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Review Article

Comprehensive Review of Analytical Methods for Post-Blast Explosives Detection

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ABSTRACT

Background: Post-blast forensic analysis is a cornerstone of modern investigative science, assisting in reconstructing events, attributing responsibility, and presenting admissible evidence in court. Traditional colour spot tests, although rapid and cost-effective, suffer from low specificity and susceptibility to environmental factors, which limit their evidential value.

Main body: This review explores the analytical advances in the detection of post-blast residues, focusing on colour tests, thin-layer chromatography (TLC), ion chromatography (IC), identification of thermally decomposed PETN in GC-MS, and instrumental methods such as gas chromatography–mass spectrometry (GC–MS) and high-performance liquid chromatography (HPLC). Colour tests remain valuable for on-site presumptive screening but are prone to false positives. TLC provides confirmatory separation of nitroaromatics, peroxides, and oxidizers, while IC enables quantitative nitrate and anion analysis with high specificity, even in environmentally stressed samples. Thermal decomposition yields unique degradation signatures, particularly for PETN, strengthening the evidential value in improvised explosive device (IED) investigations. Extended column chromatography enhances TNT resolution in complex soil matrixes. Advanced spectrometric methods (GC–MS, LC–MS/MS) provide ultra-trace detection and forensic admissibility but require expertise and infrastructure. Environmental factors such as rainfall, soil composition, and pH significantly affect residue persistence, underscoring the importance of rapid, integrated forensic workflows. Comparative tables, schematic diagrams, and charts highlight the methodological strengths, weaknesses, and practical applications.

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Conclusion: The review concludes that no single method suffices; rather, a multi-tiered workflow presumptive colour tests, TLC or IC for confirmatory separation, and GC–MS/HPLC for trace analysis offers the most reliable approach. Standardization of protocols and incorporation of portable and AI-enhanced systems represent future directions for improving reproducibility and judicial defensibility.

KEYWORDS

• Explosives • Forensic Science • Post-Blast Residues • Thin-Layer Chromatography • Ion Chromatography • PETN • TNT • Nitrate Detection • Forensic Analysis • Review

INTRODUCTION

The forensic detection of explosives has become increasingly significant in the context of rising global threats from terrorism, insurgency, and organized crime.[1–3] Explosive materials, whether military-grade or improvised, are widely misused because of their destructive potential, low cost, and relative ease of synthesis.[4] Post-blast examination of residues provides critical forensic intelligence, helping to identify the explosive used, reconstruct the sequence of events, and establish links between suspects and crime scenes.[5] However, the analysis of post-blast residues is inherently challenging because the residues are usually present in trace quantities, and are intermixed with complex matrices such as soil, debris, and soot.[6,7]

Traditional forensic approaches particularly **presumptive colour tests** have long been used as rapid, on-site tools for preliminary identification.[6,8] Although they provide immediate results, their reliability is limited by poor specificity, false positives, and environmental influences.[9,10] With the evolution of forensic science, there is a growing need for advanced confirmatory methods that provide **sensitivity, selectivity, and judicial defensibility of the results**. Analytical methods such as thin-layer chromatography (TLC), ion chromatography (IC), gas chromatography mass spectrometry (GC–MS), and high-performance liquid chromatography (HPLC) have been developed and refined to meet these needs.[11–15]

This review consolidates the existing advances in post-blast explosive analysis, emphasizing a comparative assessment of classical and modern methods, while also addressing the influence of environmental factors on residue detectability. By integrating findings from experimental studies, forensic case reports, and international guidelines, this review provides a comprehensive evaluation of detection methodologies.

1. Background

Explosives detection has historically relied on **simple colourimetric reactions**, many of which were adopted from chemical warfare and industrial testing protocols.[6] Tests such as the Griess reaction for nitrites and diphenylamine for nitrates were initially considered revolutionary for their speed and field applicability. However, decades of forensic practice have demonstrated their limitations particularly high rates of false positives caused by fertilizers, amines, and soil contaminants.[7,9] Courts have increasingly questioned their evidential reliability, demanding confirmatory analytical methods that can withstand cross-examination.[11]

In recent years, several studies including those conducted by the present authors have sought to improve the reliability of forensic explosives detection. For example, **Kumar** *et al.* demonstrated the forensic applicability of **ion chromatography for nitrate analysis in soil samples**[1] and evaluated **inorganic post-blast residues under different soil conditions.**[2] Additional research assessed the **impact of environmental factors, especially rainfall, on nitrate detectability** in post-blast soils.[3] Other works by the authors introduced **thermal decomposition analysis for PETN detection**[4] and **extended column chromatography for TNT analysis**, significantly improving resolution and specificity.[5] Collectively, these investigations highlight the limitations of traditional tests and underscore the importance of integrating advanced analytical techniques into forensic workflows.

The advent of **chromatographic and spectrometric methods** has transformed the field. **Thin-layer chromatography (TLC)** emerged as one of the first laboratory-based confirmatory tools, offering separation of multiple analytes on a single plate.[12,13] **Ion chromatography (IC)** further advanced detection by enabling quantitative analysis of inorganic explosives such as nitrate, nitrite, and perchlorate residues, even in rain-affected soils.[1–3] Studies have shown that environmental factors such as rainfall can reduce nitrate recovery by more than half within 72 hours, underscoring the urgency of timely sample collection.[3,17,18]

At the same time, **advanced techniques such as GC–MS and LC–MS/MS** have provided unparalleled sensitivity and specificity.[14,15] These methods are capable of detecting ultra-trace residues and degradation products, making them the gold standard in forensic explosives analysis.[16] However, their reliance on sophisticated instrumentation and trained analysts limits their availability in resource-constrained forensic laboratories.[19]

Recognizing these strengths and limitations, forensic practitioners now advocate for **multi-tiered analytical workflows** that combine the advantages of presumptive, confirmatory, and advanced methods.[20–22] This tiered approach ensures rapid screening at the crime scene, reliable confirmation in the laboratory, and robust evidence admissible in court. Furthermore, ongoing efforts by international bodies such as INTERPOL, UNODC, and SWGDRUG aim to standardize protocols globally, thereby improving reproducibility and judicial acceptance.[23–25]

The field has evolved from reliance on rapid but unreliable colour tests to integrated workflows that employ chromatographic and spectrometric methods for reliable, legally defensible results. This review builds upon the authors' previously published works[1–5] and integrates them with global advances to provide a comparative evaluation of detection methods, environmental challenges, and future directions.

PRESUMPTIVE METHODS: COLOUR TESTS

1. Principle and Applications

Colour spot tests rely on **redox or complexation reactions** that produce visible colour changes in the presence of explosive ions or compounds. Colour tests involve chemical reactions with specific functional groups, producing visible colour changes. The **Griess test** detects nitrites via azo dye formation, whereas **diphenylamine** reacts with nitrates to yield a blue complex. Luminol produces chemiluminescence in the presence of peroxides.[6,9]

2. Advantages

- Rapid (results in minutes)
- Portable (suitable for field application)
- Low cost and minimal training requirements

3. Limitations

Despite their utility, colour tests suffer from the following drawbacks:

- **Low specificity:** Cannot distinguish between structurally similar compounds.[6–8]
- **High false-positive rates:** Soil humic acids, fertilizers, and metals interfere.[7,9,10]
- **Environmental sensitivity:** Rainfall and humidity reduce test performance.[3]
- **Limited admissibility:** Courts increasingly demand confirmatory analysis.[11]

Table 1 lists the strengths and limitations of the colour tests.

Table 1: Strengths and limitations of colour tests

Test	Target Analyte	Strengths	Limitations	Evidential Value
Griess Test	Nitrites	Fast, field friendly	False positives with amines	Weak
Diphenylamine Test	Nitrates	Easy to perform	Non-specific, reacts with fertilizers	Weak
Luminol Test	Peroxides	High sensitivity	Requires darkness, non-specific	Moderate
Paraffin Test	Nitrates	Historically used	Highly non-specific	Obsolete

THIN-LAYER CHROMATOGRAPHY (TLC) AS A CONFIRMATORY TOOL

1. Applications in Forensic Explosives

TLC offers improved specificity compared to colour tests by separating analytes in a stationary phase. TLC is commonly used for nitroaromatics, chlorates, and peroxides, and provides **confirmatory identification** through unique retardation factors (Rf values).[8,12]

2. Strengths

- Multi-analyte separation on a single plate
- **Cost-effective** laboratory technique
- **Useful confirmatory tool** for misidentified colour test results

3. Limitations

- Requires laboratory infrastructure
- Semi-quantitative at best
- Lower sensitivity than GC–MS or HPLC[13]

Table 2 presents a comparative analysis of the colour tests and TLC.

Table 2: Comparative Analysis of Colour Tests vs TLC

Criterion	Colour Tests	Thin Layer Chromatography (TLC)
Speed / Field Use	Very fast; can be done onsite with minimal tools.	Requires lab; more time for sample prep, solvent, development, visualization.
Cost / Equipment	Low cost; minimal reagents; little training.	Moderate cost; TLC plates, solvents, visualization reagents, lab bench; training needed.
Sensitivity / Specificity	Poor specificity; may give false positives; often limited in distinguishing similar compounds.	Higher specificity; can separate multiple compounds; spot Rf values assist in identification.
Vulnerability to Interference	High; environmental contamination and matrix effects common.	Lower; better separation reduces interference; though sample cleanup often required.
Evidential Strength in Forensics	Weak when alone; may be challenged in court.	Stronger when properly validated; supports confirmatory analysis.

Figure 1 and 2 show the workflow comparison of colour tests vs. TLC. Colour Tests: Direct → Colour Change → Presumptive Result. TLC: Sample Extraction → Chromatographic Separation → Rf Measurement → Confirmatory Identification

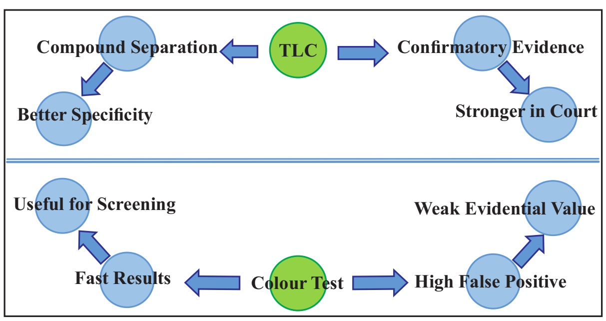

Figure 1: Workflow comparison of colour tests vs TLC

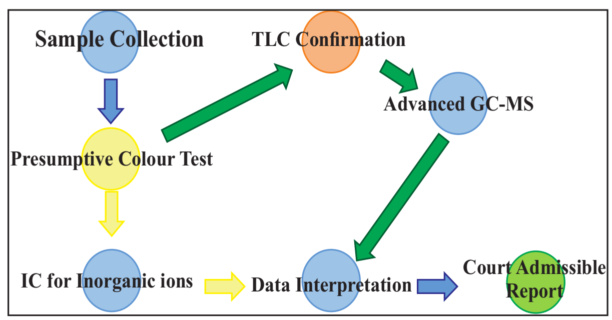

Figure 2: Workflow comparison of colour tests vs TLC

ION CHROMATOGRAPHY FOR NITRATE AND INORGANIC RESIDUES

1. Importance in Nitrate Detection

Nitrate-based inorganic explosive compositions are widely used in homemade explosives (HMEs) by anti-social elements owing to their easy availability, affordability, and high explosive potential. Among these, the nitrate ion (NO_3^-) plays a central role, acting as an oxidizing component in the detonation process. Table 3 presents the percentage of nitrate ion content by mass in the commonly encountered inorganic explosive formulations. As shown, ammonium nitrate contains the highest percentage of nitrate ions among the listed compounds, followed closely by sodium nitrate and ammonium nitrate fuel oil (ANFO).

Table 3: Nitrate ion content in common inorganic explosives.

Nitrate bases Inorganic Explosives	% of Nitrate (No3$^-$) content (by mass)
Ammonium Nitrate	77.47
Potassium Nitrate	61.33
Sodium Nitrate	72.95
Ammonium Nitrate Fuel Oil (ANFO)	72.82
Urea Nitrate	50.37
Gun Powder (Traditional)	46 (Highest % in individual components

Given its high nitrate ion concentration, ammonium nitrate was selected as the standard compound in this study. The focus on nitrate ion detection is particularly significant in the forensic analysis of post-blast soil samples, where the identification of residual nitrate ions can help confirm the use of nitrate-based explosives and support the reconstruction of the explosion event.

IC is one of the most effective methods for quantifying nitrate ions and other inorganic residues in soils. Its high sensitivity (ppb–ppm range) allows forensic analysts to distinguish nitrates from nitrites and perchlorates.[1,2]

2. Advantages over Presumptive Tests

- **High specificity** for nitrate vs nitrite.
- **Quantitative capability** (ppm–ppb detection)
- **Reduced environmental interference** with proper sample prep.

3. Case Applications

Kumar *et al.*[1,3] demonstrated the robustness of IC in quantifying nitrates in rain-exposed soils, with recovery dropping from ~80% in dry soil to ~40% after rainfall exposure for 72 hours. Their findings highlight IC's robustness in complex forensic scenarios.

Figure 3. Graph of nitrate recovery in soil (dry vs rainy conditions). (Description: Bar chart showing ~80% recovery in dry soil vs ~40% under rainfall conditions after 72h.)

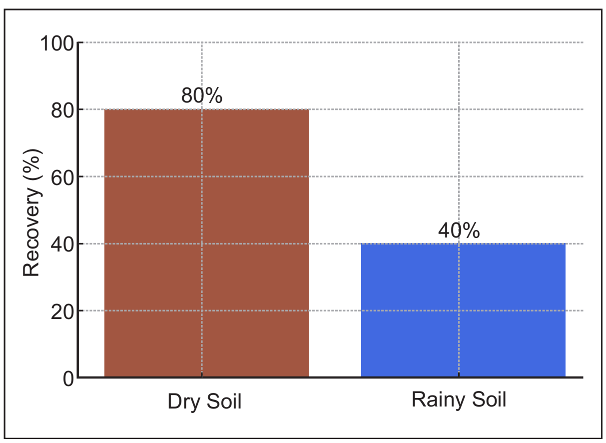

Figure 3: Nitrate recovery in soil under different conditions

THERMAL DECOMPOSITION ANALYSIS OF PETN IN GC-MS

Thermal decomposition produces **characteristic degradation profiles** when explosives are heated in the GC-MS oven under controlled conditions. For PETN, the decomposition curve and thermal signature provide unique identification.[4]

- **Advantages:** High specificity, low false positives
- **Limitations:** Requires GC-MS, not portable

This technique is particularly useful for **IED residue analysis**, where PETN is commonly encountered.

EXTENDED COLUMN ANALYSIS OF TNT IN GC-MS

1. Analytical Challenge

TNT residues often overlap with soil organic matter, leading to misidentification in conventional chromatography.[5]

2. Extended Column Approach

Increasing the column length enhances the peak resolution and reduces co-elution, yielding **clearer TNT profiles** in post-blast samples.[5] This is explained in the Table 4.

Table 4: Performance of conventional vs extended column TNT analysis

Parameter	Conventional Column	Extended Column
Retention Time (min)	2.8 ± 0.1	3.1 ± 0.1
Resolution Factor	1.2	2.4
Misidentification	Frequent	Rare

GC–MS AND HPLC

GC–MS and HPLC are the gold standards for explosives detection.[14,15] They provide high sensitivity and specificity, are capable of detecting ultra-trace residues, and are routinely accepted in courts.

Strengths:

- High selectivity
- Trace detection capacity
- Reproducibility and judicial admissibility

Limitations:

- Require trained operators
- High infrastructure costs.[16]

INORGANIC RESIDUES AND ENVIRONMENTAL INFLUENCES

Environmental conditions drastically affect residue persistence. Rainfall, in particular, accelerates the leaching of nitrates, reducing detection windows.[3,12]

1. Factors Affecting Residue Persistence

Environmental factors strongly affect residue persistence.

- **Rainfall:** accelerates leaching.[3,12]
- **Soil type:** clay retains nitrates better than sandy soil.[17]
- **pH:** acidic soils accelerate degradation.[18]

Figure 4. Flowchart – Environmental influence on nitrate detectability. Rainfall → Leaching → Reduced Surface Nitrates → Lower Detection Probability

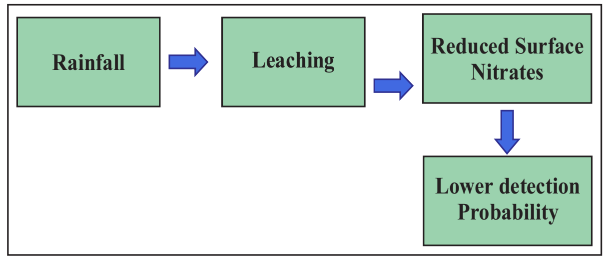

Figure 4: Environmental influence on nitrate detectability

COMPARATIVE ASSESSMENT OF TECHNIQUES

A multidimensional comparison demonstrates the complementary nature of traditional and advanced methods is given in the Table 5.

Table 5: Comparative performance of forensic explosives detection techniques

Criterion	Colour Tests	TLC	IC	Thermal Decomp. in GC-MS	GC–MS / HPLC
Speed	High	Moderate	Moderate	Moderate	Low
Specificity	Low	Moderate–High	High	High	Very High
Quantitative Capacity	None	Limited	Yes	Semi-quant	Yes
Field Applicability	Excellent	Low	Low	Low	None
Evidential Value	Weak	Strong	Strong	Strong	Very Strong

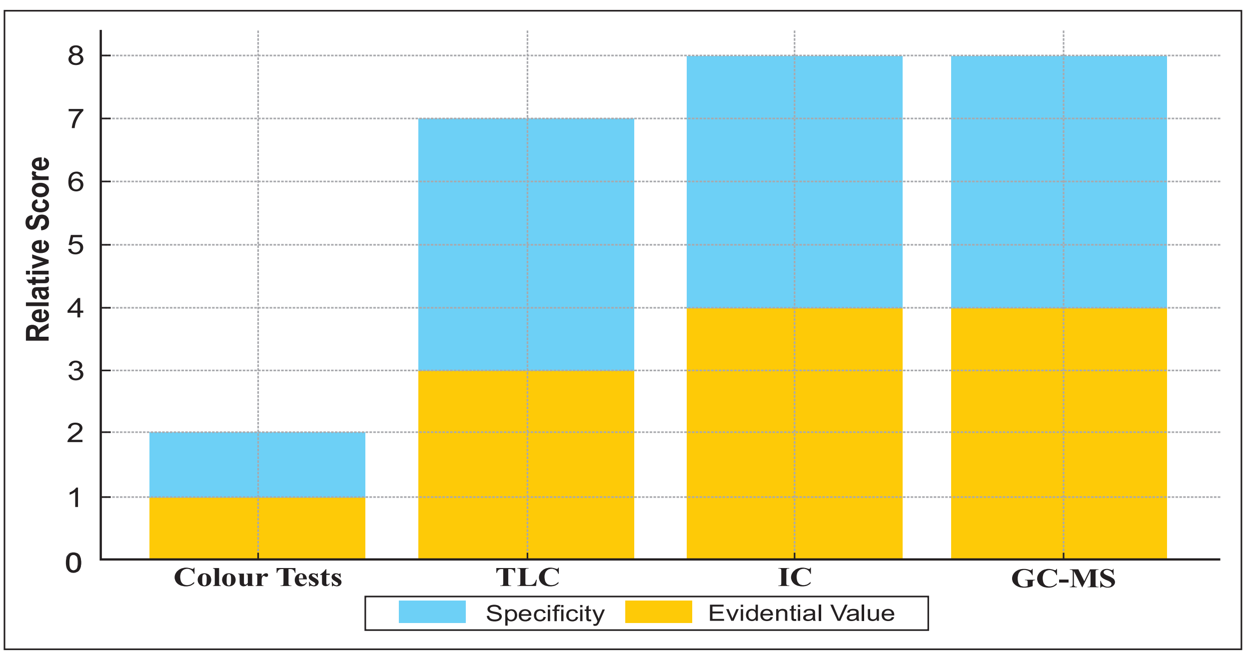

Figure 5: Comparative Strength of Forensic Techniques

FUTURE PERSPECTIVES

The future of forensic explosives analysis is defined by the need for rapid, portable, accurate, and standardized methodologies. While traditional approaches and laboratory-based techniques have provided a strong foundation, several promising directions are shaping the next generation of post-blast residue detection methods.

1. Portable and On-Site Instrumentation

A significant development is the miniaturization of these analytical systems. Portable ion chromatography (IC) and high-performance liquid chromatography (HPLC) instruments are currently being developed for on-site deployment, enabling field investigators to obtain reliable quantitative data without waiting for laboratory analysis.[19,20] These systems integrate microfluidics and compact detectors, reducing both time and cost while expanding access to advanced methods in resource-limited settings. Portable GC–MS devices, although still expensive, are increasingly used in counterterrorism operations.[21]

2. Hyphenated and Hybrid Techniques

Hyphenated techniques such as IC–MS and LC–MS/MS are revolutionizing trace explosive detection. These combinations significantly enhance sensitivity and selectivity by coupling the separation power of chromatography with the molecular identification capabilities of mass spectrometry.[14,15,21] For example, IC–MS has enabled the simultaneous detection of nitrates, nitrites, and perchlorates in complex soil matrices, providing more comprehensive evidence profiles.[14] Similarly, LC–MS/MS allows sub-ppb detection of TNT and its degradation products.[15] Hybrid techniques are likely to become the standard for confirmatory analysis in advanced forensic laboratories.

3. Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are emerging as transformative tools in the field of forensic chemistry. By automating the interpretation of spectral and chromatographic data, AI can significantly reduce human errors and accelerate reporting.[22] Pattern recognition algorithms are particularly useful for distinguishing true explosive signatures from background noise, especially in environmentally contaminated samples.[22] The integration of AI with portable devices could enable real-time decision-making at crime scenes, thereby enhancing operational efficiency.

4. Environmental and Matrix-Aware Models

Future forensic approaches must also consider the dynamic influence of environmental factors such as rainfall, soil type, temperature, and pH.[3,12,17,18] Predictive models that simulate residue persistence under varying conditions can assist investigators in prioritizing evidence collection and interpreting the analytical results. Machine learning-based models trained on environmental datasets can predict nitrate or TNT recovery probabilities, thereby contextualizing analytical findings.[22]

5. Green and Sustainable Forensic Chemistry

There is a growing emphasis on green analytical chemistry in forensics, focusing on minimizing the use of hazardous reagents, solvent consumption, and waste generation.[19] TLC and IC methods are already relatively eco-friendly, but future developments aim to further reduce the environmental footprint of forensic laboratories. For instance, solvent-free microextraction techniques and energy-efficient miniaturized detectors are under active research.[20]

6. Standardization and Global Harmonization

Perhaps the most urgent need is the standardization of forensic protocols across all jurisdictions. Disparities in sample collection, preparation, and reporting often compromise the comparability of results. International organizations such as INTERPOL[23,] UNODC[24,] and SWGDRUG[25] have published guidelines that emphasize the best practices for explosives residue analysis. The adoption of globally harmonized standards will improve reproducibility, enhance judicial defensibility, and strengthen cross-border collaboration in counterterrorism efforts.

7. Training and Capacity Building

Even the most advanced technologies cannot fulfill their potential without skilled practitioners to operate them. The expansion of forensic training programs in chromatography, spectrometry, and data interpretation is critical. Moreover, incorporating AI-assisted systems into forensic curricula will prepare future analysts to work with hybrid human-machine workflows.[22]

8. Integration into Judicial Systems

Finally, future perspectives must address the integration of these scientific advances into legal frameworks. Courts increasingly demand not only analytical accuracy but also transparency, reproducibility, and validation of methods.[11] The next decade will likely see the expansion of forensic accreditation bodies mandating the use of validated, multi-tiered protocols for explosives detection.

The future of forensic explosives analysis lies in **portable systems, hyphenated techniques, AI-driven interpretation, environmentally informed modeling, sustainable practices, and international standardization**. By embracing these advances, forensic science will be better equipped to provide timely, accurate, and legally defensible evidence in the fight against the criminal and terrorist misuse of explosives.

CONCLUSION

The forensic investigation of post-blast residues remains a highly complex and indispensable aspect of modern criminalistics and counterterrorism operations. This review highlights that while **traditional colour spot tests** continue to serve as valuable **presumptive tools** because of their rapidity, simplicity, and affordability[6,7,] they cannot be relied upon in isolation for evidential purposes. Their inherent limitations low specificity, susceptibility to false positives, and environmental interference make them useful primarily as field screening tools rather than confirmatory techniques.[8–10]

Thin-layer chromatography (TLC) has emerged as a critical step forward in improving reliability. TLC's ability to separate nitroaromatics, peroxides, and inorganic oxidizers provides significant forensic advantages over colour tests, particularly when coupled with validated protocols.[8,12] However, its semi-quantitative nature and limited sensitivity compared to advanced spectrometric techniques mean that TLC is best deployed as an intermediate confirmatory tool.[13]

Ion chromatography (IC) has established itself as one of the most robust methods for detecting and quantifying nitrate and inorganic residues in post-blast soil matrices.[1–3] Its ability to distinguish between nitrates, nitrites, and perchlorates with high sensitivity makes it especially valuable under complex environmental conditions. Case studies have demonstrated that rainfall and soil composition significantly influence residue persistence, reducing recovery by more than 50% in some cases.[3,12,17] These findings emphasize the need for **time-sensitive evidence collection** and preservation strategies to mitigate environmental degradation.[18]

For specific explosives such as **PETN and TNT**, advanced methods including the **analysis** of **thermally decomposed products** and **extended column chromatography** provide unique analytical signatures and improved resolution.[4,5] These methods strengthen the forensic toolbox by reducing misidentification, enhancing reproducibility, and increasing the scientific weight of the evidence presented in court.

At the highest tier, **GC–MS and HPLC** remain the **gold standards** for confirmatory analysis because of their ultra-trace detection limits, high specificity, and widespread acceptance in judicial proceedings.[14–16] However, they are resource-intensive, require trained analysts, and may not always be feasible in resource-limited forensic laboratories.[19] Nevertheless, their role in delivering legally defensible evidence cannot be underestimated.

An important theme that emerges across all these methodologies is that **no single technique is sufficient**. Instead, a **multi-tiered workflow** rapid presumptive screening (colour tests), intermediate confirmation (TLC or IC), and advanced trace analysis (GC–MS/HPLC) is required to ensure both operational efficiency and evidential reliability.[20–22] This tiered approach not only balances speed and accuracy but also aligns with international forensic guidelines that emphasize standardization and reproducibility.[23–25]

Looking forward, the future of forensic explosives analysis lies in the integration of **portable chromatographic systems**, **hyphenated methods** (e.g., IC–MS, LC–MS/MS), and **artificial intelligence-driven spectral interpretation.**[14,21,22] These innovations have the potential to overcome the current limitations of laboratory dependency, improve on-site analytical capacity, and enhance reproducibility across jurisdictions.

In conclusion, the forensic community must prioritize **methodological integration, environmental awareness, and global standardization of forensic practices**. By adopting multi-tiered analytical strategies supported by emerging technologies, post-blast explosives analysis can achieve greater scientific rigor, operational efficiency, and judicial defensibility ultimately strengthening the fight against the criminal and terrorist use of explosives.

Abbreviations

The following abbreviations are used in this manuscript:

TLC	Thin Layer Chromatography
GC-MS	Gas Chromatography Mass Spectrometry
IC	Ion Chromatography
ANFO	Ammonium Nitrate Fuel Oil
PETN	Penta Erythritol Tetra Nitrate
TNT	Tri Nitro Toluene
HPLC	High Performance Liquid Chromatography
IED	Improvised Explosive Device
LC-MS/MS	Liquid Chromatography-Tandem Mass Spectrometry.
AI	Artificial Intelligence
ML	Machine Learning
HME	Home Made Explosives
mg	Milligram
L	Liter
Rf	Retention factor
IC-MS	Ion Chromatography–Mass Spectrometry
INTERPOL	International Criminal Police Organization
UNODC	United Nations Office on Drugs and Crime
SWGDRUG	Scientific Working Group for the Analysis of Seized Drugs

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