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Forensic Toxicological Verification and Technical Evidence Patterns in Allegations of Chemical Weapon Use: A Retrospective Documentary Analysis of OPCW Fact-Finding Mission Reports

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Özet

Çatışma ortamlarında kimyasal silah kullanım iddialarının adli toksikolojik olarak doğrulanması; gecikmiş saha erişimi, numune bozunması, güvenlik kısıtları ve eksik delil zinciri nedeniyle güçleşmektedir. Bu çalışma, Suriye'ye ilişkin kamuya açık OPCW Olay Tespit Misyonu raporlarında bildirilen teknik kanıt örüntülerini olay düzeyinde incelemiştir. Toplam 44 belge taranmış, olay düzeyinde sonuç içeren 18 nihai veya olaya özgü rapor analize dahil edilmiş ve 25 olay kaydı çıkarılmıştır. Biyomedikal, çevresel, klinik/tıbbi, tanıksal, materyal ve laboratuvar kanıtı olmak üzere altı alan kodlanmıştır. Kayıtların 14'ü pozitif/olası pozitif, 11'i ortaya konulamayan sonuç olarak sınıflandırılmıştır. Ortaya konulamayan sonuçlar üçlü bir adli toksikolojik sınırlılık tipolojisiyle yorumlanmıştır: örnek yetersizliği (Tip A), özgül olmayan toksidrom (Tip B) ve kaynak bağlantısı sınırlılığı (Tip C). Bulgular, doğrulamanın yalnızca klinik belirtilere değil, kimyasal olarak özgül, kaynakla ilişkilendirilebilir ve usule uygun güvenilir teknik kanıtların birlikte değerlendirilmesine bağlı olduğunu göstermektedir.

Çalışmanın Önemi

Bu çalışma, kimyasal silah kullanım iddialarında adli toksikolojik doğrulamanın klinik belirtilerle sınırlı olmadığını göstermektedir. OPCW raporları olay düzeyinde incelenerek biyomedikal, çevresel, klinik, tanıksal, materyal ve laboratuvar kanıtlarının birlikte nasıl değerlendirildiği ortaya konmuştur. Bulgular, zamanında numune alma, delil zinciri ve çok kaynaklı teknik yorumun önemini vurgulamaktadır.

KBRN Hazırlığı | Biyomedikal Kanıt | Çevresel Numuneler | Delil zinciri | Analitik Doğrulama

Abstract

Forensic toxicological verification of alleged chemical weapon incidents is challenging in conflict settings because delayed access, sample degradation, security constraints, incomplete documentation, and chain-of-custody gaps may limit interpretation. This retrospective documentary analysis examined technical evidence patterns in publicly available OPCW Fact-Finding Mission reports on alleged chemical weapon incidents in Syria. Forty-four OPCW-related documents were screened; 18 final or incident-specific reports were included; and 25 incident-level records were extracted. Six domains were coded: biomedical, environmental, clinical/medical, witness/interview, munition/cylinder/remnant, and laboratory evidence. Fourteen records were classified as positive/likely-positive and 11 as not established. Not-established outcomes were interpreted through a three-part forensic-toxicological limitation typology: sample-deficient limitation (Type A), non-specific toxidrome limitation (Type B), and source-linkage limitation (Type C). Positive outcomes were generally supported by chemically specific, source-linked, and procedurally reliable evidence, whereas not-established outcomes commonly reflected unavailable samples, lack of targeted analysis, non-specific toxidromes, limited site access, inconsistent documentation, or weak source linkage. The findings indicate that verification depends on integrated technical evidence patterns rather than clinical symptoms alone.

Significance

This study shows that forensic toxicological verification of alleged chemical weapon use cannot rely on clinical symptoms alone. By examining OPCW Fact-Finding Mission reports at the incident level, it demonstrates how biomedical, environmental, clinical, testimonial, material, and laboratory evidence are evaluated together. The findings highlight the importance of timely sampling, chain-of-custody preservation, and integrated technical interpretation.

CBRN Preparedness | Biomedical Evidence | Environmental Samples | Chain of Custody | Analytical Verification

1. Introduction

Allegations of chemical weapon use in armed conflict create a complex evidentiary problem for forensic toxicology. Unlike routine toxicological casework, investigations in conflict settings are frequently affected by delayed access to the incident site, unstable security conditions, disrupted medical documentation, incomplete sampling, uncertain source linkage, and limited control over the initial collection and preservation of evidence. These constraints are particularly important for volatile, reactive, or non-persistent agents, such as chlorine and other irritant gases, for which direct biological confirmation may be difficult after delayed access. In such settings, the central forensic question is not simply whether a toxic substance can be detected in a single biological or environmental sample, but whether multiple lines of evidence can be integrated to establish that a toxic chemical was used as a weapon.

Analytical verification of chemical warfare agent exposure has historically relied on the complementary use of biomedical and environmental samples. Biomedical matrices can provide evidence of human exposure through parent compounds, metabolites, degradation products, or covalent adducts, whereas environmental samples and material evidence can support scene reconstruction, source linkage, and identification of the agent or its degradation products (Black & Read, 2007; Black, 2010; Witkiewicz & Neffe, 2020). Mass spectrometric approaches, including GC-MS, LC-MS/MS, and LC-HRMS-based methods, have substantially improved the capacity to detect nerve agents, vesicants, and related biomarkers in biological and environmental matrices (Black et al., 1994; Fischer et al., 2017; Witkiewicz & Neffe, 2020). However, the evidentiary value of such findings depends not only on analytical sensitivity and specificity, but also on sampling time, sample stability, storage conditions, chain of custody, and the strength of the link between the sample and the alleged exposure event (Timperley et al., 2018).

The Organisation for the Prohibition of Chemical Weapons (OPCW) Fact-Finding Mission (FFM) in Syria was established to establish facts surrounding allegations of toxic chemical use in the Syrian Arab Republic. The mandate of the FFM is limited to establishing whether toxic chemicals were used as weapons and does not include attributing responsibility for the alleged use (OPCW, 2017b, 2017c). The FFM reports are therefore particularly relevant for forensic toxicology because they document how evidence is collected, evaluated, limited, and integrated in real conflict-related investigations. Across its reports, the FFM repeatedly describes a multi-domain investigative approach, including interviews with casualties, witnesses and medical personnel, review of clinical and hospital documentation, collection or receipt of biomedical and environmental samples, examination of munition or cylinder evidence, and analysis by OPCW or designated laboratories (OPCW, 2017b, 2017c, 2019).

From a forensic toxicological perspective, the Syrian FFM reports provide a unique publicly available dataset. They include positive/likely-positive conclusions involving agents such as sarin, sulfur mustard, chlorine, and reactive chlorine, but they also include incidents in which the available evidence was insufficient to establish that toxic chemicals had been used as a weapon. This combination of positive and not-established outcomes makes the FFM corpus suitable for examining not only what types of evidence support verification, but also what recurring evidentiary gaps prevent a conclusion from being reached.

Agent-specific differences are important in this context. For nerve agents such as sarin, biomedical evidence may include cholinesterase-related markers, protein adducts, urinary metabolites, or other analytically specific indicators of exposure. The forensic verification of fatal sarin poisoning in Syria within an international laboratory network illustrates the value of chemically specific biomarkers and coordinated laboratory confirmation in conflict-related chemical exposure investigations (John et al., 2018). Similarly, sulfur mustard exposure can be retrospectively supported by biomarkers such as thiodiglycol, beta-lyase metabolites, or protein adducts, including albumin-derived adducts detected in real human poisoning cases (John et al., 2019; Steinritz et al., 2016). These approaches show that biomedical evidence can provide high interpretive value when appropriate samples are available and analytically informative.

Chlorine-related allegations present a different challenge. Chlorine is reactive and non-persistent, and its clinical effects, such as coughing, dyspnoea, lacrimation, respiratory distress, and mucous membrane irritation, may overlap with other inhalational irritants or non-chemical causes. Recent studies have explored potential biomedical markers of chlorine exposure, including chlorinated tyrosine adducts, nasal lavage fluid markers, and phospholipid chlorohydrins, but these approaches remain more complex than simply detecting a stable parent compound (de Bruin-Hoegée et al., 2022; Hemström et al., 2024; Lindén et al., 2022). Consequently, chlorine investigations often require broader integration of environmental residues, material evidence such as cylinders or remnants, clinical patterns, witness accounts, and laboratory findings.

Environmental and alternative matrices may also contribute to retrospective verification. Persistent biomarkers in plants have been investigated as indicators of exposure to chemical warfare agents, including sulfur mustard, sarin, and chlorine, suggesting that scene-associated biological or environmental material may retain useful information after direct human samples are unavailable (de Bruin-Hoegée et al., 2023b). Similarly, dried blood spot-based approaches have been proposed to bridge the gap between field collection and laboratory verification of nerve agent biomarkers, highlighting the importance of sampling strategies that are feasible under operational constraints (de Bruin-Hoegée et al., 2023a; Hamelin et al., 2016). These developments are relevant to CBRN preparedness because real-world investigations often depend on what can be collected safely, preserved reliably, and transported under acceptable conditions.

Clinical information remains essential but insufficient on its own. Toxidromes may provide early suspicion and guide emergency response, but signs and symptoms are rarely specific enough to establish chemical weapon use without analytical or material corroboration. This limitation is directly visible in OPCW FFM reports. For example, in the Douma final report, the FFM noted that many reported signs and symptoms indicated exposure to an inhalational irritant or toxic substance, but also stated that, in the absence of biomedical samples from dead bodies or autopsy records, the cause of those signs and symptoms could not be precisely linked to a specific chemical (OPCW, 2019). Conversely, the same report concluded that reasonable grounds existed for the use of a toxic chemical as a weapon only after integrating witness testimony, environmental and biomedical sample analysis, toxicological and ballistic expert assessments, digital information, and cylinder-related evidence (OPCW, 2019).

In this context, first-contact healthcare personnel, emergency medical services, first responders, and treating physicians have a practical evidentiary role in addition to their clinical role. Early documentation of time of exposure, presenting symptoms, treatment, decontamination procedures, casualty transfer, clothing or personal effects, and potential secondary contamination can help preserve information that may later support forensic interpretation. These responsibilities are consistent with quality-assured forensic and CBRN practice, in which standardized documentation, traceability, validated procedures, chain-of-custody awareness, and safe handling of potentially contaminated material are necessary for reliable downstream analysis (Fischer et al., 2017; Timperley et al., 2018).

Despite the scientific and legal relevance of OPCW FFM reports, their forensic toxicological evidence patterns have rarely been examined as a structured incident-level dataset. Existing discussions often focus on individual events, analytical methods, chemical agents, or political and legal consequences. A document-based forensic toxicology analysis allows a narrower technical question to be addressed: which evidence domains are associated with positive/likely-positive verification outcomes, and which evidentiary limitations are repeatedly associated with not-established outcomes?

This study was therefore designed as a retrospective documentary analysis of publicly available OPCW FFM reports on alleged chemical weapon incidents in Syria. The unit of analysis was the alleged incident rather than the report itself. The aim was to characterize forensic toxicological evidence patterns reported in these documents and to compare evidence profiles between positive/likely-positive verification outcomes and not-established outcomes. The technical contribution of this study is the structured coding of forensic-toxicological evidence domains and the development of a descriptive evidence-convergence framework for CBRN-related documentary investigations. The framework is empirical for this dataset, but it is conceptually aligned with holistic forensic reconstruction and data-fusion logic, where independent evidence streams are interpreted together rather than in isolation. This study does not reassess legal responsibility, perpetrator attribution, or the validity of OPCW conclusions. Instead, it examines how biomedical, environmental, clinical, testimonial, material, and laboratory evidence were reported, and how their convergence or absence shaped forensic toxicological interpretation.

2. Material and Method

2.1. Study design

This study was designed as a retrospective documentary analysis of publicly available reports issued by the Organisation for the Prohibition of Chemical Weapons Fact-Finding Mission in Syria. The analysis focused on forensic toxicological evidence patterns in alleged chemical weapon incidents. The unit of analysis was the alleged incident rather than the report itself.

The study did not aim to reassess legal responsibility, perpetrator attribution, military causation, or political interpretation of the incidents. It was limited to the structured extraction and comparison of biomedical, environmental, clinical, testimonial, material, and laboratory evidence as reported in OPCW FFM documents.

2.2. Data source and document identification

The data source consisted of publicly available OPCW documents related to the Fact-Finding Mission in Syria. A total of 44 PDF documents were screened. These included final FFM reports, interim reports, summary updates, corrigenda, Director-General statements, future-activity documents, security updates, confidentiality-related documents, and other FFM-related technical documents.

The initial document set was assembled from the OPCW Fact-Finding Mission document list and included documents available up to 31 March 2026. Although the screening boundary extended to 2026, the main analytical dataset was restricted to final or incident-specific FFM reports that contained incident-level findings and conclusions; these included reports were published between 2014 and 2024. Summary updates, corrigenda, administrative notes, security updates, and documents without incident-specific verification outcomes were excluded from the primary dataset. The document screening process and construction of the incident-level analytical dataset are shown in Figure 1.

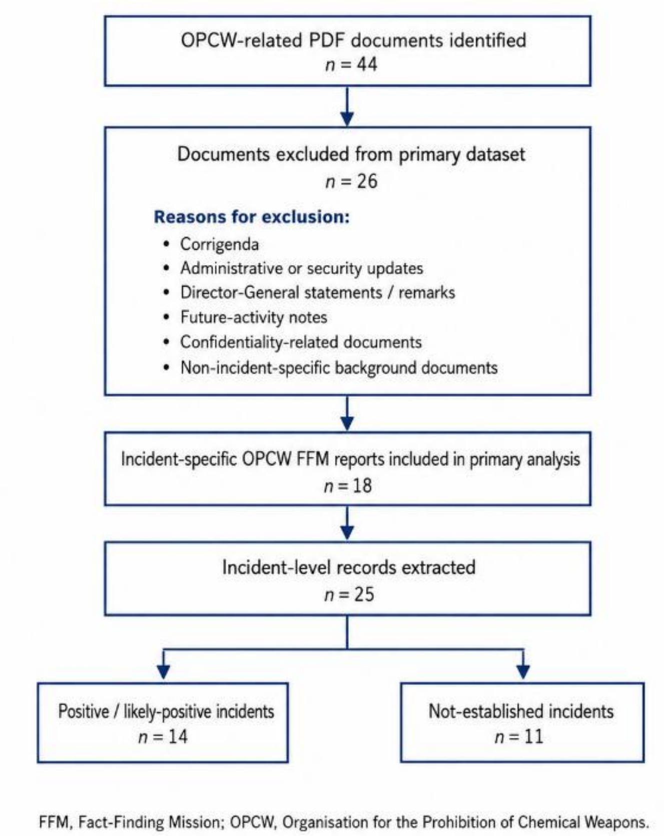

Figure 1. Flow diagram of document screening and incident-level dataset construction. A total of 44 OPCW-related PDF documents were screened. Administrative updates, corrigenda, Director-General statements or remarks, security updates, future-activity notes, confidentiality-related documents, and other non-incident-specific background documents were excluded from the primary analysis. Final or incident-specific OPCW Fact-Finding Mission reports were retained. From these reports, 25 incident-level records were extracted; 14 were classified as positive/likely-positive and 11 as not established. Abbreviations: FFM, Fact-Finding Mission; OPCW, Organisation for the Prohibition of Chemical Weapons.

2.3. Eligibility criteria

Documents were included in the primary dataset if they met all of the following criteria: (1) the document was a publicly available OPCW FFM report; (2) the document addressed one or more alleged chemical weapon incidents in Syria; (3) the document contained incident-specific findings; (4) the document reported an explicit verification outcome or conclusion; and (5) the document included information relevant to forensic toxicological interpretation, such as sample availability, biomedical evidence, environmental evidence, clinical documentation, witness accounts, munition or cylinder evidence, or laboratory analysis.

Documents were excluded from the primary dataset if they were corrigenda, administrative updates, Director-General statements, general security updates, future-activity notes, confidentiality-related documents, or documents that did not contain incident-specific verification outcomes. Corrigenda were used only to correct information in the corresponding main report and were not counted as separate analytical records. When interim and final reports existed for the same incident, the final report was used as the primary source. Interim reports or later updates were consulted only for contextual understanding and were not counted as separate incident records.

2.4. Incident-level dataset and outcome classification

The final analytical dataset consisted of 25 incident-level records extracted from 18 final or incident-specific OPCW FFM reports. In most cases, the incident could be coded as a specific location and date. In early FFM reports where allegations were presented as location-based clusters rather than fully separated event-level records, the cluster was retained as the analytical unit. This conservative approach was adopted to avoid over-disaggregation and potential double counting.

Verification outcomes were classified into two analytical categories: positive/likely-positive and not established. Incidents were classified as positive/likely-positive when the FFM concluded that a toxic chemical was used, likely used, very likely used, more than likely used, or when the report stated that there were reasonable grounds to believe that a toxic chemical was used as a weapon. Incidents were classified as not established when the FFM concluded that the available information was insufficient to determine whether toxic chemicals had been used as a weapon, or when a specific chemical could not be confidently identified or linked to the reported event. This classification was used only for descriptive comparison and did not modify, reinterpret, or re-grade OPCW conclusions.

2.5. Data extraction and evidence-domain coding

A structured coding sheet was developed before data extraction. For each incident-level record, the following variables were extracted: report symbol, publication year, incident date or period, incident location, suspected or identified agent category, FFM conclusion or verification wording, analytical dataset classification, biomedical evidence, environmental evidence, clinical or medical documentation, witness or interview evidence, munition/cylinder/remnant evidence, OPCW or designated laboratory analysis, reported fatalities or casualties where available, site-access limitations, chain-of-custody or source-linkage limitations, and the principal forensic-toxicological limitation.

Six evidence domains were coded: biomedical evidence, environmental evidence, clinical or medical documentation, witness or interview evidence, material evidence, and laboratory analysis. Biomedical evidence referred to blood, urine, plasma, tissue, autopsy material, post-mortem specimens, or other biological samples collected, received, analysed, or discussed in relation to the incident. Environmental evidence referred to soil, surface wipes, clothing, vegetation, environmental residues, scene-related samples, or other environmental material connected to the alleged incident. Clinical or medical documentation referred to hospital records, admission records, physician reports, treatment records, clinical signs and symptoms, autopsy reports, or other medical documentation. Witness or interview evidence referred to interviews with casualties, witnesses, first responders, treating physicians, medical personnel, or other relevant individuals. Material evidence referred to munition remnants, cylinders, projectiles, devices, fragments, craters, or other delivery-system evidence. Laboratory analysis referred to OPCW Laboratory, OPCW-designated laboratory, or other reported analytical testing of biomedical, environmental, or material samples.

Each domain was coded as Y, P, or N: Y indicated that the evidence domain was clearly present, analysed, or used; P indicated that it was partially present, indirect, limited, not decisive, or affected by major analytical, source-linkage, or chain-of-custody limitations; and N indicated that it was not available, not reported, or not used. When evidence was available but not decisive, not directly source-linked, not available for targeted toxicological analysis, or affected by major limitations, the domain was coded as partial.

2.6. Forensic-toxicological evidence convergence score

For descriptive purposes, a six-domain forensic-toxicological evidence convergence score was developed. One point was assigned for each evidence domain coded as clearly present (Y). A half point was assigned for each domain coded as partial (P). No point was assigned for domains coded as absent or unavailable (N). The maximum possible score was 6.0.

The score was designed only to summarize the degree of reported evidence convergence across incident-level records. It was not intended to serve as an official OPCW metric, a legal standard of proof, a measure of causality, or a tool to reclassify verification outcomes. A higher score indicated that more evidence domains were reported, but it did not necessarily indicate that the evidence was chemically specific or sufficient for a positive verification outcome. The equal weighting of evidence domains was intentionally simple and descriptive and should not be interpreted as reflecting the legal or toxicological weight of each evidence type. Because an analytically confirmed biomarker or OPCW-designated laboratory result carries greater probative value than nonspecific clinical documentation or witness testimony, the numerical score was always interpreted together with qualitative specificity, source linkage, and procedural reliability. This approach was used to prevent false score inflation, whereby several low-specificity domains could mimic high convergence without analytically robust support.

2.7. Handling of clustered, overlapping, and ambiguous records

Some early OPCW FFM reports presented allegations by location or incident cluster rather than as fully separated event-level records. These reports were not split into more detailed event-level units unless the document itself provided sufficient incident-specific information. This approach was used to preserve consistency with the structure of the source documents and to avoid double counting.

When the same incident appeared in more than one OPCW document, the most complete final or incident-specific report was used for the primary dataset. Corrigenda were not counted as separate documents but were considered where they corrected factual information in the main report. Summary updates were excluded from the primary analysis unless they clarified the status of reports already included in the dataset.

Because the study was conducted by a single author, coding consistency was addressed through repeated extraction and verification against report summaries, methodological sections, conclusion sections, and annexes where available. Ambiguous cases were coded conservatively as partial rather than clearly present. The coding process did not attempt to verify the underlying factual accuracy of OPCW findings; it analysed how evidence was reported, structured, and used within the publicly available documents.

2.8. Data analysis, ethics, and data availability

Data were analysed descriptively. Categorical variables were summarized as frequencies and percentages. Evidence domains were compared between positive/likely-positive and not-established outcomes. Because the evidence convergence score was ordinal, descriptive, and based on a small document-derived dataset, medians and ranges were emphasized. A Mann-Whitney U test was used as an exploratory non-parametric comparison of score distributions between outcome groups; the result was interpreted cautiously and did not imply causality or reclassification of any OPCW conclusion. The analysis focused on identifying recurring forensic-toxicological evidence patterns and limitations across the incident-level records.

This study used publicly available institutional documents and did not involve direct interaction with human participants, collection of personal data, biological sampling, intervention, or access to confidential records. Therefore, ethics committee approval was not required. The source documents analysed in this study are publicly available OPCW FFM reports. The coded dataset generated during the study can be made available by the author upon reasonable request.

3. Results and Discussion

3.1. Document screening and incident-level dataset construction

A total of 44 OPCW-related PDF documents were screened. Documents without incident-specific verification outcomes, including corrigenda, administrative updates, Director-General statements, future-activity notes, security updates, confidentiality-related documents, and non-incident-specific background documents, were excluded from the primary analytical dataset. Corrigenda were used only to correct information in the corresponding main reports and were not counted as separate records.

The final dataset consisted of 25 incident-level records extracted from 18 final or incident-specific OPCW Fact-Finding Mission reports. The included records covered alleged incidents occurring between 2014 and 2018. Although the overall document screening boundary extended to 31 March 2026, the included final or incident-specific reports were published between 2014 and 2024 because later documents were administrative, security-related, corrective, or non-incident-specific and did not add new incident-level verification outcomes. In most cases, the analytical unit was a specific location and date. In early reports where allegations were presented as location-based clusters rather than fully separated incident-level records, the cluster was retained as the analytical unit to avoid over-disaggregation.

Of the 25 incident-level records, 14 were classified as positive/likely-positive, and 11 were classified as not established. Positive/likely-positive records included incidents involving chlorine or reactive chlorine, sarin, and sulfur mustard or sulfur mustard-related vesicant agents. Not-established records primarily involved allegations of unknown toxic gases, non-specific irritant exposures, or chlorine-related allegations where the available evidence was insufficient to determine chemical use as a weapon. The core incident-level dataset is presented in Table 1.

3.2. Verification outcomes by chemical agent category

Chlorine or reactive chlorine was the most frequent agent category among positive/likely-positive records. Chlorine-related positive records included the early 2014 cluster involving Talmenes, Al Tamanah, and Kafr Zeita; the Idlib Governorate 2015 cluster; Kafr Zeita in 2016; Ltamenah Hospital in 2017; Saraqib in 2018; and Douma in 2018. In the Douma final report, the FFM concluded that the toxic chemical contained reactive chlorine and was likely molecular chlorine after integrating witness testimony, environmental and biomedical sample analysis results, toxicological and ballistic expert analyses, and additional digital information (OPCW, 2019).

Sarin-related positive records included Khan Shaykhun on 4 April 2017, Ltamenah on 24 March 2017, and Ltamenah on 30 March 2017. In the Khan Shaykhun investigation, the FFM attended autopsies, witnessed the collection of biomedical specimens, and transferred specimens to the OPCW Laboratory, where they were split according to OPCW procedures and sent to designated laboratories (OPCW, 2017b). In the Ltamenah 30 March report, the FFM concluded that sarin was more than likely used as a chemical weapon after considering the presence of sarin in samples from the alleged site, clinical consistency with sarin exposure, and munition parts consistent with chemical weapon application (OPCW, 2017c).

Sulfur mustard or vesicant-related positive records included Marea, Um-Housh, and Marea on 1 September 2015. The Um-Housh report confirmed exposure of two casualties to sulfur mustard and reported that a 217-mm mortar associated with the incident contained sulfur mustard (OPCW, 2017a). In the Marea September 2015 investigation, environmental samples from black-substance splatter contained thiodiglycol and thiodiglycol sulfoxide, supporting the conclusion that degradation products of sulfur mustard-related scheduled chemicals were present (OPCW, 2022a).

These patterns show that agent category shaped the evidentiary route to verification. Sarin and sulfur mustard incidents were more likely to involve chemically specific biomedical, environmental, or degradation-product evidence. Chlorine-related incidents, by contrast, often required broader integration of environmental residues, cylinder or munition evidence, clinical irritant patterns, witness accounts, and source-linkage assessment. This distinction is consistent with the broader analytical literature: nerve agents and vesicants can often be investigated through biomarkers, metabolites, or protein adducts, whereas chlorine is reactive and non-persistent, making direct retrospective confirmation more difficult (Black & Read, 2007; Black, 2010; John et al., 2018; John et al., 2019; Witkiewicz & Neffe, 2020).

3.3. Evidence-domain distribution and convergence score

The six-domain evidence convergence score ranged from 1.0 to 6.0 across the 25 incident-level records. In the positive/likely-positive group, scores ranged from 2.0 to 6.0, with a median of 4.5. In the not-established group, scores ranged from 1.0 to 5.0, with a median of 2.5. An exploratory Mann-Whitney U test indicated higher score distributions in the positive/likely-positive group than in the not-established group ($U = 113.0$, $p = 0.047$); however, this statistical result should be interpreted only as a descriptive comparison because the score is not a validated legal or toxicological weighting system

Table 1. Core incident-level records extracted from OPCW FFM reports

No	Source report	Incident / location	Incident date	Agent category	FFM conclusion / verification wording	Dataset classification
1	S/1230/2014	Talmenes	2014 cluster	Chlorine	Chlorine used as a weapon, high degree of confidence	Positive
2	S/1230/2014	Al Tamanah	2014 cluster	Chlorine	Chlorine used as a weapon, high degree of confidence	Positive
3	S/1230/2014	Kafr Zeita	2014 cluster	Chlorine	Chlorine used as a weapon, high degree of confidence	Positive
4	S/1319/2015	Idlib Governorate incidents	16 Mar-20 May 2015	Probably chlorine-containing toxic chemical	Incidents likely involved one or more toxic chemicals, probably containing chlorine	Positive/likely-positive
5	S/1320/2015	Marea	Aug 2015	Sulfur mustard	At least two people exposed to sulfur mustard; baby death very likely related	Positive
6	S/2017/2022	Marea	1 Sept 2015	Vesicant / sulfur mustard-related scheduled chemical	Reasonable grounds that a vesicant chemical substance from 1.A.04 scheduled chemicals was used as a weapon	Positive
7	S/2017/2022	Marea	3 Sept 2015	Vesicant suspected	Similar signs and symptoms, but available data did not allow establishment of chemical use	Not established
8	S/1444/2016	Al-Awamid, Aleppo	2 Aug 2016	Non-specific irritant / unknown	Specific chemical could not be confidently determined	Not established
9	S/1901/2020	Saraqib	1 Aug 2016	Non-specific irritant / chlorine alleged	Irritant toxidrome suspected, but chemical use as a weapon could not be established	Not established
10	S/1491/2017	Um-Housh	16 Sept 2016	Sulfur mustard	Two casualties exposed to sulfur mustard; mortar determined to contain sulfur mustard	Positive
11	S/2020/2022	Kafr Zeita	1 Oct 2016	Chlorine	Reasonable grounds that a chlorine cylinder was used as a weapon	Positive
12	S/1642/2018	Al-Hamadaniyah	30 Oct 2016	Non-specific irritant / unknown	Specific chemical use as a weapon could not be confidently determined	Not established
13	S/1642/2018	Karm al-Tarrab	13 Nov 2016	Non-specific irritant / unknown	Specific chemical use as a weapon could not be confidently determined	Not established
14	S/1636/2018	Ltamenah, south	24 Mar 2017	Sarin	Sarin was very likely used as a chemical weapon	Positive
15	S/1636/2018	Ltamenah Hospital and surrounding area	25 Mar 2017	Chlorine	Chlorine was very likely used as a chemical weapon	Positive
16	S/1548/2017	Ltamenah, south	30 Mar 2017	Sarin	Sarin was more than likely used as a chemical weapon	Positive
17	S/1510/2017	Khan Shaykhun	4 Apr 2017	Sarin / sarin-like substance	Sarin used as a chemical weapon	Positive
18	S/2186/2023	Kharbit Massasneh	7 Jul 2017	Unknown / non-specific irritant alleged	Not sufficient reasonable grounds to determine toxic chemical use as a weapon	Not established
19	S/2186/2023	Kharbit Massasneh	4 Aug 2017	Unknown / non-specific irritant alleged	Not sufficient reasonable grounds to determine toxic chemical use as a weapon	Not established
20	S/2295/2024	Qalib al-Thawr	9 Aug 2017	Unknown toxic gas alleged	Not sufficient reasonable grounds to determine toxic chemical use as a weapon	Not established
21	S/2254/2024	Al-Yarmouk, Damascus	22 Oct 2017	Unknown toxic gas alleged	Not sufficient reasonable grounds to determine toxic chemical use as a weapon	Not established
22	S/2295/2024	Al-Balil, Souran	8 Nov 2017	Unknown / poisonous gas alleged	Not sufficient reasonable grounds to determine toxic chemical use as a weapon	Not established
23	S/1626/2018	Saraqib, Al Talil neighbourhood	4 Feb 2018	Chlorine	Chlorine released from cylinders through mechanical impact was likely used as a chemical weapon	Positive/likely-positive
24	S/1731/2019	Douma	7 Apr 2018	Reactive chlorine / likely molecular chlorine	Reasonable grounds that a toxic chemical was used as a weapon; likely molecular chlorine	Positive
25	S/1902/2020	Aleppo / Al-Khalidiyah and surroundings	24 Nov 2018	Non-specific irritant / chlorine alleged	Available information did not allow establishment of chemical use as a weapon	Not established

Positive/likely-positive incidents generally showed higher evidence convergence, particularly when biomedical or environmental evidence was combined with clinical documentation, witness or casualty interviews, munition/cylinder/remnant evidence, and OPCW or designated laboratory analysis. The highest-scoring positive records were Um-Housh and Douma, both of which reached the maximum score of 6.0. Evidence-domain coding and convergence scores are shown in Table 2.

However, the presence of multiple evidence domains did not automatically correspond to a positive verification outcome. Several not-established incidents had relatively high convergence scores because interviews, medical documentation, environmental or material evidence, and laboratory analysis were present in some form. Nevertheless, the evidence remained analytically non-specific, insufficiently linked to the alleged exposure, or unable to identify a defined chemical agent. This pattern was observed in Al-Awamid, Al-Hamadaniyah, Karm al-Tarrab, and Aleppo/Al-Khalidiyah.

Therefore, verification outcomes were shaped not only by the number of evidence domains present, but also by their specificity, source linkage, chain-of-custody strength, and ability to support a defined toxicological interpretation. This finding is consistent with the broader principle that chemical warfare agent verification depends on the integration of sample type, analytical specificity, sample stability, and evidentiary reliability, rather than analytical detection alone (Black & Read, 2007; Timperley et al., 2018; Witkiewicz & Neffe, 2020).

3.4. Evidence convergence in positive/likely-positive incidents

Positive/likely-positive incidents were generally supported by multiple converging evidence streams. In sarin-related incidents, the evidentiary structure was often chemically specific because biomedical or environmental findings could support a defined nerve-agent exposure interpretation. The Khan Shaykhun investigation is a clear example: biomedical specimens, autopsy-related materials, interviews, supporting documentation, and environmental samples formed a multi-domain evidentiary basis (OPCW, 2017b). This aligns with the forensic literature showing that sarin exposure can be verified through coordinated laboratory analysis of biological markers within an international laboratory network (John et al., 2018).

The Ltamenah investigations also illustrate the importance of convergence between environmental findings, clinical consistency, and material evidence. In the 30 March 2017 incident, environmental samples and alleged munition remnants were received, handled under OPCW procedures, and analysed in designated laboratories; these findings supported the conclusion that sarin was more than likely used as a weapon (OPCW, 2017c). In the 24 and 25 March 2017 incidents, the FFM similarly relied on environmental samples, alleged munition parts, interviews, and designated laboratory analyses to evaluate sarin and chlorine allegations (OPCW, 2018b).

Sulfur mustard-related incidents showed a similar pattern of specificity. In Um-Housh, the FFM reported both biomedical evidence of sulfur mustard exposure and material evidence from a mortar containing sulfur mustard (OPCW, 2017a). This type of convergence is consistent with laboratory studies and real-case reports showing that sulfur mustard exposure may be retrospectively supported by albumin-derived protein adducts and other bioanalytical evidence (John et al., 2019; Steinritz et al., 2016). In Marea, the detection of thiodiglycol and thiodiglycol sulfoxide in environmental samples further illustrates how degradation products can support interpretation when direct parent-agent detection is not available (OPCW, 2022a).

Chlorine-related incidents required a different evidentiary logic. In Douma, the FFM described on-site visits, environmental sample collection and receipt, biomedical sample collection and receipt, witness and casualty interviews, cylinder assessment, and expert analyses in toxicology, ballistics, structural engineering, and metallurgy (OPCW, 2019). The conclusion that reactive chlorine, likely molecular chlorine, had been used as a weapon was not based on clinical symptoms alone, but on the integration of multiple evidence streams. This is important because chlorine exposure biomarkers are more challenging than stable parent-compound detection. Recent studies have explored chlorinated tyrosine adducts, nasal lavage fluid, and phospholipid chlorohydrins as potential approaches for chlorine exposure verification, but these remain analytically specialised and context-dependent (de Bruin-Hoegée et al., 2022; Hemström et al., 2024; Lindén et al., 2022).

3.5. Why evidence-rich incidents can remain not established

A key finding of this analysis is that not-established outcomes were not simply low-information cases. Some not-established incidents included interviews, medical documentation, environmental or material samples, and laboratory activity. However, these evidence domains did not support a chemically specific or source-linked conclusion. This distinction is central to forensic toxicology: the presence of evidence is not the same as the presence of decisive forensic-toxicological evidence.

The not-established cases repeatedly showed similar limitations. These included absence of biomedical samples available to the FFM, lack of targeted analysis of blood samples collected for medical purposes, absence of environmental samples from the incident location or casualty clothing, inability to access unsafe sites, non-specific respiratory or irritant symptoms, and inconsistent accounts of the alleged gas, munitions, casualties, or timing. These limitations are summarized in Table 3.

Table 2. Evidence domains by incident and forensic-toxicological evidence convergence score

No	Incident / location	Outcome	Biomedical	Environmental	Clinical / medical documentation	Witness / interview	Munition / cylinder / remnant	OPCW / designated lab analysis	Score
1	Talmenes	Positive	N	N	P	Y	P	N	2.0
2	Al Tamanah	Positive	N	N	P	Y	P	N	2.0
3	Kafr Zeita, 2014 cluster	Positive	N	N	P	Y	P	N	2.0
4	Idlib Governorate incidents, 16 Mar-20 May 2015	Positive/likely-positive	N	Y	P	Y	Y	Y	4.5
5	Marea, Aug 2015	Positive	Y	N	P	Y	N	Y	3.5
6	Marea, 1 Sept 2015	Positive	N	Y	Y	Y	P	Y	4.5
7	Marea, 3 Sept 2015	Not established	N	N	P	P	N	N	1.0
8	Al-Awamid, Aleppo, 2 Aug 2016	Not established	N	Y	Y	Y	P	Y	4.5
9	Saraqib, 1 Aug 2016	Not established	N	N	Y	Y	P	N	2.5
10	Um-Housh, 16 Sept 2016	Positive	Y	Y	Y	Y	Y	Y	6.0
11	Kafr Zeita, 1 Oct 2016	Positive	N	P	P	Y	Y	Y	4.0
12	Al-Hamadaniyah, 30 Oct 2016	Not established	P	Y	Y	Y	P	Y	5.0
13	Karm al-Tarrab, 13 Nov 2016	Not established	P	N	Y	Y	Y	Y	4.5
14	Ltamenah, 24 Mar 2017	Positive	N	Y	Y	Y	P	Y	4.5
15	Ltamenah Hospital, 25 Mar 2017	Positive	N	Y	Y	Y	Y	Y	5.0
16	Ltamenah, 30 Mar 2017	Positive	N	Y	Y	Y	Y	Y	5.0
17	Khan Shaykhun, 4 Apr 2017	Positive	Y	Y	Y	Y	P	Y	5.5
18	Kharbit Massasneh, 7 Jul 2017	Not established	N	N	Y	Y	N	N	2.0
19	Kharbit Massasneh, 4 Aug 2017	Not established	N	N	Y	Y	N	N	2.0
20	Qalib al-Thawr, 9 Aug 2017	Not established	N	N	Y	Y	N	N	2.0
21	Al-Yarmouk, 22 Oct 2017	Not established	N	Y	N	Y	N	Y	3.0
22	Al-Balil, 8 Nov 2017	Not established	N	N	Y	Y	N	N	2.0
23	Saraqib, Al Talil, 4 Feb 2018	Positive/likely-positive	N	Y	Y	Y	Y	Y	5.0
24	Douma, 7 Apr 2018	Positive	Y	Y	Y	Y	Y	Y	6.0
25	Aleppo / Al-Khalidiyah, 24 Nov 2018	Not established	N	Y	Y	Y	P	Y	4.5

Note. Y = clearly present, analysed, or used; P = partial, indirect, limited, or available with major limitations; N = not available, not reported, or not used. Score: Y = 1, P = 0.5, N = 0. The score is descriptive only and does not reclassify OPCW conclusions.

Table 3. Forensic-toxicological limitations in not-established incidents

No	Incident / location	Report	Site access limitation	Biomedical limitation	Environmental limitation	Clinical / toxidrome limitation	Documentation / consistency limitation	Main forensic-toxicological limitation
1	Marea	S/2017/2022	Not primary issue	Casualties from 3 Sept not available for interview/sample	Limited/no decisive samples for 3 Sept	Similar signs to 1 Sept but not independently verified	Limited casualty access	Similar clinical picture, but insufficient direct evidence to establish chemical use
2	Al-Awamid, Aleppo	S/1444/2016	Limited direct scene access	No biomedical evidence sufficient for specific attribution	Sample results did not identify causal chemical	General clinical presentation consistent with brief irritant exposure but non-specific	Evidence did not support specific agent identification	Specific chemical could not be confidently determined
3	Saraqib	S/1901/2020	FFM could not visit site	No biomedical evidence sufficient for specific attribution	No conclusive environmental evidence	Irritant toxidrome, but substance unidentified	Metal remnants could not be linked to exposure source	Available evidence was insufficient to establish chemical use as a weapon
4	Al-Hamadaniyah	S/1642/2018	Site access and source linkage limited	Available data not sufficient for specific toxicological attribution	Laboratory findings not decisive for weaponized chemical use	Possible non-persistent irritant exposure, but non-specific	Evidence did not allow confident determination	Specific chemical use as a weapon could not be confidently determined
5	Karm al-Tarrab	S/1642/2018	Site/source linkage limited	Available data not sufficient for specific toxicological attribution	Environmental/material findings not conclusive	Possible non-persistent irritant exposure, but non-specific	Evidence did not allow confident determination	Specific chemical use as a weapon could not be confidently determined
6	Kharbit Massasneh	S/2186/2023	Location near confrontation line; unsafe for deployment	Blood samples taken for medical purposes but no targeted analysis; samples not available to FFM	No environmental samples from incident locations or clothing	Symptoms not consistent with a single well-defined toxidrome	No photographs/videos of incident locations or munitions; munitions not retrieved	FFM could not provide toxicological assessment because no targeted biomedical/environmental evidence was available
7	Kharbit Massasneh	S/2186/2023	Location near confrontation line; unsafe for deployment	Blood samples taken but no targeted analysis; samples not available to FFM	No environmental samples from incident location or clothing	Clinical signs not linked to specific chemical class	Photographs/videos and munition evidence insufficient	Available evidence was insufficient to establish toxic chemical use as a weapon
8	Qalib al-Thawr	S/2295/2024	Incident location near confrontation line; unsafe for FFM deployment	Blood samples taken medically but no targeted analysis; not available to FFM	No environmental samples from incident location; uniforms reportedly unavailable/destroyed	Respiratory distress reported, but no well-defined toxidrome	No photos/videos of location or munitions; munition evidence absent	No biomedical or environmental material available for toxicological assessment
9	Al-Yarmouk	S/2254/2024	Field visit occurred to locations of interest, but evidence remained limited	No medical records/supporting documentation available for casualties	Samples did not indicate scheduled chemicals, riot-control agents, chlorinated organic chemicals, or reactive chlorine	Signs/symptoms could not be linked to a specific factor or chemical class	Inconsistent witness accounts, casualty numbers, gas descriptions, and munition descriptions	Available evidence was insufficient to establish toxic chemical use as a weapon
10	Al-Balil	S/2295/2024	Incident location near confrontation line; unsafe for FFM deployment	Blood samples taken medically but no targeted analysis; not available to FFM	No environmental samples or casualty clothing collected	Respiratory distress reported, but no well-defined toxidrome	No photographs/videos of location or munitions	Absence of targeted toxicological evidence prevented chemical attribution
11	Aleppo / Al-Khalidiyah	S/1902/2020	FFM performed field/hospital-related activities, but source linkage could not be established from available information	No biomedical evidence sufficient for specific attribution	Fragments/samples could not establish chemical use as weapon	Mild-to-moderate airway irritation possible, but non-specific	Device/source of dispersion could not be determined	Available evidence was insufficient to establish whether chemicals were used as a weapon

Qalib al-Thawr and Al-Balil provide clear examples. The FFM reported that the incident locations were close to confrontation lines and unsafe for deployment; no photographs or videos of the locations or munitions were available; environmental samples were not collected; and blood samples taken for medical purposes were not subjected to targeted analysis or made available to the FFM. The same report stated that neither environmental nor biomedical samples were available for toxicological assessment and that the information was insufficient to provide reasonable grounds for determining that toxic chemicals were used as a weapon (OPCW, 2024b).

Kharbit Massasneh showed a similar limitation pattern. The FFM reported that the incident locations were unsafe, no environmental samples were collected from the incident sites or casualty clothing, blood samples taken for medical purposes were not subjected to targeted analysis and were not made available to the FFM, and symptoms were not consistent with a single well-defined toxidrome. The report therefore did not provide reasonable grounds to determine that toxic chemicals had been used as a weapon (OPCW, 2023).

Al-Yarmouk further illustrates how analytical and documentary insufficiency can limit interpretation. Although the FFM conducted interviews, reviewed material, performed a field visit to locations of interest, and examined chemical analyses of samples, the report described inconsistent witness accounts, absence of medical records, non-specific signs and symptoms, and analytical results that did not indicate scheduled chemicals, riot-control agents, chlorinated organic chemicals, or reactive chlorine. The available information was therefore insufficient to establish chemical use as a weapon (OPCW, 2024a).

A not-established outcome should therefore not be interpreted as definitive evidence that an alleged exposure did not occur. Rather, within the structure of the FFM reports, it means that the available evidence was insufficient to establish, to the FFM's evidentiary threshold, that a toxic chemical was used as a weapon. This distinction is important because conflict settings often involve delayed access, missing samples, incomplete documentation, degraded evidence, and weak chain-of-custody continuity.

3.6. Forensic-toxicological limitation typology

Across not-established records, three broad limitation types were identified. Type A was a sample-deficient limitation. This pattern occurred when neither biomedical nor environmental samples were available for targeted analysis. Qalib al-Thawr, Al-Balil, and Kharbit Massasneh are representative examples. These incidents show that clinical samples taken for medical purposes have limited forensic value if they are not preserved, made available, or subjected to targeted toxicological analysis.

Type B was a non-specific toxidrome limitation. This pattern occurred when symptoms such as dyspnoea, respiratory irritation, lacrimation, coughing, or loss of consciousness were reported, but the clinical presentation could not be linked to a defined chemical class. This was common in allegations involving unknown toxic gases or non-persistent irritants. Clinical findings are therefore useful for raising suspicion and guiding emergency response, but they are insufficient for chemical weapon verification without analytical or material corroboration.

Type C was a source-linkage limitation. This pattern occurred when material, fragments, munitions, or environmental findings were present but could not be confidently linked to the reported exposure event. This limitation was especially relevant in not-established incidents where samples or fragments were collected after delays, came through indirect chains, or were not clearly connected to the alleged source of dispersion.

These limitations show why forensic-toxicological verification depends on the quality and interpretive value of evidence domains rather than their mere presence. In conflict-related investigations, symptoms may trigger suspicion, but robust conclusions require source-linked, analytically specific, and procedurally reliable evidence.

3.7. Implications for forensic toxicology and CBRN preparedness

The findings have practical implications for forensic toxicology and CBRN preparedness. First, timely access to incident sites remains central. When access is delayed, especially for volatile or reactive chemicals, environmental and biological evidence may degrade or become difficult to interpret. This is particularly relevant for chlorine-related allegations, where direct biological confirmation can be challenging and interpretation may depend on environmental residues, cylinder evidence, and contextual convergence.

Second, targeted sampling is essential. Blood, urine, plasma, tissue, clothing, wipe samples, soil, vegetation, cylinder surfaces, and munition remnants can have forensic value only when collected, documented, preserved, and analysed appropriately. The importance of sample stability and storage has been emphasised by the OPCW Scientific Advisory Board, which highlighted that investigative capability depends not only on analytical methods but also on sample preservation and storage conditions (Timperley et al., 2018).

These findings also have direct relevance for forensic medicine and emergency healthcare. First-contact clinicians and emergency personnel may be the only professionals who observe casualties before evidence degrades, clothing is discarded, decontamination occurs, or patients are transferred. Accurate early clinical documentation, preservation of potential evidence, documentation of treatment and decontamination steps, and awareness of chain-of-custody requirements can therefore improve later forensic case management without interfering with urgent medical care.

Third, alternative and field-adapted sampling strategies may have value in future investigations. Dried blood spots have been proposed as a way to bridge the gap between sample collection and laboratory verification of nerve agent biomarkers, and plant-based persistent biomarkers may support retrospective environmental verification when conventional human samples are unavailable or delayed (de Bruin-Hoegée et al., 2023a, 2023b; Hamelin et al., 2016). These developments are especially relevant for conflict settings, where immediate access to victims or sites may be impossible.

Fourth, the evidence convergence score used in this study may be useful as a descriptive framework for comparing investigations. However, it should not be used as a substitute for expert judgement. A high score does not automatically mean positive verification, and a low score does not automatically exclude exposure. The specificity, reliability, source linkage, and analytical relevance of each evidence domain remain more important than the number of domains alone.

3.8. Overall interpretation

Overall, this analysis shows that OPCW FFM verification outcomes were shaped less by the mere presence of reported symptoms and more by the convergence of chemically specific, source-linked, and procedurally reliable evidence. Positive/likely-positive incidents generally involved stronger integration of biomedical, environmental, clinical, testimonial, material, and laboratory evidence. Not-established incidents generally reflected gaps in evidence availability, analytical specificity, site access, or source linkage.

In conflict-related chemical weapon investigations, forensic toxicological verification is therefore best understood as a process of evidence convergence. Symptoms may raise suspicion, but robust conclusions require timely, source-linked, analytically specific, and procedurally reliable evidence across multiple domains.

4. Conclusion

This retrospective documentary analysis shows that forensic toxicological verification of alleged chemical weapon incidents in Syria depended on the convergence of multiple evidence domains rather than on clinical signs alone. Positive/likely-positive OPCW FFM outcomes were generally associated with analytically meaningful biomedical or environmental evidence, material findings such as cylinders or munition remnants, clinical consistency, witness testimony, and OPCW or designated laboratory analysis. In contrast, not-established outcomes commonly reflected three recurring forensic-toxicological limitation types: sample-deficient limitation (Type A), non-specific toxidrome limitation (Type B), and source-linkage limitation (Type C). This typology represents one of the main technical outputs of the study and helps explain why evidence-rich cases can still remain insufficient for a chemically specific and source-linked verification outcome.

The findings indicate that a not-established outcome should not be interpreted as definitive evidence that an incident did not occur. Rather, within the context of OPCW FFM reporting, it usually indicates that the available evidence was insufficient to establish that a toxic chemical was used as a weapon. This distinction is important for conflict-related investigations, where delayed access, sample degradation, interrupted chain-of-custody continuity, and limited analytical material can substantially constrain forensic interpretation.

Overall, this study highlights the value of an evidence-convergence framework for forensic toxicology and CBRN preparedness. Timely sample collection, preservation of chain of custody, targeted laboratory analysis, and integrated interpretation across biomedical, environmental, clinical, testimonial, and material domains are central to robust chemical weapon verification. Future preparedness efforts should therefore prioritize field-adapted sampling protocols, preservation of analytically useful matrices, systematic documentation of clinical and scene evidence, and laboratory networks capable of confirming chemically specific exposure markers under conflict-related constraints.

Declaration of Ethical Standards

This study used publicly available institutional documents and did not involve direct interaction with human participants, collection of personal data, biological sampling, intervention, or access to confidential records. Therefore, ethics committee approval was not required.

Credit Authorship Contribution Statement

İsmail Ethem Gören: Conceptualization, Methodology / Study design, Validation, Formal analysis, Investigation, Resources, Data curation, Writing original draft, Writing - review and editing, Visualization, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The source documents analysed in this study are publicly available OPCW Fact-Finding Mission reports. The coded dataset generated during the study can be made available by the author upon reasonable request.

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