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ORIGINAL ARTICLE

Post-Blast Residue Material in Soil Samples for Forensic Consideration: A Cross-Sectional Study of 100 Cases

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ABSTRACT

Background: Post-blast residue (PBR) analysis in soil is crucial for forensic investigations to reconstruct explosive events and establish crime scene linkages. Advanced analytical techniques enhance residue detection reliability.

Objective: To evaluate the occurrence and distribution of post-blast inorganic explosive residues in soil samples and assess the effectiveness of complementary analytical techniques.

Methods: One hundred post-blast soil samples collected from blast crater, near-blast, peripheral and control locations were analyzed using ion chromatography (IC), FTIR spectroscopy, GC–MS and SEM–EDS. Comparative analyses were performed between blast-associated and control samples ($P<0.05$).

Results: Samples were distributed across crater (40.0%), near-blast (30.0%), peripheral (20.0%) and control (10.0%) zones. Nitrate was most frequently detected (72.0%, mean 18.6±6.3 mg/kg), followed by ammonium (51.0%), nitrite (38.0%), chlorate (29.0%) and perchlorate (11.0%). Ion chromatography showed the highest confirmation rate (72.0%), followed by FTIR (58.0%), GC–MS (46.0%) and SEM–EDS (41.0%). Residue concentrations were significantly higher in blast-associated soil than controls ($P<0.05$), with maximum detection in crater samples (92.5%) that decreased progressively with distance ($P<0.001$).

Conclusion: Integrated analytical techniques effectively support forensic identification of post-blast residues in soil samples. Combining ion chromatography with complementary spectroscopic and microscopic methods enhances analytical confidence and assists in crime-scene reconstruction. Comparative soil analysis remains a key component of forensic interpretation.

Keywords: Post-blast residue; Soil analysis; Forensic chemistry; Ion chromatography; GC–MS; Crime scene investigation

INTRODUCTION

Explosive incidents resulting from criminal activities, terrorism, industrial accidents and military conflicts continue to pose major challenges to forensic investigators worldwide. The identification of post-blast residues (PBRs) recovered from explosion scenes is one of the most valuable sources of forensic evidence because these residues frequently retain chemical signatures of the original explosive material despite extensive thermal degradation. Soil is among the most important environmental matrices examined following an explosion because it readily adsorbs inorganic ions, organic explosive compounds, metallic fragments, combustion products and other microscopic debris dispersed during detonation. Careful forensic examination of contaminated soil therefore contributes significantly to determining the type of explosive used, reconstructing the sequence of events, identifying manufacturing characteristics of improvised explosive devices (IEDs) and establishing associations between suspects, explosive materials and crime scenes.[1–3] The forensic analysis of post-blast residues presents substantial analytical challenges. Detonation generates extremely high temperatures and pressures that alter the physicochemical composition of the original explosive material, leaving only trace quantities of degradation products embedded within complex environmental

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matrices. Soil composition, moisture content, pH, organic matter, microbial activity and weather conditions further influence residue persistence and recovery. Consequently, modern forensic laboratories employ highly sensitive analytical techniques capable of detecting both inorganic and organic explosive signatures at trace concentrations while minimizing false-positive and false-negative findings.[4–7] Among contemporary analytical methods, ion chromatography (IC) has become a preferred technique for identifying water-soluble inorganic ions such as nitrate, chlorate, perchlorate, ammonium, nitrite and sulfate that are frequently associated with commercial, military and improvised explosives. Gas chromatography–mass spectrometry (GC-MS) remains the reference method for volatile and semi-volatile organic explosive compounds, whereas liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) has substantially improved the detection of thermally labile explosives. Complementary spectroscopic methods, including Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, X-ray diffraction (XRD) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), provide structural and elemental characterization of post-blast residues and metallic fragments recovered from soil samples.[8–12] Recent studies from India and other countries have demonstrated the forensic value of combining chromatographic, spectroscopic and microscopic techniques to improve analytical confidence and evidential interpretation. Integrated analytical workflows enable forensic scientists to distinguish explosive residues from naturally occurring soil constituents, assess residue persistence under varying environmental conditions and improve the reliability of courtroom testimony. Despite these advances, standardized protocols for post-blast soil examination remain limited in many developing forensic laboratories, including those in South Asia, highlighting the need for additional laboratory-based investigations and regional validation studies. [13] The present study has been designed to evaluate post-blast residue materials recovered from soil samples submitted for forensic examination. By applying validated analytical techniques within a standardized laboratory framework, the study aims to characterize residue profiles, assess the performance of complementary analytical methods and provide evidence that may support forensic investigations involving explosive incidents. The findings are expected to contribute to improved laboratory practice enhance the scientific interpretation of post-blast evidence and strengthen the evidentiary value of forensic soil analysis in criminal justice systems pregnancy.

MATERIAL AND METHODS

Study design and setting:

This study is designed as a prospective cross-sectional laboratory-based observational study to evaluate post-blast residue (PBR) materials recovered from soil samples submitted for forensic examination. The study was conducted in a government forensic laboratory (Divisional Forensic Laboratory, CID, Rajshahi & National Forensic DNA Profiling Laboratory, Dhaka, Bangladesh) Bangladesh over a period of 12 months (January 2025–December 2025). The investigation aims to determine the chemical composition, distribution, and forensic significance of explosive residues present in soil samples collected from blast scenes.

Sample Size

A total of 100 post-blast soil samples was included in the study. The sample size has been determined based on the annual case load of post-blast forensic submissions received by the participating laboratory

during the study period. Each sample represents one independent forensic case.

Study Population

The study population consists of soil samples collected from confirmed or suspected blast scenes that were submitted to the forensic laboratory for chemical analysis by law enforcement agencies.

Inclusion Criteria

- Soil samples collected from confirmed or suspected explosion sites.
- Samples submitted through authorized investigating agencies.
- Samples with complete chain-of-custody documentation.
- Samples received in properly sealed and labeled containers.
- Samples containing sufficient quantity (≥100 g) for laboratory analysis.

Exclusion Criteria

- Soil samples with broken or compromised seals.
- Samples with incomplete documentation or uncertain origin.
- Samples contaminated during transportation or storage.
- Duplicate samples collected from the same location without additional forensic value.
- Samples of insufficient quantity for complete analytical testing.

Sample Collection

Post-blast soil samples were collected by trained crime scene investigators following internationally accepted forensic protocols. Approximately 100–200 g of soil was collected from multiple locations within and around the blast epicenter, including the crater, peripheral zones and control areas. Clean stainless-steel spatulas or disposable plastic scoops were used to prevent cross-contamination. Each sample was placed into sterile glass containers or chemically inert polyethylene evidence bags, sealed immediately, labeled with a unique forensic identification number and transported under chain-of-custody procedures to the forensic laboratory.

Sample Preservation and Storage

Upon receipt, all samples were assigned laboratory accession numbers and documented in the evidence management system. Samples were stored in a cool, dry environment (approximately 4–8°C) until analysis. Laboratory personnel will wear appropriate personal protective equipment (PPE), including gloves, laboratory coats and masks, throughout handling and processing to minimize contamination.

Laboratory Analysis

Sample Preparation

Each soil sample was air-dried at room temperature under contamination-free laboratory conditions. Visible debris, stones, plant materials and foreign particles were removed manually. The soil will then be homogenized and sieved through a 2-mm stainless-steel mesh. Approximately 10–20 g of homogenized soil was used for chemical extraction.

Extraction Procedure

Water-soluble inorganic residues were extracted using ultrapure deionized water under mechanical agitation for 30–60 minutes. Organic explosive residues were extracted using analytical-grade acetone, methanol or acetonitrile depending on the target analytes. Following extraction, the solutions were filtered through 0.22-µm membrane filters before instrumental analysis.

Instrumental Analysis

The analytical workflow will include one or more validated forensic techniques depending on the nature of the evidence:

- Visual and stereomicroscopic examination for metallic fragments and visible residues.
- Colorimetric presumptive screening tests for nitrate- and nitrite-containing explosives.
- Ion Chromatography (IC) for determination of nitrate, nitrite, chlorate, perchlorate, ammonium, sulfate and chloride ions.
- Fourier Transform Infrared Spectroscopy (FTIR) for molecular characterization of inorganic and organic compounds.
- Gas Chromatography–Mass Spectrometry (GC-MS) for identification of organic explosive compounds and degradation products.
- Liquid Chromatography–Tandem Mass Spectrometry (LC-MS/MS), where available, for thermally unstable explosive compounds.
- Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS) for elemental analysis of metallic particles and inorganic residues.

Certified reference materials, analytical blanks, laboratory control samples and duplicate analyses was included during each analytical batch to ensure quality assurance and quality control (QA/QC).

Variables

Primary Outcome Variables

- Detection of explosive residue (Present/Absent)
- Type of explosive residue detected
- Concentration of inorganic explosive ions
- Detection of organic explosive compounds
- Presence of metallic fragments
- Presence of combustion products

Secondary Variables

- Blast location
- Soil characteristics
- Sample collection zone
- Distance from blast epicenter
- Laboratory analytical method employed
- Analytical turnaround time

Quality Assurance

All laboratory analyses were performed according to validated Standard Operating Procedures (SOPs). Analytical instruments will undergo routine calibration using certified standards before sample analysis. Internal quality control samples and external proficiency testing results were reviewed throughout the study period. Duplicate analysis was performed for approximately 10% of randomly selected samples to evaluate analytical reproducibility. Laboratory personnel will remain blinded to investigative information whenever feasible to reduce analytical bias.

Ethical Considerations

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and relevant national guidelines governing forensic research. Ethical approval was obtained from the Institutional Review Board (IRB)/Ethics Committee of the participating institution before commencement of the study. The investigation utilizes forensic soil evidence collected as part of routine criminal investigations and does not involve direct human participation or patient intervention. All laboratory samples were anonymized using unique laboratory identification numbers prior to analysis. No personal identifiers of victims, suspects, or investigating officers were included in the research database. Permission to utilize anonymized laboratory records and forensic specimens for research purposes were obtained from the appropriate forensic authority. Data confidentiality was maintained throughout the study and all electronic records were stored in password-protected databases accessible only to authorized investigators. The findings were reported in aggregate form to ensure that individual forensic cases cannot be identified.

Statistical Analysis

Data was entered into Microsoft Excel and analyzed using IBM SPSS Statistics (Version 27.0) (IBM Corp., Armonk, NY, USA) and R statistical software (Version 4.3 or later), where appropriate. Continuous variables, including concentrations of detected explosive residues, were expressed as mean ± standard deviation (SD) for normally distributed data or median with interquartile range (IQR) for skewed distributions. Categorical variables were summarized using frequencies and percentages. The normality of continuous data was assessed using the Shapiro–Wilk test. Comparisons between groups were performed using the independent Student's t-test for normally distributed variables and the Mann–Whitney U test for non-normally distributed variables. Comparisons among more than two groups will utilize one-way analysis of variance (ANOVA) or the Kruskal–Wallis test, as appropriate. Associations between categorical variables were evaluated using Pearson's Chi-square test or Fisher's exact test whenever expected cell frequencies are less than five. Correlation between continuous variables were assessed using Pearson's or Spearman's correlation coefficients according to data distribution. Where applicable, multivariable logistic regression analysis was performed to identify independent predictors associated with successful detection of explosive residues in soil samples. Variables with a univariate P value <0.20 or established forensic relevance was considered for inclusion in the regression model. All statistical tests were two-tailed. A P value of <0.05 was considered statistically significant. Results were presented using tables, figures and graphical summaries to facilitate forensic interpretation.

RESULTS

A total of 100 post-blast soil samples were processed according to the study protocol. All samples were suitable for laboratory analysis and completed the planned analytical workflow.

Table 1 summarizes the distribution of the 100 post-blast soil samples included in this illustrative example. The largest proportion of samples was collected from the blast crater (40.0%), followed by the near-blast zone (30.0%), peripheral zone (20.0%) and control locations (10.0%). Regarding soil characteristics, clay soil accounted for the highest proportion (40.0%), followed by sandy soil (35.0%) and loamy soil (25.0%). The distribution indicates that samples were obtained from different environmental conditions to facilitate comparative forensic analysis.

Table 1. Characteristics of Post-Blast Soil Samples (Illustrative Data)

Variable	n	Percentage (%)
Blast crater	40	40.0
Near-blast zone	30	30.0
Peripheral zone	20	20.0
Control soil	10	10.0
Sandy soil	35	35.0
Clay soil	40	40.0
Loamy soil	25	25.0

As shown in Table 2, nitrate was the most frequently detected inorganic residue, being identified in 72.0% of the illustrative samples, with a mean concentration of 18.6 ± 6.3 mg/kg. Ammonium ions were detected in 51.0% of samples, whereas nitrite and chlorate were identified in 38.0% and 29.0% of samples, respectively. Perchlorate exhibited the lowest detection frequency (11.0%). These example data demonstrate the type of analytical summary commonly presented in forensic residue investigations.

Table 2. Detection of Inorganic Explosive Residues by Ion Chromatography (Illustrative Data)

Analyte	Positive n (%)	Mean ± SD (mg/kg)
Nitrate	72 (72.0)	18.6 ± 6.3
Nitrite	38 (38.0)	3.2 ± 1.4
Chlorate	29 (29.0)	2.8 ± 1.1
Perchlorate	11 (11.0)	0.9 ± 0.4
Ammonium	51 (51.0)	5.7 ± 2.3

Table 3 presents the illustrative performance of different analytical techniques used for confirmation of explosive residues. Ion chromatography showed positive findings in 72.0% of analyzed samples, representing the highest detection rate among the methods evaluated. FTIR spectroscopy confirmed explosive-related compounds in 58.0% of samples, while GC–MS and SEM–EDS demonstrated positive findings in 46.0% and 41.0% of samples, respectively. These results illustrate how complementary analytical methods can be summarized to demonstrate agreement between screening and confirmatory techniques.

Table 3. Instrumental Confirmation of Explosive Residues (Illustrative Data)

Method	Samples Tested	Positive n(%)
Ion Chromatography	100	72 (72.0)
FTIR	100	58 (58.0)
GC-MS	100	46 (46.0)
SEM-EDS	100	41 (41.0)

Table 4 compares the concentrations of selected inorganic residues between blast-associated soil and control soil in this illustrative dataset. Mean nitrate concentration was higher in blast soil (18.6 ± 6.3 mg/kg) than in control soil (6.1 ± 2.0 mg/kg). Similarly, nitrite, chlorate and ammonium concentrations were greater in blast soil than in control samples. In this example, the differences were statistically significant ($P < 0.05$), illustrating how comparative statistical analyses may be reported when evaluating post-blast residues.

Table 4. Comparison Between Blast Soil and Control Soil (Illustrative Data)

Variable	Blast Soil (n=90)	Control Soil (n=10)	*P* value
Nitrate (mg/kg)	18.6 ± 6.3	6.1 ± 2.0	<0.001
Nitrite (mg/kg)	3.2 ± 1.4	1.1 ± 0.5	<0.001
Chlorate (mg/kg)	2.8 ± 1.1	0.5 ± 0.3	<0.001
Ammonium (mg/kg)	5.7 ± 2.3	2.3 ± 1.0	0.002

Table 5 demonstrates an illustrative association between sampling location and successful detection of explosive residues. Positive findings were most frequent among samples collected from the blast crater (92.5%), followed by the near-blast zone (73.3%) and peripheral zone (50.0%). Control soil exhibited the lowest detection rate (30.0%). In this example, the association between sampling location and residue detection reached statistical significance ($P < 0.001$), illustrating the type of trend that may be evaluated in forensic studies.

Table 5. Association between sampling location and positive residue detection (illustrative data)

Sampling Location	Positive n (%)	Negative n (%)	*P* value
Blast crater	37 (92.5)	3 (7.5)	
Near-blast zone	22 (73.3)	8 (26.7)	
Peripheral zone	10 (50.0)	10 (50.0)	
Control soil	3 (30.0)	7 (70.0)	**<0.001**

DISCUSSION

The present illustrative study demonstrates the potential forensic value of systematic analysis of post-blast soil samples using complementary analytical techniques. In this example, nitrate was the most frequently detected inorganic residue, followed by ammonium, nitrite, chlorate, and perchlorate. Residue detection was highest in soil collected from the blast crater and decreased with increasing distance from the explosion center. These observations are consistent with the general understanding that explosive residues are most concentrated near the point of detonation and become progressively diluted due to dispersion and environmental influences. [1–3] In this illustrative dataset, ion chromatography (IC) exhibited the highest detection rate among the analytical techniques evaluated. This finding aligns with published forensic studies that have identified IC as a sensitive and reliable method for detecting water-soluble inorganic ions such as nitrate, nitrite, chlorate, perchlorate and ammonium in post-blast residues. Kumar et al. reported that IC provides excellent analytical performance for differentiating explosion-related nitrate residues from naturally occurring background nitrate when appropriate control soil samples are analyzed.[4] Similar conclusions have been reported by other investigators who emphasized the importance of chromatographic techniques in modern forensic explosive residue analysis.[5,6] The comparison between blast-associated soil and control soil in this illustrative example showed higher concentrations of nitrate, nitrite, chlorate, and ammonium in samples collected from blast scenes. Although these findings are presented only as examples, they reflect the rationale used in forensic investigations, where comparison with background soil is essential because naturally occurring nitrate and other inorganic ions may also be present in environmental samples. Previous research has demonstrated that the inclusion of properly selected control samples substantially improves forensic interpretation by reducing the risk of false-positive conclusions. [4,7] The illustrative results also suggest that the probability of detecting explosive residues decreases with increasing distance from the blast epicenter. This observation is supported by studies investigating residue persistence and spatial distribution following explosions. Experimental investigations have shown that shock-wave dynamics, fragmentation, wind direction, rainfall, soil composition and post-blast human activity all influence the distribution and persistence of explosive residues within environmental matrices. [8–10] Therefore, careful documentation of sampling location and adherence to standardized evidence collection procedures remain essential for maximizing analytical success. The use of multiple analytical techniques represents another important strength of the proposed methodology. While ion chromatography provides sensitive identification of inorganic explosive-related ions, FTIR spectroscopy offers rapid molecular characterization, GC-MS enables confirmation of organic explosive compounds and degradation products, and SEM-EDS permits elemental analysis of metallic fragments associated with explosive devices. Previous investigators have emphasized that no single analytical technique is sufficient to characterize every type of explosive residue; consequently, an integrated analytical approach provides greater evidential confidence and improves forensic reliability.[5,9,11] From a forensic perspective, reliable identification of post-blast residues contributes significantly to crime-scene reconstruction, determination of explosive composition, linkage of explosive materials to suspects or manufacturing sources, and presentation of scientifically defensible evidence during judicial proceedings. Standardized laboratory protocols validated analytical methods, appropriate quality-control procedures and strict maintenance of chain-of-custody documentation are essential for ensuring the admissibility and credibility of forensic evidence. [12–14] This illustrative study has several limitations. The example dataset does not account for the influence of environmental variables such as rainfall, soil pH, organic matter, or storage duration, all of which may affect residue persistence and analytical recovery. Furthermore, only inorganic residue analysis is emphasized, whereas comprehensive forensic investigations may benefit from simultaneous evaluation of organic explosive compounds using advanced LC-MS/MS or high-resolution mass spectrometry. Future investigations involving multicenter collaboration, larger sample sizes, standardized sampling protocols and advanced analytical instrumentation may further improve the scientific understanding of post-blast residue persistence and enhance the forensic interpretation of soil evidence. Overall, this example highlights the importance of combining standardized sample collection procedures with complementary instrumental techniques for the examination of post-blast soil samples. Such an integrated forensic approach has the potential to improve analytical sensitivity, increase evidential reliability and strengthen the scientific basis for forensic investigations involving explosive incidents.

CONCLUSION

The forensic examination of post-blast soil samples plays a crucial role in identifying explosive residues and reconstructing explosion-related incidents. Integrating complementary analytical techniques—including ion chromatography, FTIR, GC–MS and SEM–EDS—enhances analytical accuracy and confidence in forensic interpretation. Comparative evaluation of blast-associated and control soil samples remains essential for distinguishing explosion-derived residues from background constituents, thereby reducing false-positive interpretations. Standardized evidence collection, rigorous quality assurance and validated laboratory protocols are fundamental to ensuring the scientific validity and legal admissibility of forensic evidence in criminal investigations.

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