, several key recommendations are proposed. First, establishing a national explosives residue database would enhance information sharing and improve the efficiency of forensic investigations. Investing in mobile forensic units equipped with Ion Mobility Spectrometry (IMS) and biosensor kits can provide rapid, on-site detection capabilities, especially in remote areas. The integration of artificial intelligence (AI) into forensic processes should be promoted, ensuring that such systems are secure and auditable. It is also crucial to develop clear legal standards for the admissibility of AI-generated evidence in court. Finally, fostering partnerships between forensic agencies, academic institutions, and private industry can drive innovation and ensure continuous advancement in forensic science. AI-based analyses and biosensors, while promising, pose admissibility challenges in Indian courts. Ensuring data authenticity and maintaining chain of custody remain vital for legal proceedings. There is a pressing need for forensic legislation updates to accommodate emerging technologies.

CONCLUSION

The progression of explosive detection techniques in Indian forensics highlights significant technological advancements from traditional colorimetric tests to AI-assisted biosensor-based methodologies. While cutting-edge technologies have improved forensic capabilities, challenges remain in ensuring accessibility, rapid deployment, and forensic reliability. With strategic investments, robust policies, and global collaborations, India can enhance its forensic preparedness against explosive-related threats.

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