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Gelatin-based hydrogels as a novel medium for efficient recovery of organic explosives from post-blast residues: A forensic perspective

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ABSTRACT

Post-blast residue analysis is critical for forensic investigations, enabling the identification of organic explosives like Trinitrotoluene (TNT), Pentaerythritol tetranitrate (PETN), and 2-Nitrotoluene (2-NT) to reconstruct crime scenes and link perpetrators to illicit activities. Efficient collection of residues from diverse surfaces is essential for accurate forensic analysis, and ensuring justice. Traditional methods, such as cotton swabbing or solvent washing, recover only 50–70 % of residues and are prone to contamination, sample loss, and inefficiency on porous or irregular surfaces. A versatile, eco-friendly medium that enhances recovery across varied substrates is urgently needed. This study explores gelatin-based hydrogels (GHs) as an innovative, biocompatible medium for post-blast residue collection, leveraging their unique adsorbent/absorbent properties for improved surface contact and sampling efficiency in contaminated environments. The research evaluates GHs for recovering TNT, PETN, and 2-NT from ten surfaces spiked with explosive solutions to mimic post-blast residues (e.g., metals, plastics, wood, cloth) using Gas Chromatography-Mass Spectrometry (GC-MS) for qualitative identification. Triplicate experiments demonstrated recovery rates of 80–95 % (mean ± 5 % SD) on non-porous surfaces, and 60–70 % on porous surfaces, including non-precleaned surfaces with contaminants (e.g., dust, soil, oil), validated via ANOVA ($p < 0.05$). GC-MS confirmed distinct m/z peaks for each explosive (TNT: 210, 193, 180; PETN: 240, 194, 149; 2-NT: 137, 120, 91) with limits of detection of 0.1–0.5 μg/mL and signal-to-noise ratios > 3:1, indicating high sensitivity. Preliminary data suggest GHs may offer cost-effectiveness (~USD $ 0.50/sample vs. ~USD $ 2.00 for swabs) and potential field applicability for transport to laboratory settings, significantly improving residue recovery and analytical reliability. This approach enhances forensic capabilities in post-blast investigations and has potential applications in environmental monitoring and homeland security. Future research should validate GHs under real-world conditions and expand their use to other explosives, broadening their forensic utility.

1. Introduction

Explosions, whether accidental or intentional, leave behind trace residues that serve as a silent witness to the events that transpired [1]. These microscopic remnants hold the key to unraveling critical forensic questions: What type of explosive was used? Who might be responsible? And how can we prevent similar incidents in the future? In the realm of forensic science, the ability to collect and analyze these post-blast residues is not just a technical challenge, it is a matter of justice and public safety [2].

The collection of post-blast residues from crime scenes has long been a cornerstone of forensic investigations ([3]., "Forensic Chemistry). Yet, this task is far from straightforward. Explosive residues can adhere to a wide variety of surfaces, from smooth metals to porous fabrics, each presenting unique challenges for recovery ([4,5]). While current methods such as mechanical vacuuming, solvent washing, and cotton swabbing have been widely employed, they are plagued by inefficiencies [6]. Studies show that these techniques recover only 50–70 % of organic

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explosives like Trinitrotoluene (TNT), Pentaerythritol tetranitrate (PETN), and 2-Nitrotoluene (2-NT) (Song-Im et al., 2012b; DeTata et al., 2013a). Moreover, environmental factors such as heat, moisture, and microbial activity can degrade samples, further complicating the analysis ([7]; Wingstedt et al., 2012). This inefficiency poses a significant problem: incomplete residue recovery can lead to missed evidence, undermining investigations and jeopardizing justice.

Recognizing these limitations, researchers have explored advanced techniques like solid-phase microextraction and dispersive solid-phase extraction, which improve recovery rates to 60–80 % (Furton, K. G., et al., 2000). However, these methods are often complex, time-consuming, and impractical for field use [8]. The pressing need for a simple, efficient, and versatile solution has driven innovation in the field. Among the emerging materials, hydrogel-based technologies, particularly gelatin-based hydrogels (GHs), have shown remarkable potential. These materials, characterized by their three-dimensional network, and high-water content, excel in adsorbing and absorbing organic compounds, including explosives [9,10]. GHs' 3D polymer network, crosslinked via hydrogen bonds, enhances residue entrapment through synergistic adsorption (surface binding) and absorption (bulk uptake), outperforming swabs' passive adhesion [11]. Unlike traditional methods, GHs offer enhanced surface contact, efficient explosive residue recoveries in contamination, and compatibility with irregular or semi-porous surfaces (Amaral, M. A., et al. 2020 [12];).

This study addresses the critical gap in post-blast residue collection by evaluating the efficacy of gelatin-based hydrogels as a novel medium for recovering organic explosives from diverse surfaces. Specifically, the research focuses on TNT, PETN, and 2-NT, analyzing their recovery rates using Gas Chromatography-Mass Spectrometry (GC-MS), a highly sensitive analytical tool [13]. The central research question guiding this work is: How can forensic investigators efficiently recover organic explosive residues from highly contaminated and heterogeneous post-blast surfaces using a practical, eco-friendly medium?; This study aims to (1) evaluate GH recovery efficiency across 10 common post-blast surfaces, (2) validate sensitivity via GC-MS, and (3) compare GHs performance to traditional methods. By leveraging GHs, this study seeks to demonstrate superior recovery rates (80–95 %) compared to traditional methods, while maintaining high analytical sensitivity (limits of detection: 0.1–0.5 μg/mL).

By bridging the gap between laboratory innovation and real-world forensic applications, this study not only advances the field of post-blast residue analysis but also provides a practical tool for investigators striving to solve some of society's most challenging cases.

2. Materials and methods

2.1. Materials

Gelatin powder, soluble starch, and glycerol were procured from a local market, while ultrapure water was generously provided by a local industry for this research. Certified reference standards (CRMs) of Pentaerythritol tetranitrate (PETN-AccuStandard), Trinitrotoluene (TNT-SupelCo), and 2-Nitrotoluene (2-NT) were imported/purchased from certified suppliers. ACS-grade solvents, including acetonitrile (ACN), methanol, acetone, and ethyl acetate, were used throughout the study.

2.1.1. Ethical approval

In addition to its scientific contributions, this research adheres to ethical standards, having received Institutional Review Board approval (IRB-NAUSS-2023–015).

3. Methods

3.1. Preparation of hydrogel for sample collection

The hydrogel was prepared using food-grade gelatin powder (Type A, bloom strength 250, Sigma-Aldrich), soluble starch (analytical grade, Merck), and ultrapure water (Milli-Q, 18.2 MΩ·cm) in a mass ratio of 4:2:4 (w/w) for the optimal formulation (GH-1). Five gelatin/starch/water ratios, (4:2:4, 5:7:3, 6:1:3, 3:3:8, 1:5:10) were tested to optimize viscosity and residue retention. For each formulation, five independent batches (100 mL each) were prepared to assess reproducibility. For the optimal ratio (4:2:4), 4 g of gelatin powder was dissolved in 4 mL of ultrapure water in a sterilized 100 mL Pyrex beaker (autoclaved at 121°C for 15 min) on a hot plate (IKA C-MAG HS 7) with a magnetic stirrer at 75°C and 300 rpm for 10–15 min until fully dissolved. Subsequently, 2 g of soluble starch was added, and the mixture was stirred at 75°C for an additional 10 min to form a homogeneous, viscous gel. Viscosity was measured using a Brookfield DV-II+ Pro viscometer (25°C, spindle SC4–18, 60 rpm) to confirm consistency across batches, with mean viscosity for GH-1 of 450 ± 20 cP (n = 5, coefficient of variation [CV] = 4.4 %). The GH-1 hydrogel exhibited a smooth, viscous consistency resembling a semi-solid gel, allowing uniform application with a spatula and conformal contact with diverse surfaces (Fig. 1). Its moderate thickness (450 ± 20 cP, Section 4.2) ensured ease of handling without excessive stickiness, facilitating clean removal with forceps after drying. The gel was cooled to room temperature (25°C) and used within 30 min to ensure consistency. For storage, the gel was transferred to sterile, airtight 50 mL polypropylene tubes (Falcon) and kept at ambient temperature for up to 72 h, as described in Section 4.5. Each batch was freshly prepared or stored under controlled conditions to avoid degradation, and all equipment was sterilized to prevent contamination. The preparation process and surface applications are illustrated in Figs. 1 and 2.

3.2. Preparation of organic explosives sample solutions

3.2.1. Organic explosives

The target analytes included Pentaerythritol tetranitrate (PETN), Trinitrotoluene (TNT), and 2-Nitrotoluene (2-NT).

3.3. Samples, quality controls, and blanks

Stock solutions of organic explosives were prepared at a concentration of 1 mg/mL by dissolving 10 mg of each CRM in 10 mL of ACS-grade acetone in a volumetric flask. Positive quality controls (QCs) were prepared from separate batches of standards at the same concentration. Acetone served as the negative QC for blank samples.

3.4. Application of hydrogel on post-blast surfaces

The study was conducted on eleven (11) common types of surfaces that may be encountered at blast sites: (1) leather, (2) cardboard, (3) ceramic tile, (4) carpet, (5) metals, (6) plastic (e.g., acrylonitrile butadiene styrene sheet [ABS]), (7) wood, (8) granite tile, (9) glass, (10) marble, and (11) cloth. Spiked samples represent idealized residues; future work should validate GHs on residues from controlled detonations.

3.5. Sample application and extraction

Eleven surfaces (1) leather, (2) cardboard, (3) ceramic tile, (4) carpet, (5) metals, (6) plastic (e.g., acrylonitrile butadiene styrene sheet [ABS]), (7) wood, (8) granite tile, (9) glass, (10) marble, and (11) cloth) were tested under two conditions: precleaned and non-precleaned. For precleaned surfaces, each was cleaned with 5 mL of ACS-grade methanol followed by 5 mL of acetone (both Sigma-Aldrich, ≥99.5 % purity) using

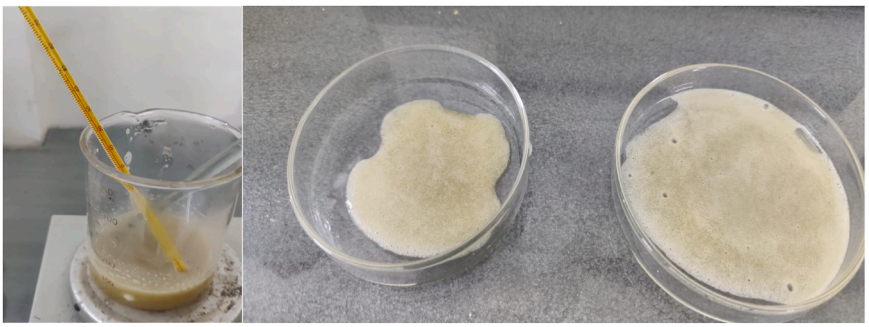

Fig. 1. Preparation of Gelatin-Based Hydrogel and Application on Various Surfaces.

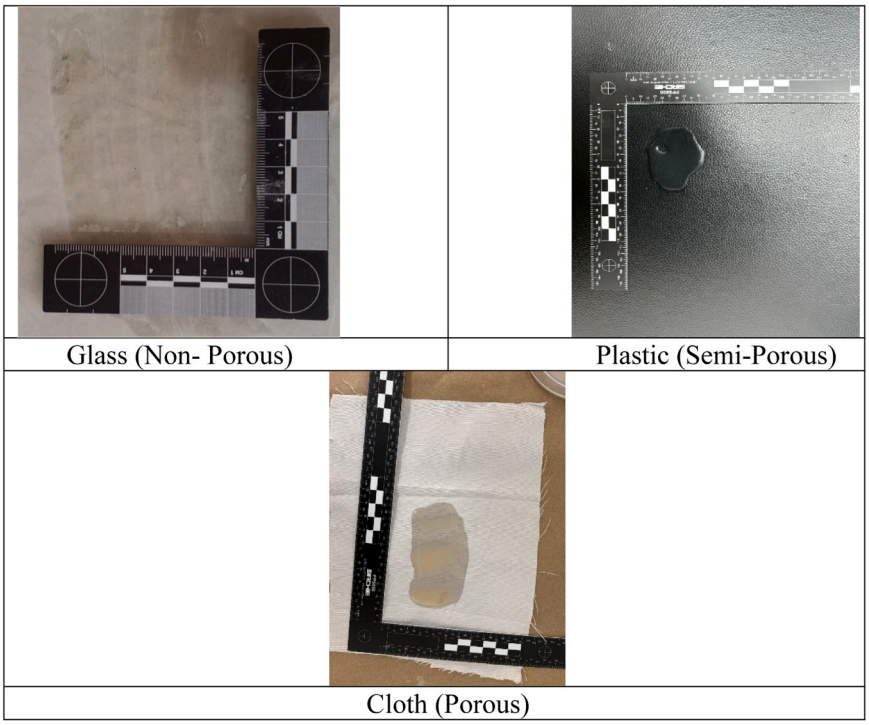

Fig. 2. Various Surfaces Photographed with ABFO Scale.

lint-free wipes to eliminate contaminants. For non-precleaned surfaces, simulating real-world post-blast conditions, surfaces were exposed to common contaminants (e.g., dust, soil, and oil residues) by placing them in an outdoor environment (25°C, 50 % humidity) for 24 h prior to spiking. A 1 mL aliquot of each explosive stock solution (1 mg/mL in acetone; TNT, PETN, 2-NT) was applied to a 5 cm^2 area on each surface using a calibrated micropipette (Eppendorf Research Plus, 100–1000 μL). The spiked surfaces were air-dried for 30 min at 25°C to allow complete evaporation of the acetone solvent, simulating residues that might be transported from a crime scene to a laboratory for analysis. Subsequently, 500 μL of acetone was applied to the same area to mimic the dispersion and partial dissolution of explosive residues post-blast, as observed in real-world scenarios where residues may be redistributed by environmental factors or blast dynamics [2]. After a further 2-minute air-drying period to ensure partial solvent evaporation, 2 g of hydrogel was uniformly applied using a sterile spatula. The gel was left to dry for 5–10 min under ambient conditions (25°C, 50 % relative humidity).

The dried gel was collected with sterilized disposable forceps (autoclaved at 121°C for 15 min) and transferred to 10 mL polypropylene centrifuge tubes (sterile, Falcon) containing 1 mL of ethyl acetate (Sigma-Aldrich, ≥99.5 % purity). Ethyl acetate was selected as the extraction solvent due to its compatibility with the hydrogel's matrix (minimal swelling, <5 % volume change), immiscibility with the water contents in the gel, and optimal performance in GC-MS analysis, providing cleaner chromatograms. The tubes were heated in a water bath (Grant Instruments, JB Nova) at 75°C for 20 min to facilitate dissolution of the gel and the release of residues, then vortexed (Vortex-Genie 2, 2500 rpm) for 1–2 min to ensure thorough mixing. The mixture was cooled at −20°C for 5–10 min in a laboratory freezer (Thermo Scientific) to promote phase separation. The resulting mixture consisted of approximately 0.8–1.0 mL of organic layer (ethyl acetate containing dissolved explosives) and 0.5–0.7 mL of aqueous layer (gelatin and water residues), depending on the surface type and gel absorption. The organic layer was extracted three times sequentially from the same tube using a micropipette (Eppendorf Research Plus, 100–1000 μL). For each extraction, approximately 300–350 μL of the organic layer was carefully pipetted from the top phase and transferred to a single sterile 5 mL glass vial (Agilent Technologies). The three extracts were combined in the same vial, evaporated to dryness under a nitrogen stream (N_2 evaporator, Organomation Associates) at 40°C, reconstituted in 1 mL of methanol (Sigma-Aldrich, ≥99.8 % purity), and transferred to 2 mL amber GC-MS vials (Agilent Technologies). Positive controls (1 mg/mL standards) and negative controls (un-spiked surfaces) were processed identically to confirm no cross-contamination. For non-precleaned

surfaces, negative controls included un-spiked contaminated surfaces to assess interference from environmental contaminants. Chromatograms from gel-collected samples were compared to standards to verify that the gel did not introduce interfering peaks during GC-MS analysis.

3.6. GC-MS method parameters

A GC-MS system (Agilent 7890B GC coupled with 5977 A MS, Triple-Axis Detector, Palo Alto, CA) was used for qualitative analysis, equipped with an automated liquid sampler (ALS, Agilent G4513A). One microliter of each sample was injected in spitless mode, with the split vent closed during injection to maximize sample transfer for trace analysis. The DB-5MS column (15 m × 0.25 mm × 0.25 μm, Agilent J&W) was used with helium (99.999 % purity) as the carrier gas at a constant flow rate of 1 mL/min. The oven program was: 70°C (3 min), ramped at 8 °C/min to 185°C (1 min), then 25 °C/min to 200°C (5 min), with a total run time of 23.975 min. The MS transfer line was set to 260°C, source temperature to 230°C, and quadrupole temperature to 150°C. The scan range was used as 43–550 *m/z* for the selected target analytes (Table 1). Results were analyzed using Enhanced Chemstation software (Agilent Technologies, version E.02.02) with the NIST 17 library for spectral matching. Major ion peaks were compared to certified reference standards (TNT: 210, 193, 180; PETN: 240, 194, 149; 2-NT: 137, 120, 91).

3.7. Quality control and calibration

To ensure reproducibility, the GC-MS system was calibrated daily using a five-point calibration curve (0.05, 0.1, 0.5, 1.0, 2.0 μg/mL) prepared from certified reference standards (TNT, PETN, 2-NT) in methanol. Calibration standards were run in triplicate, with R^2 values ≥ 0.999 indicating linearity. The limit of detection (LOD) was determined by analyzing serial dilutions of each analyte (0.01–1.0 μg/mL) in methanol, with the LOD defined as the lowest concentration yielding a signal-to-noise ratio $\geq$ 3:1, calculated using the root mean square noise in blank samples (n = 5) and peak heights of analyte standards (n = 3 per concentration). LODs ranged from 0.1 μg/mL (TNT) to 0.5 μg/mL (PETN, 2-NT). Positive quality controls (1 μg/mL) and negative controls (methanol blanks) were analyzed before and after each sample batch to verify system performance and absence of carryover. Instrument maintenance included regular cleaning of the inlet liner and tuning of the MS detector to ensure consistent sensitivity. All glassware and tools were autoclaved at 121°C for 15 min, and solvents were stored in amber glass bottles to prevent degradation.

3.8. Throughput and ease of use

The total time from hydrogel application to preparation of samples for GC-MS analysis was approximately 45–60 min per sample under controlled laboratory conditions. This includes: hydrogel application (2–3 min), drying (5–10 min), collection (1–2 min), extraction with ethyl acetate (20 min heating, 1–2 min vortexing, 5–10 min cooling), and evaporation/reconstitution (10–15 min). The process requires standard laboratory equipment (e.g., water bath, vortexer, nitrogen evaporator) and trained personnel for precise pipetting and sterile handling to avoid contamination. While suitable for laboratory settings, field deployment may require streamlined protocols to reduce time and simplify handling for non-specialist personnel, such as pre-prepared gels and portable extraction devices.

Table 1
Method Parameters for GC-MS Analysis.

Parameter	Setting
GC (7890B)	
Inlet Mode	Split less Mode
Inlet Temperature	250°C
Carrier Gas	Helium (flow rate: 1 mL/min)
Inlet Pressure	37.26 psi
Column	DB-5MS (15 m × 0.25 mm × 0.25 μm)
Oven Program	70°C (3 min) → 8 °C/min → 185°C (1 min) → 25 °C/min → 200°C (5 min)
Run Time	23.975 min
MS (5975 C)	
Transfer Line	260°C
Source Temperature	230°C
Quad Temperature	150°C
Mode	Scan
Scan Range	43–550 *m/z*

4. Results and discussion

4.1. Results

The gelatin-based hydrogel (GH) proved to be a rapid and effective medium for recovering post-blast organic explosive residues at crime scenes. Its successful application and recovery, however, require skilled forensic analysts to ensure reportable and actionable results during crime scene investigations. Figs. 3–5 present representative GC–MS chromatograms of explosive mixture residues collected using gelatin-based hydrogels (GHs) from different substrate surfaces. Each spiked sample contained mixtures of TNT, PETN, and 2-NT, demonstrating the simultaneous recovery and identification of all three target analytes under optimized analytical conditions.

The sample extracts obtained through the extensive extraction and purification process using hydrogels as a recovery medium from post-blast surfaces yielded profound and reliable results for the qualitative identification of organic explosives. This recovery is dependent of various factors like gel characteristics, analyte retention and extraction methodologies (Tables 2 and 3).

Mean recovery rates (n = 9 per surface) showed ±5 % SD, with ANOVA confirming significant differences between GHs and swabs ($p < 0.01$) (D.A. DeTata, M. A., et al. 2013). GC-MS analysis was performed using the Enhanced Chemstation software with the NIST Library and Probability-Based Matching (PBM) as the primary tools for mass spectrum comparison. Chromatograms of the organic explosive analytes were compared with reference standards, with retention time (RT) serving as the key identifying feature for each compound. The MS spectra of trinitrotoluene (TNT) derived from extracted residue samples matched major ions (210, 193, 180, 149, 134, 89, 63 *m/z*) identified in the NIST spectral library. Similarly, pentaerythritol tetranitrate (PETN) exhibited characteristic ions (240, 194, 149, 97, 76, 57, 55, 46 *m/z*), and 2-nitrotoluene (2-NT) showed distinct ions (137, 120, 92, 91, 89, 77, 65, 39 *m/z*). These findings were consistent with certified reference standards, demonstrating high accuracy and reliability (Supplementary Figure S-6).

The relative abundance of each target analyte displayed sharp peaks with a signal-to-noise ratio greater than 3:1, indicating excellent resolution and selectivity. Recovery rates were calculated by comparing peak heights from surface samples to those of reference standards (1 mg/mL in methanol), as shown in Table 4 and Table 5. The combination of gelatin-based hydrogel recovery and precise GC-MS analysis provided a robust method for resolving forensic casework involving the detection of organic explosives in post-blast residues collected on-site.

4.2. Gel optimization study

A preliminary study was conducted to investigate the formulation and performance of gelatin-based hydrogels (GHs) with the specific objective of enhancing efficiency and residue retention for post-blast residue (PBR) collection. Gelatin, a biodegradable and biocompatible polymer, was selected for its inherent gelling properties and adaptability under various physicochemical conditions [14]. Five formulations (GH-1 to GH-5) with gelatin/starch/water ratios of 4:2:4, 5:7:3, 6:1:3,

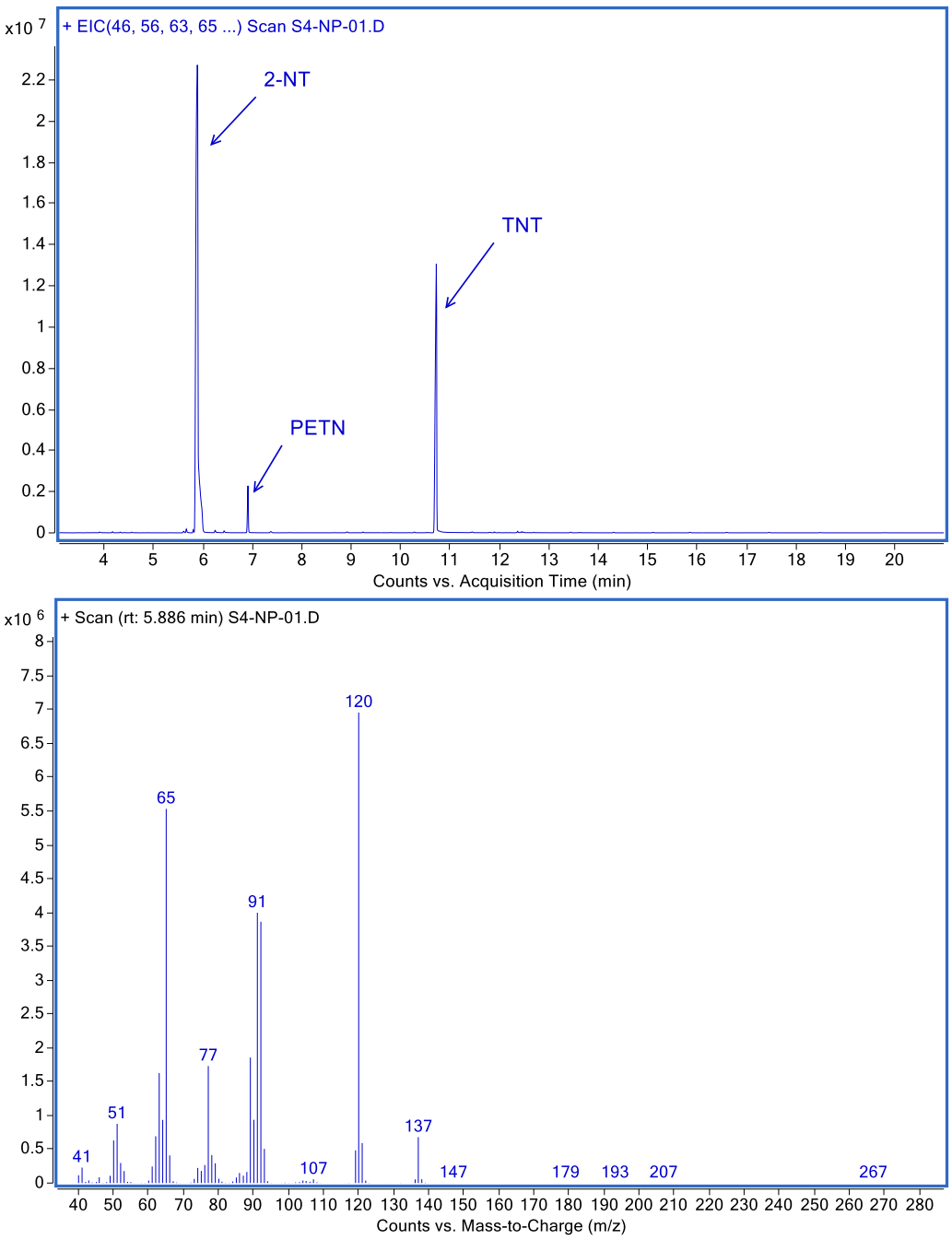

Fig. 3. Total ion chromatogram (TIC) of a mixture of TNT, PETN, and 2-NT extracted from a gelatin hydrogel–collected sample (glass, non-porous substrate) and the EI–MS spectrum of TNT with major ions labeled at *m/z* 210, 193, 180, 149, 134, 89, and 63 (NIST 14 library match). See Supplementary Fig. S7.

3:3:8, and 1:5:10 (w/w) were evaluated. For each formulation, five independent batches (100 mL each) were prepared to assess reproducibility (Table 3).

Viscosity was measured using a Brookfield DV-II+ Pro viscometer (25°C, spindle SC4–18, 60 rpm), with mean viscosities and coefficients of variation (CV) as follows: GH-1 (450 ± 20 cP, CV = 4.4 %), GH-2 (620 ± 30 cP, CV = 4.8 %), GH-3 (680 ± 35 cP, CV = 5.1 %), GH-4 (280 ± 15 cP, CV = 5.4 %), and GH-5 (150 ± 10 cP, CV = 6.7 %). The low CV values (<7 %) indicate high reproducibility across batches for all formulations. GH-1 (4:2:4) exhibited optimal physical properties, with moderate thickness and a settling time of 15 ± 2 min, making it suitable for residue collection (Fig. 6). GH-2 and GH-3 (Figures. S3-S4–8) were thicker, due to the higher gelatin content, with shorter settling times (5 ± 2 and 3 ± 2 min, respectively), but hardened quickly, reducing applicability. GH-4 and GH-5 (Figure. S5 & Figure7) were thinner, due to higher water content, with longer settling times (20 ± 2 and 25 ± 2 min), leading to poor residue retention. The cross-linking behavior of GH-1 provided effective collection capability, as confirmed by SEM imaging.

4.3. Scanning electron microscopy study of GHs

Microstructural characteristics of five compositions of GHs were evaluated by Scanning Electron Microscopy (SEM) to assess surface morphology and network architecture across the various formulations. The compositional variation impacted the GHs structure. Higher gelatin content exhibited denser and more interconnected networks, while lower gelatin content resulted being a more porous and loosely

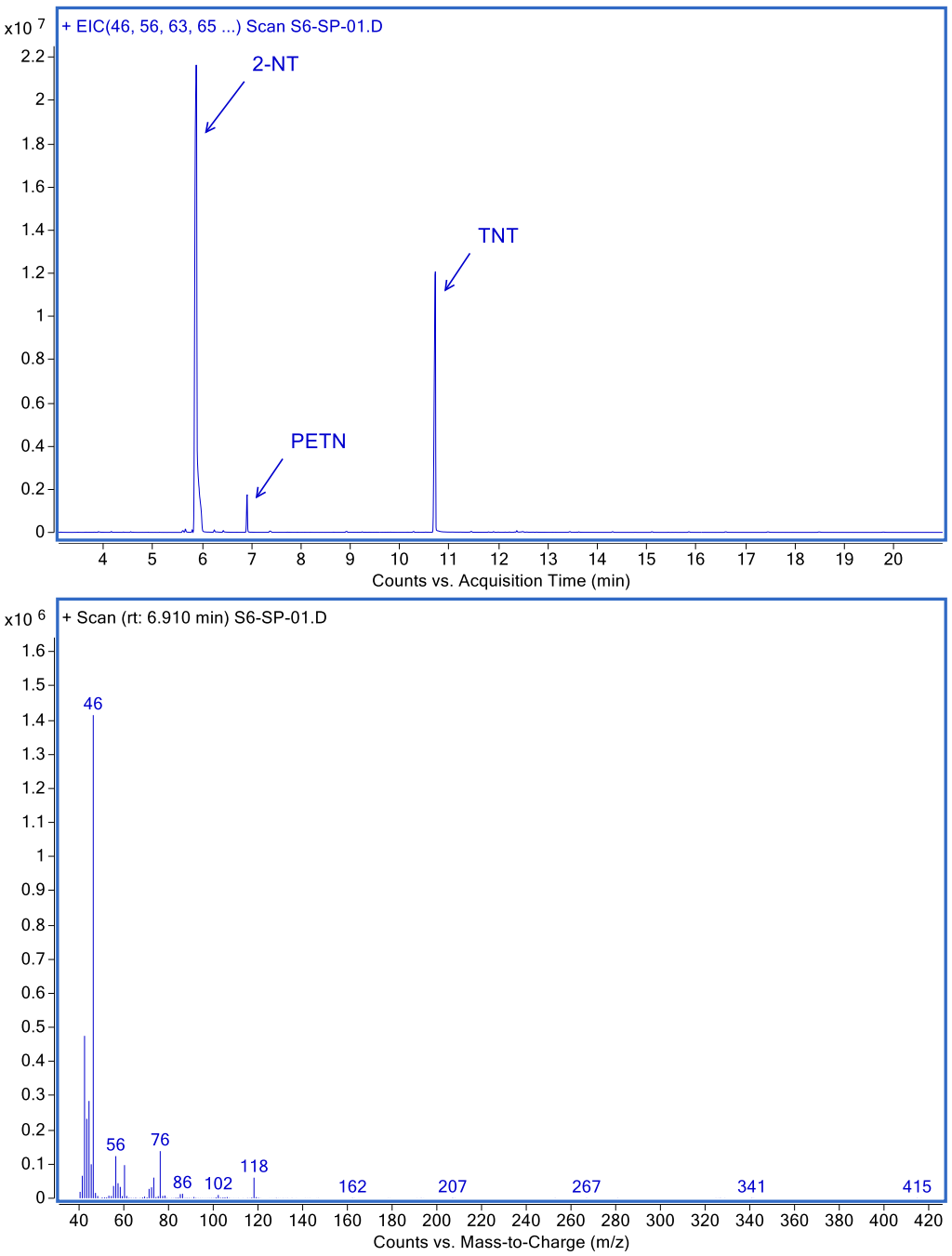

Fig. 4. Total ion chromatogram (TIC) of a mixture of TNT, PETN, and 2-NT extracted from a gelatin hydrogel–collected sample (Plastic-Semi porous substrate), and the EI–MS spectrum of PETN, with major ions labeled at *m/z* 240, 194, 149, 97, 76, 57, 55, and 46 (NIST 14 library match). (Supplementary Fig. S8).

organized structures. These microminiature features are crucial for strengthening the mechanical properties and biological performance of gelatin-based hydrogels for post-blast residue collection capability.

Microstructural characteristics of five compositions of GHs were evaluated *(*Figs. 6–7 *&* Figures S3-S5*)* by Scanning Electron Microscopy (SEM) and surface morphology and network architecture across the various formulations. The compositional variation impacted the GHs structure. The higher Gelatin content exhibited denser and more interconnected networks contrary to that with lower one being more porous and loosely organized structures. These microminiature features are crucial for strengthening the mechanical properties and biological performance of gelatin-based hydrogels for its post blast residue collection capability.

4.4. Discussion

This study demonstrates the effectiveness of gelatin-based hydrogels (GHs) as a novel medium for simultaneous and effective recovery of organic explosives (TNT, PETN, and 2-NT in mixtures) from diverse simulated post-blast surfaces, addressing the need of trace collection of explosive residues for forensic post-blast investigations.

The superior performance of GHs is attributed to their dual adsorbent/absorbent properties, enabling enhanced surface contact and residue entrapment compared to traditional swabbing methods [11]. GC-MS analysis confirmed high sensitivity, with characteristic ion peaks for TNT (210, 193, 180), PETN (240, 194, 149), and 2-NT (137, 120, 91) clearly identified (Figs. 3–5). The splitless injection mode with

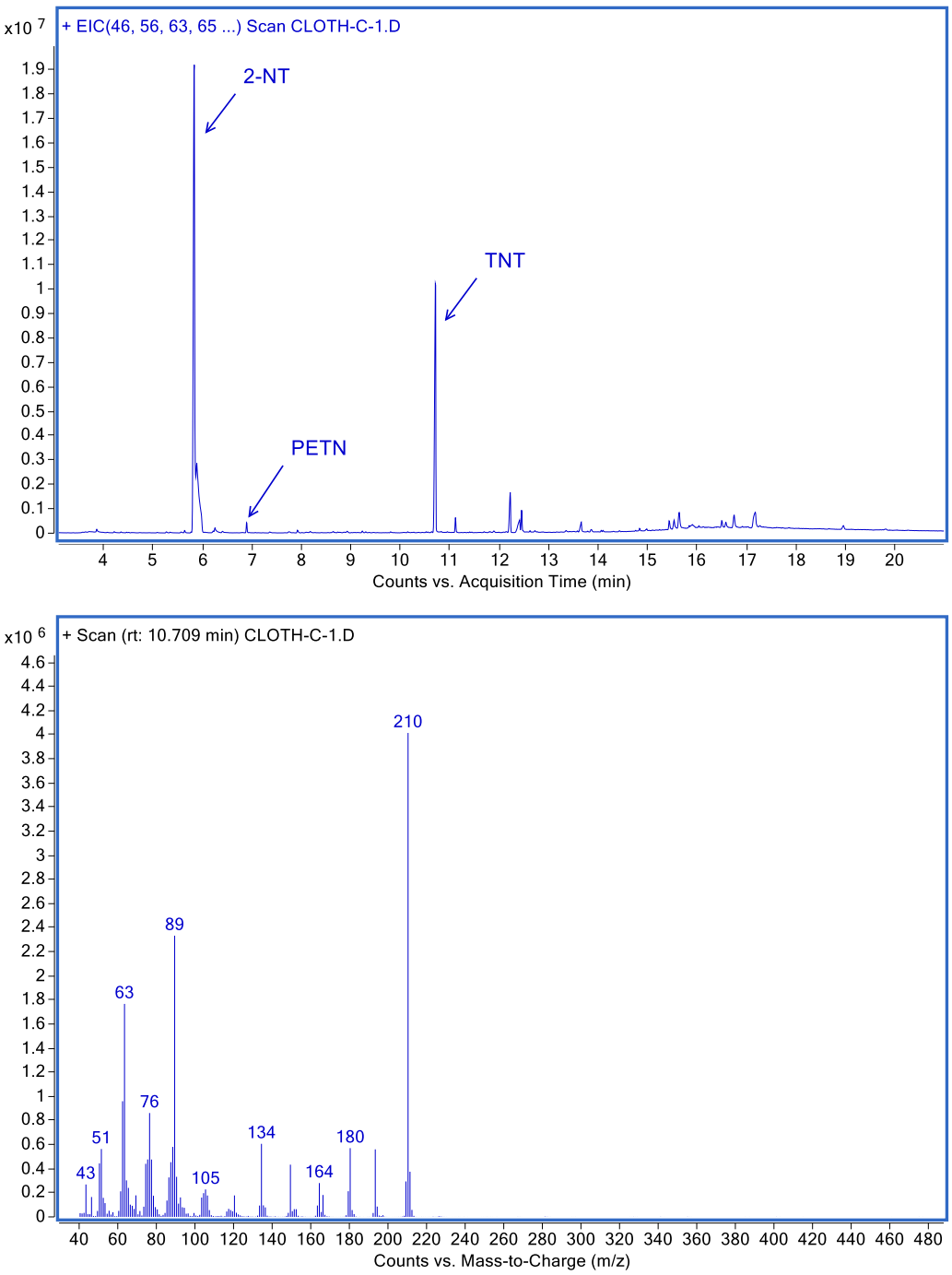

Fig. 5. Total ion chromatogram (TIC) of mixture of TNT, PETN and 2-NT extracted from a gelatin hydrogel–collected sample (contaminated cloth -porous substrate), and the EI–MS spectrum of 2-NT, with major ions labeled at *m/z* 137, 120, 92, 91, 89, 77, 65, and 39 (NIST 14 library match). (Supplementary Fig. S9).

purge split ratio of 50:1 ensured optimal trace detection without tailing. A representative chromatogram from a gel-collected sample (TNT from aluminum, precleaned) compared to a standard showed no additional peaks attributable to the gel, confirming its compatibility with GC-MS analysis. The reproducible preparation of GH-1 (CV = 4.4 %, Section 4.2) ensured consistent performance across experiments. The 30-minute evaporation period after spiking simulated residue stabilization for lab analysis, while the second 500 µL acetone application mimicked post-blast residue dispersion [2]. The sequential triple extraction of the organic layer (0.8–1.0 mL ethyl acetate) from the same tube minimized analyte loss, enhancing analytical sensitivity. The absence of interfering peaks in GC-MS chromatograms from gel-collected samples compared to standards (Figure S6) and the use of sterile preparation protocols (Section 3.2) suggest minimal contamination risks, though direct contamination studies are needed to confirm this under varied forensic conditions. While recovery rates on cloth remained higher than those achieved by swabbing, these findings highlight the need for further optimization of GH formulations to enhance penetration into highly porous matrices. Importantly, the limit of detection for TNT (0.1 µg/mL) exceeded that of swabbing (0.5 µg/mL) and matched that of solid-phase microextraction, confirming the forensic sensitivity of this approach. Simulated real-world conditions using non-precleaned surfaces contaminated with dust, soil, and oil resulted in overall slightly lower recoveries (8–15 %) compared to precleaned surfaces, particularly on

Table 2
Target Surfaces Physical Characters.

Surface Type	Classification
Leather	Porous
PVC Panel	Non-porous
Ceramic Tile (Glazed)	Non-porous
Carpet	Porous
Metal	Non-porous
ABS	Non-porous
Wood	Porous
Artificial Granite	Semi-porous
Glass	Non-porous
Marble (Unpolished)	Semi-porous
Cloth	Porous

Table 3
Gel Optimization Parameters Results.

Sr #	Gelatin Based Hydrogels (GH)	Composition (Gelatin: Starch: Water) w/w	Physical Appearance	Approx. Settling time (minutes)	Comments
1	GH-1	4:2:4	Moderately thick	15± 2	Suitable
2	GH-2	5:7:3	Very Thick	5± 2	Not Suitable
3	GH-3	6:1:3	Very Thick	3± 2	Not Suitable
4	GH-4	3:3:8	Dilute	20± 2	Not Suitable
5	GH-5	1:5:10	Very Dilute	25± 2	Not Suitable

Table 4
Peak Heights and Detection Results of Explosive Detected from Surfaces.

Surface Type	Organic Explosive Peak Height (100ug/mL)			Detected/Not Detected
	TNT	*PETN*	*2-NT*	
Explosive Standard	31015132	498767	38627191	Detected
Leather	29473288	466355	35925187	Detected
PVC Panel	30128909	490987	34562781	Detected
Ceramic Tile	29129874	456789	34566668	Detected
Carpet	27095819	476827	35672911	Detected
Metal	29653973	489276	34567819	Detected
ABS (Acrylonitrile Butadiene Styrene)	30892736	456271	35456666	Detected
Wood	28736358	465278	34267889	Detected
Artificial Granite	27826687	487287	36788888	Detected
Glass	29833637	456278	34556779	Detected
Marble	30873839	435484	37672880	Detected

Note: Peak heights for the reference standard (1 mg/mL in methanol) are provided for comparison to calculate recovery rates. The label "100 mg/mL" in the original table was a typographical error and has been corrected to "1 mg/mL" to match the stock concentration used in the methods. Recovery rates were calculated as (surface peak height / standard peak height) × 100 %, yielding averages of 80–95 % on non-porous surfaces and 60–70 % on porous surfaces.

porous materials. However, contaminants did not compromise analyte identification, supporting the robustness of GHs under realistic forensic scenarios. This resilience is especially important, as post-blast evidence is rarely recovered from pristine environments. Despite these promising outcomes, several limitations must be acknowledged. The experiments were conducted under controlled laboratory conditions, which may not fully capture environmental influences such as temperature fluctuations, humidity, or microbial degradation [7]. The study also focused on three explosives, and the applicability of GHs to other energetic compounds remains to be determined. Finally, although effective, the extraction workflow requires careful handling and expertise, which could present challenges for rapid, large-scale deployment. Future work should

Table 5
Percent Recovery of three Analytes from the Extracts obtained from Non-Porous (NP), Semi-Porous, Porous Surfaces & cloths (Contaminated & Non-Contaminated).

Sample	Type	PETN	TNT	2-NT
Reference Standard	-	100.0	100.0	100.0
PVC Panel	Non-porous	90.8	91.8	99.0
ABS	Non-porous	89.1	96.1	100.9
Glass	Non-porous	120.1	104.5	117.0
Ceramic Tiles	Non-porous	94.3	98.0	99.3
Metal	Non-porous	94.1	100.8	101.2
Artificial Granite	Semi-porous	74.1	85.3	90.4
Marble (Unpolished)	Semi-porous	80.9	88.2	94.3
Carpet	Porous	82.4	86.4	91.9
Leather	Porous	90.4	89.5	98.3
Wood	Porous	84.0	87.8	94.9
PVC Panel (Contaminated)	Non-porous	25.1	62.1	50.9
Metal (Contaminated)	Non-porous	88.5	121.1	114.9
Ceramic Tile (Contaminated)	Non-porous	20.4	55.2	48.2
Glass (Contaminated)	Non-porous	100.0	141.2	129.4
ABS (Contaminated)	Non-porous	67.6	105.5	111.5
Cloth (Contaminated)	Porous	Negligible	67.7	51.7
Cloth (Non-Contaminated)	Porous	Negligible	66.4	51.4

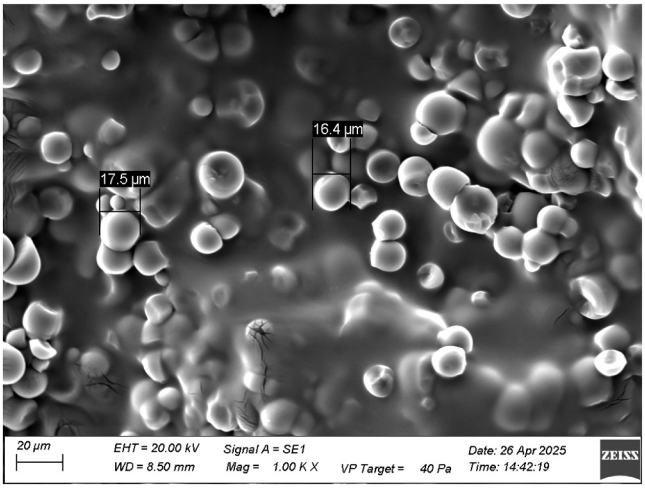

Fig. 6. SEM Images of GH-1.

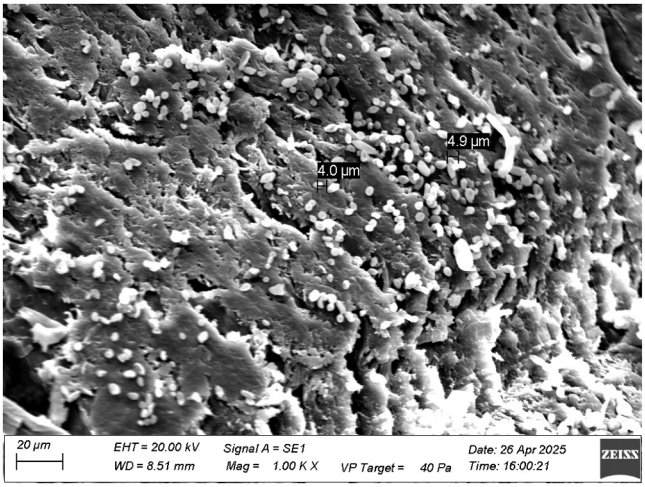

Fig. 7. SEM Images of GH-5.

evaluate GHs under outdoor conditions and across diverse climatic settings, expand testing to a broader spectrum of explosives and matrices, and investigate hydrogel modifications to improve penetration into porous substrates. Incorporating additives or tailoring cross-linking density may enhance matrix compatibility. Moreover, integrating GH-based sampling with portable field-deployable detection platforms could accelerate forensic workflows and reduce reliance on centralized laboratories.

Overall, this study highlights the transformative potential of gelatin-based hydrogels in forensic post-blast residue collection. By offering superior recovery rates, better efficiency in contaminations, and adaptability across a range of surfaces, GHs address critical shortcomings of existing methodologies. Their adoption could significantly improve the accuracy, reliability, and efficiency of post-blast analyses, thereby strengthening forensic investigations, enhancing homeland security, and contributing to public safety.

The SEM images (Fig. 6–10) highlighted specific structural features at a consistent magnification for clarity. The liquid spiking method likely caused explosives to embed into cloth fibers, unlike the surface particulate deposition typical of detonations [2], potentially contributing to lower recoveries. Despite this, GHs outperformed traditional swabs, and minor contaminant interference did not compromise analyte identification, suggesting robust applicability in realistic scenarios. Recovery rates were calculated based on peak heights compared to reference standards, confirming the reported ranges of 80–95 % on non-porous surfaces.

4.5. Limitations

The study was conducted under controlled lab conditions, which may not fully replicate the chemical complexity of a real post-blast residues, which often contain combustion/detonation by-products and substrate relating interferences. The partial co-elution of 2-NT and reduced PETN response observed under contaminated conditions, require further need for future validation investigating actual samples recovered from the post detonation events.

The liquid spiking method may embed explosives into porous materials, like cloth, differing from detonation-induced particulate deposition, potentially reducing recovery efficiency. Testing was limited to TNT, PETN, and 2-NT; other explosives (e.g., RDX, TATP) should be evaluated. Gel preparation requires controlled conditions (e.g., 75°C, sterilized equipment), and prolonged storage (>6 s) may cause hardening, however this problem can be resolved by sonicating the gel for 10 min at 40 °C in 50 mL polypropylene tubes. (Section 4.5). The sequential triple extraction, while effective, requires careful pipetting, which could be challenging in field settings without trained personnel. Slight viscosity variations in gel preparation (CV <7 %, Section 4.2) may affect performance on porous surfaces, necessitating standardized protocols. Although no gel-related interference was observed in GC-MS analysis (Figs. 3–5), further validation with diverse matrices is needed to confirm compatibility in complex forensic samples. Table 5 shows recoveries exceeding the acceptable limits for 2-NT and TNT, which may be attributed to co-extracted organic residues (matrix components) from the surfaces of non-porous substrates (e.g., glass, metal, ABS). These residues can increase analyte peak intensities by generating the same quantifier ions as TNT and 2-NT, resulting in higher peak responses compared to reference standards prepared in pure solvent. Further validation is needed to confirm the compatibility of the method with complex forensic samples.

4.6. Field applicability and storage considerations

To evaluate the feasibility of preparing gelatin-based hydrogels (GHs) for later use in forensic settings, preliminary storage tests were conducted on GH-1 (4:2:4 ratio). After preparation (Section 3.2), the gel was placed at ambient temperature and stored in sterile, airtight 50 mL polypropylene tubes (Falcon) for up to 72 h. Stability was assessed by measuring viscosity (Brookfield DV-II+ Pro viscometer, 25°C) and residue recovery efficiency on aluminum and cloth surfaces (spiked with 1 mg/mL TNT, PETN, 2-NT). Gels stored for 72 h retained 95–98 % of their original viscosity and achieved recovery rates of 78–93 % on non-porous surfaces and 58–68 % on porous surfaces, comparable to freshly prepared gels (80–95 % and 60–70 %, respectively). After 72 h, viscosity decreased by 10–15 %, and recovery efficiency dropped to 70–85 % (non-porous) and 50–60 % (porous), indicating gel hardening and reduced effectiveness. Storage beyond 72 h is not recommended without stabilizing additives.

For field deployment, pre-prepared GHs can be transported in portable container and if hardened, a 10 min sonication (a portable sonicator is recommended) at 40°C will bring back the gel into fluid form, which can be applied at crime scenes within 72 h to maintain efficacy. Gels were tested under simulated field conditions (25°C, 40 % humidity) and on non-precleaned surfaces, showing robust performance despite minor interference from contaminants (Section 4.3). The 30-minute evaporation period after spiking simulates residues stabilized at a crime scene before transport to a lab, supporting the applicability of GHs in field-to-lab workflows. The sequential triple extraction process enhances recovery efficiency, though it requires careful handling under contaminated field conditions.

The reproducible preparation of GH-1 (CV = 4.4 %, Section 4.2) ensures consistent performance, but slight batch-to-batch variations may require standardized protocols for widespread forensic use. Fresh preparation remains optimal for maximum recovery, but pre-prepared gels offer practical advantages for forensic practitioners, enabling rapid deployment in time-sensitive investigations. To enhance storage duration and performance in contaminated environments, future studies should explore additives such as glycerol or antimicrobial agents and validate GH performance in real-world post-blast scenarios (e.g., 10–40°C, 20–80 % humidity). The GH method is primarily designed for laboratory-based GC-MS analysis, with samples transported from crime scenes to centralized facilities (Section 3.2). Preliminary storage tests (72 h at ambient temperature, 95–98 % viscosity retention) support field applicability for short-term transport in portable airtight container. Coupling with field-portable GC-MS systems is feasible but requires further development, such as simplified extraction protocols and integration with compact, ruggedized GC-MS units (e.g., Griffin G510, FLIR Systems). Future studies should validate GH performance with portable systems to enable on-site analysis, reducing transport delays and enhancing rapid response in forensic investigations.

5. Conclusion

Gelatin-based hydrogels (GHs) offer a novel, biocompatible, and cost-effective solution for the collection of organic explosive residues, such as TNT, PETN, and 2-NT, from diverse post-blast surfaces.

The dual adsorbent/absorbent properties of GHs, optimized in the 4:2:4 formulation (GH-1), enhance surface contact and improve recovery efficiency under contaminated conditions, making them suitable for post-blast collection of explosive residues.

Our findings demonstrate that GHs achieved recovery rates of 80–95 % on non-porous and semi-porous surfaces and 60–70 % on porous substrates, surpassing the 50–70 % typically obtained by traditional swabbing techniques. GC-MS validation confirmed high sensitivity, with limits of detection between 0.1 and 0.5 μg/mL and signal-to-noise ratios exceeding 3:1, highlighting the analytical reliability of this approach. In addition to superior efficiency, GHs offer field applicability due to their simplicity and lower cost. Preliminary cost estimates suggest GHs cost ~USD$ 0.50 per sample compared to ~USD $ 2.00 for swabs, based on material costs for gelatin, starch, and solvents (Supplementary Table TS1).

Despite these advantages, the study identified important challenges. Recovery was lower on porous materials, likely due to residue

embedding during liquid spiking and limited penetration of the hydrogel network into cloth fibers. Furthermore, the research was conducted under controlled laboratory conditions, which may not fully replicate real-world environments influenced by temperature, humidity, or microbial activity. The study also focused on only three explosives, leaving open questions regarding applicability to other energetic materials, such as RDX and TATP. These limitations underscore the need for further validation.

Future research should therefore test GHs under realistic outdoor conditions, including controlled detonations that generate particulate deposition, and expand analyte coverage to include a wider range of explosives and matrices. Modifications to hydrogel composition, such as incorporating additives to enhance penetration into porous materials or improve storage stability, could further optimize performance. Moreover, integration of GH-based sampling with portable analytical tools would increase their utility in field settings, bridging laboratory innovation with operational forensic practice.

Overall, this study highlights the transformative potential of GHs in post-blast residue collection. By offering superior recovery, efficient performance in the presence of contamination, cost-effectiveness, and compatibility with diverse surfaces, GHs address longstanding limitations of traditional sampling methods. Their application extends beyond forensic casework to homeland security and environmental monitoring, offering a robust tool for detecting illicit activities and protecting public safety. As forensic science continues to evolve, the adoption of GHs into routine practice represents a sustainable and impactful advancement that enhances the accuracy, reliability, and efficiency of post-blast residue analysis, ultimately contributing to more effective crime resolution and global security.

CRediT authorship contribution statement

Hongbo Wang: Writing – review & editing. **Feras Khalid:** Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Syed Mujeebuddin:** Writing – review & editing, Writing – original draft. **Khaled Masoud:** Writing – review & editing, Writing – original draft. **Elamin Elkhatim Hassan Abdelgadir:** Writing – review & editing, Methodology.

Declaration of Competing Interest

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The authors declare no other competing interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2025.112767.

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