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Research Article

Comparative Forensic Profiling of Primer-Derived Inorganic Gunshot Residues Using SEM-EDX Spectroscopy

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Abstract: Gunshot Residue (GSR) analysis presents a significant challenge in forensic science due to the need to detect and identify minute traces of powders and initiating compositions formed during the chemical decomposition and deflagration processes within cartridge cases. This research is a qualitative comparative profiling study, designed to create a reference database of the most characteristic elemental markers for commonly used ammunition types in Europe and the Middle East. This study focuses on characterizing inorganic GSR using Scanning Electron Microscopy coupled with energy-dispersive X-ray Spectroscopy (SEM/EDX). Inorganic residue samples were collected from cartridge cases of American, German, Italian, Belgian, and Egyptian ammunition following firearm discharge. A comparative investigation was conducted to identify and differentiate the elemental compositions of primer residues associated with each ammunition type. The results revealed distinct elemental signatures, with metals such as lead (Pb), Barium (Ba), antimony (Sb), and Calcium (Ca) serving as key indicators for residue identification. SEM/EDX analysis provided high-resolution morphological and elemental data, allowing for the differentiation of GSR particles based on their origin. The findings support the use of SEM/EDX as a reliable tool for comparative GSR analysis, contributing to the forensic differentiation of ammunition types based on their inorganic residue profiles.

Keywords: GSR Analysis, Forensic Investigation of GSR, IGSR, SEM-EDX Analysis, Ammunition Comparative Study, Analysis of Cartridge Swabs

Introduction

Gunshot residue (GSR) analysis has emerged as a basis of forensic science that provides foundational evidence in the investigation of firearm-related incidents (Serol *et al*., 2023). GSR consists of microscopic particles expelled during the discharge of a firearm, which are deposited on the shooter, nearby objects, and victims (Charles *et al*., 2023; Krishna *et al*., 2023; Ditrich, 2022). The detection and characterization of GSR are essential in reconstructing shooting incidents, determining the distance between the firearm and target, and establishing potential links between suspects, firearms, and crime scenes (Minzière *et al*., 2023; Moskovchenko *et al*., 2023). However, GSR analysis poses significant challenges due to the minute quantities of residue present and the complex thermal and chemical decomposition it undergoes during the firing process (Shrivastava *et al*., 2021). The composition of GSR is influenced by the materials used in ammunition, including the primer, propellant, bullet jacket, cartridge casing, and the firearm itself (Hallett *et al*., 2020). Primers are a key contributor, containing a pyrotechnic mixture designed to ignite the propellant (Saverio and Margot, 2001; Chang *et al*., 2013). Common primer components include lead styphnate, barium nitrate, antimony sulfide, potassium chlorate, and calcium silicate (Lundgaard *et al*., 2019). During firing, the intense heat generated by the primer's ignition vaporizes these components, which then condense into spheroidal, noncrystalline particles ranging in diameter from 0.5 to 5.0 µm (Yetter *et al*., 2009). In addition to these core elements, other metallic residues, such as Copper (Cu), Zinc (Zn), and iron (Fe), may be present due to the interaction of the bullet, cartridge casing, and firearm barrel during firing. Nonspecific elements, including Aluminum (Al), Silicon (Si), Sulfur (S), potassium (K), and calcium Ca, further complicate the analytical process, as they may originate from external environmental sources (Martiny *et al*., 2008).

Inorganic GSR (IGSR), n–Residues from the primer, cartridge case, projectile, e.g., bullet or shot pellets, and/or the firearm that are primarily made of metal, metal oxides, or metal salts (E30 Committee, 2024). Trace evidence examiners started to assess the value of incorporating two complementary analytical measurements: Primer residue (pGSR) and organic gunshot residue (OGSR) data, aiming to strengthen firearms-related investigations (Dalzell *et al*., 2025). In addition to primer residues, the analysis of propellants, specifically double-base smokeless powders, is an integral component of ammunition residue studies (Maitre *et al*., 2018). Double-base powders are composed primarily of Nitrocellulose (NC) and Nitroglycerin (NG), along with stabilizers, plasticizers, and other additives (Reese *et al*., 2014). These propellants generate the pressure and heat necessary to propel the bullet, leaving behind chemical residues that provide valuable forensic evidence (Sisco and Forbes, 2021). Analyzing these residues requires chromatographic techniques, such as Gel Permeation Chromatography (GPC) and High-Performance Liquid Chromatography (HPLC). GPC effectively separates high-molecular-weight compounds like NC, while HPLC facilitates the analysis of smaller, volatile components, offering a comprehensive chemical profile of the propellant. Analyzing organic GSR is notoriously challenging. When focusing on the main components of smokeless powder nitrocellulose (NC) and nitroglycerin (NG)-NC presents difficulties when analyzed by TLC or GC-MS due to its polymeric nature and lack of volatility. Additionally, NG, as a nitrate ester, requires specialized analytical techniques on GC-MS (Salem *et al*., 2025).

Conventional Atomic Absorption Spectroscopy (AAS) has been reported to be sensitive enough for the detection of Pb in GSR samples, but inadequate for Ba and Sb. However, the introduction of electrothermal atomizers (carbon rod, tantalum, and graphite tube furnace) made flameless AAS suitable for the analysis of Ba and Sb in GSR samples. Samples are most commonly collected using cotton-tipped swabs and 5% nitric acid. 20 Flameless AAS has been reported as a successful technique for the analysis of inorganic GSR, as it is both readily available and cost-effective. It has an advantage over NAA, having excellent sensitivity for Ba and Sb, and can be used to detect other elements of interest, including Pb (Dalby, 2011). Rayana A. Costa and her co-worker studied the GSR originating from a clean range ammunition of a 0.38 caliber revolver and a 0.40 caliber pistol by using colorimetric test, Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM/EDX), and ICP-MS as a function of the number of shots. They reported that the SEM showed "unique particles" for the clean range ammunition GSR, in contrast to the literature. Elemental compositions of the "unique particles" were reported by EDX. The results primarily identified Al, C, Cl, Cr, Cu, O, Fe, K, Mo, S, Si, Sr, Ti, and Zn. They suggested that the main elements detected were Cu and Zn, which were obtained from Cu & Zn alloy used in the cartridge (Phermpornsagul *et al*., 2020). A study comparing different swabbing techniques found that cotton swabs moistened with 10% nitric acid (HNO_3) yielded the highest amounts of IGSR, making them highly effective for sampling (Merli *et al*., 2019). These methodologies highlight the significance of choosing appropriate swabbing materials and solvents for the efficient collection of IGSR from fired cartridges, ultimately ensuring precise forensic analysis.

Traditional methods, such as colorimetric tests and basic spectroscopic techniques, often lacked the sensitivity and specificity required for definitive analysis (Cioccia *et al*., 2024). Methods such as SEM/EDX and flameless atomic absorption spectroscopy have become the gold standards for GSR detection (Brünjes *et al*., 2022). SEM/EDX enables high-resolution imaging and precise elemental characterization of individual GSR particles (Brożek-Mucha and Klag, 2024; Charles *et al*., 2020), while atomic absorption spectroscopy offers enhanced sensitivity for detecting trace levels of metallic residues (Sardans *et al*., 2010; Lindenmayer *et al*., 2023; Kenawy *et al*., 2000). The current standard testing method for GSR detection accepted by the forensic science community and NIST (National Institute of Standards and Technology) is via the use of SEM-EDS (Fabian, 2024). These techniques allow for a comprehensive analysis of GSR, enabling forensic scientists to differentiate between particles originating from firearms and those from environmental contamination.

Most previous GSR studies have primarily focused on detecting organic and inorganic residues, estimating shooting distance, or comparing swab findings from different body or object surfaces. However, no comparable research has examined and differentiated the GSR of primers across various ammunition types and manufacturers. The primary purpose of this study is to investigate and compare the inorganic GSR profiles of cartridge cases from American, German, Italian, Belgian, and Egyptian ammunition using SEM/EDX. The motivation stems from the need for reliable, high-resolution analytical techniques that can differentiate between GSR sources based on their elemental and morphological characteristics, particularly in forensic investigations where such distinctions can influence case outcomes. This work is justified by the lack of comprehensive comparative studies on ammunition from diverse geographical origins, and it seeks to enhance forensic discrimination by establishing distinctive elemental signatures associated with each cartridge type.

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This research is a qualitative comparative profiling study, designed to create a reference database of the most characteristic elemental markers for commonly used ammunition types in Europe and the Middle East. The aim is not to perform population-level statistical inference but to document qualitative elemental signatures for comparative forensic purposes.

Ultimately, the study contributes to the advancement of forensic methodology by improving the accuracy, reliability, and evidentiary value of inorganic GSR analysis.

The novelty of this work lies in assembling, for the first time, a qualitative elemental signature database of GSR from ammunition of diverse geographical origins, enabling forensic differentiation between ammunition types based on primer-derived inorganic residues.

Materials and Methods

The GSR samples analyzed in this study were obtained from firearm discharges conducted at the Studies of Forensic Investigations Calabria (SEMAF) and in Egypt. Samples were collected from cartridge cases of American, German, Italian, Belgian, and Egyptian ammunition to facilitate a comparative analysis of GSR composition. The investigation aimed to distinguish between these different ammunition types and identify the unique residue patterns left behind after firing each one. A comparison was conducted to examine the variations in inorganic residues across different cartridge cases post-discharge. To collect the samples, the interior of the cartridge cases was swabbed using cotton stubs after firing. For quality assurance, blank cotton stubs were used as blanks. The sample size is equivalent to the small amount of primer used in ammunition. The ammunition selected to ensure representation of the most widely used ammunition brands across multiple countries, rather than to meet statistical representativeness criteria. This approach reflects the primary qualitative objective of identifying distinctive elemental patterns for comparative database development.

Sampling was conducted immediately post-discharge in controlled indoor or secure outdoor ranges to minimize environmental exposure. Blank cotton stubs were analyzed alongside samples and showed no presence of Pb–Ba–Sb combinations characteristic of primer residues. The ammunition selection prioritizes geographical diversity and differences in primer composition to maximize qualitative variation in elemental profiles rather than meeting a quantitative sample-size criterion.

Sample Collection

Samples were collected by swabbing the interior surfaces of the cartridge cases using cotton stubs immediately after the firing process to ensure the preservation of inorganic GSR. This technique allows for the recovery of trace elements deposited as a result of primer ignition and propellant combustion. Figure 1 illustrates the G.F.L. Parabellum 7.65 mm cartridge as a representative example, showing the condition of the cartridge case after discharge. Images of all twenty-three cartridge cases and stubs from various calibers and manufacturers for GSR analysis are presented in the supplementary document panels (a-w).

Fig. 1: Illustration of G.F.L. Parabellum 7.65 mm cartridge case surface morphology after Discharge

A cotton single-tipped wooden stick was used to collect GSR from the cartridges. Initially, the dry cotton bud was rolled over the inside surface of the cartridge. A blank of the cotton bud was also prepared for quality assurance purposes. All cotton buds were then cut and stored in a refrigerator at 4°C for preservation until investigated.

Table 1 presents a comparative overview of cartridge specifications from four countries: United States, Belgium Germany, Italy, and Egypt, organized by manufacturer brand and corresponding caliber. It includes a diverse range of ammunition types, such as rimfire and centerfire cartridges, with calibers ranging from small arms (.22 rimfire, 9 mm, 7.65 mm) to military-grade rounds (7.62 x 39 mm, 5.56 x 45 mm). The table facilitates an understanding of the geographical diversity and technical variation in ammunition used for the study.

Instrumentation

The SEM/EDX system used is a LEO 1430 VP with a 5-axis stage, equipped with a 4-quadrant backscattered electron detector (BSD), an Energy Dispersive X-ray analysis (EDS) system, and an Oxford "mini-CL" cathodoluminescence detector. The SEM/EDX technique was utilized to reveal detailed surface characteristics of examined particles, enabling comparison with known examples of GSR and allowing for image capture. This method distinguishes large particles of partially burned powder and spherical residues from contaminants. Samples were transferred from cotton plugs to aluminum stubs, and subsequently analyzed using SEM/EDX.

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Table 1: Specifications of cartridges from various countries by brand and caliber

United States		Germany		Italy		Egypt		Belgian	
Brand	Caliber	Brand	Caliber	Brand	Caliber	Brand	Caliber	Brand	Caliber
U	.22 rimfire	GECO	9x21 mm	GFL	9x21 mm	NATO	7.62 x 51 mm	FNB	5.56x45 mm
SMI	7.62x39 mm		9 mm		380 auto	SS 109	5.56 x 45 mm		
38 SPL	Winchester		7.65 mm (=32 USA)		.22 rimfire		7.62 x 39 mm		
	7.65 mm				9x19 mm		9 x 19 mm		
					44SW				
					9 mm Luger				
					40 SW				
					357 Magnum				
					9 mm Steyr				
					7.65 parabellum				
					7.65 mm (=32 USA)				
				SMI	7.62x39 mm				

GSR Analysis

Each examined ammunition was fired individually in duplicates and samples were collected from the cartridges using a cotton swab. Cotton swabs were applied to the interior cartridge wall with uniform rolling pressure for approximately 10 seconds per cartridge, then immediately sealed in sterile containers and refrigerated at 4°C until SEM/EDX analysis. SEM was operated at 20 kV accelerating voltage with a 10 mm working distance.

After each sample was carefully removed from the cotton swab, it was meticulously placed onto an aluminum stub as shown in Fig. 2, ensuring proper placement for further analysis.

Analysis of GSR on SEM/EDX

Samples were collected by swabbing the interior of cartridges using dry cotton wooden sticks, which were then transferred to aluminum stubs for analysis. Positive and negative controls, as well as blank stubs, were used to ensure quality. The detection of any of the desired metals alone was considered characteristic of GSR.

GSR Analysis Studies

GSR analysis and detection pose significant challenges due to the need to identify minute traces that remain after undergoing thermal and chemical destruction during the shooting process. Primer residue samples were collected from cartridge cases using cotton stubs, and comparative analyses were conducted to evaluate the inorganic residues left in different cartridge cases after firing. The cartridges studied were analyzed using SEM/EDX. This technique successfully detected primer residues, including metals from lead styphnate, barium nitrate, antimony sulfide, potassium chlorate, and calcium silicate, demonstrating the effectiveness of these methods for GSR detection.

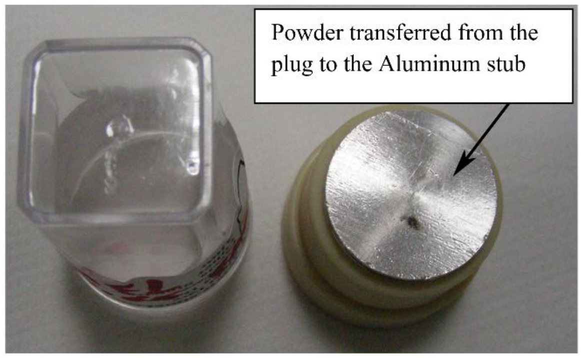

Fig. 2: Transfer of Residual Powder from Cotton Plug to Aluminum SEM Stub for Microscopic and Elemental Analysis

Samples collected from cartridge cases via cotton swabs underwent comparative analysis to assess the inorganic residues present after firing.

Results and Discussion

The most reliable method to determine whether a particle is characteristic of or consistent with GSR is by analyzing its elemental profile (Ferreira *et al*., 2021). This involves comparing the elemental profile of the recovered particles with that of a known source, such as the recovered weapon, cartridge case, or items related to the victim, when necessary. In some cases (Hannigan *et al*., 2015), non-routine elemental profiles of GSR particles, including the presence of additional elements not typically classified as GSR, may be encountered. These particles can still be considered characteristic of or consistent with GSR if the additional elements can be traced to specific case-related sources, such as cartridge, ammunition, or weapon test fire residues (Christopher *et al*., 2013).

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Sampling was conducted immediately post-discharge in controlled indoor or secure outdoor ranges to minimize environmental exposure. Blank cotton stubs were analyzed alongside samples and showed no presence of Pb–Ba–Sb combinations characteristic of primer residues. Trace elements such as Si, Ca, and Fe were interpreted with caution, acknowledging the possibility of environmental contribution.

Samples Analysis

Morphological examination, as in Fig. 3, for the 9X21 mm-GECO Germany as an example of the GSR morphology under the SEM, revealed that the GSR particles were typically spheroidal, non-crystalline (asymmetrical) in shape, with diameters ranging from 0.5 µm to 5.0 µm.

Figure 4, shows the EDX elemental spectrum of 9X21 mm-GECO Germany. Characteristic peaks correspond to elements commonly found in GSR, such as Pb, Ba, and Sb, which are typical components of primer residues. The Pb peaks around 2.3 keV, 10.5 keV, and 12.6 keV, Ba Peaks around 4.4 keV and 5.2 keV, Sb Peaks around 3.6 keV, and 4.1 keV.

Cu & Al can be attributed to the body of the bullet's cartridge, while the other detected elements were associated with specific primers, as shown in Table 2.

Swabs collected from different cartridges revealed varying concentrations of the same detected elements. These differences in concentration can be attributed to variations in the primer's burning rate in each bullet.

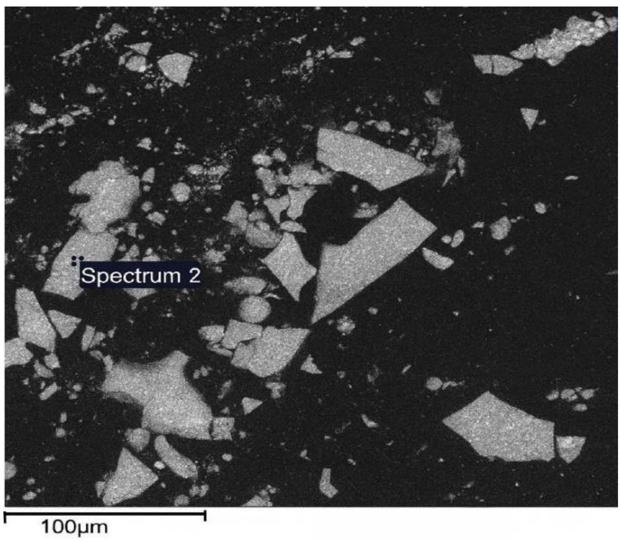

Fig. 3: Scanning electron micrograph showing the morphology of GSR particles collected from the 7.65 mm (-32 USA)-GECO-Germany cartridge case surface at 100 µm scale

The analysis was categorized by the number of elements' traces found in each cartridge. The number of element traces found in each cartridge ranges from two to seven. A consistent color scheme was applied for elemental data across all figures (e.g.: Pb = blue, Ba = yellow, Sb = violet, Fe = orange, Cu = green, Al = pink, Ca = dark green,…etc.) to facilitate direct comparison between charts."Fig. 5 presents a side-by-side comparison of the elemental composition of GSR from two distinct cartridge types: The USA-manufactured 22 Rimfire and the 357 Italian-manufactured Magnum by GFL. The GSR from the 22 Rimfire cartridge is overwhelmingly composed of Pb, accounting for nearly 100% of the elemental content, with a negligible presence of Cu, estimated at approximately 2–3%. In contrast, the bar chart on the right reveals that the .357 Magnum GSR consists predominantly of Ba, which makes up nearly 95–97% of the detected elemental mass, while Pb appears only as a minor constituent, contributing around 3–5%.

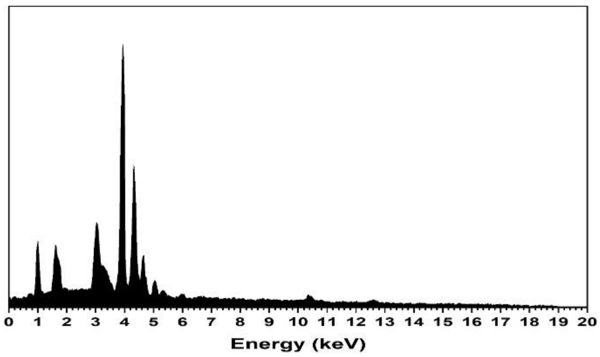

Fig. 4: EDX Spectrum showing the elemental composition of GSR particles from the 9×21 mm GECO-Germany cartridge

Table 2: Relationship between detected primer elements and the initiating compositions of the primers

Detected element	Initiating composition (primer)
Pb	Lead styphnate
Ba	Barium nitrate
Sb	Antimony sulphide
K and Cl	Potassium chlorate
Ca	Calcium silicate

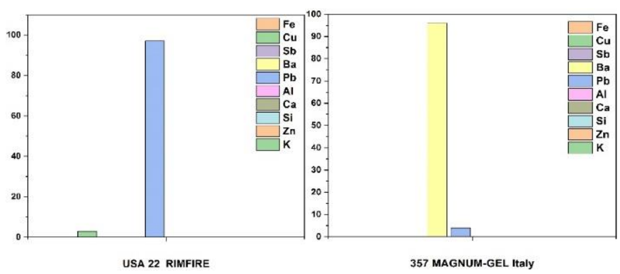

Fig. 5: Comparative elemental profile composition of GSR from USA .22 Rimfire and Italian .357 Magnum cartridges

Figure 6 presents a comparative analysis of the elemental composition of inorganic GSR collected from six cartridge types manufactured by GECO (Germany) and GFL (Italy), based on weight percentage distributions of key elements including Al, Ba, Pb, and Sb. The two 9 mm GECO Germany samples exhibit nearly identical profiles, with Ba accounting for approximately 85–90% of the residue composition, Pb present at around 10%, and Al detected in trace amounts below 5%. The 7.65 mm Parabellum cartridge from GFL Italy demonstrates a Ba-dominated profile (~70%), with moderate levels of Sb (~15%) and minor Pb content (~10%). The .40 SW cartridge produced by GFL Italy shows a more evenly distributed residue, with Ba contributing around 60%, and both Sb and lead present at approximately 20% each. The 22 Rimfire cartridge from GFL displays a slightly more balanced composition, with Ba at 50%, Sb at 35%, and Pb at 15%, while the 44 SW cartridge follows a similar trend with respective proportions of 45, 30, and 25%.

Figure 7 illustrates the elemental composition, by weight percentage, of inorganic GSR particles collected from four different cartridge types: 7.65 mm GECO Germany, 9×19 mm GFL Italy, 9×21 mm GFL Italy, and .38 SPL Winchester USA. For the 7.65 mm GECO Germany cartridge, Ba constitutes the majority of the residue at approximately 65%, followed by Sb and Pb each around 15%, with a minor contribution from Si at under 5%. The 9×19 mm GFL Italy cartridge displays a dominant Ba content of about 75%, with Pb around 13% and Sb approximately 9%, and Cu present in trace amounts under 3%. Similarly, the 9×21 mm GFL Italy cartridge shows Ba as the highest component at roughly 58%, Pb at about 22%, and Sb at 17%, while Cu remains negligible. In the case of the .38 SPL Winchester USA cartridge, the residue is more evenly distributed, with Ba at 42%, Pb at 33%, Sb at 24%, and trace Cu around 1–2%.

Figure 8 presents a comprehensive elemental profile comparison of GSR compositions from ten different cartridges originating from Italy, Belgium, Egypt, and the United States. The elemental profiles are characterized based on five principal elements: Cu, Sb, Ba, Pb, and one additional element that varies across samples (e.g., Al, Zn, Fe, Ca). For the 380 AUTO (9×17 mm) GFL Italy cartridge, Ba constitutes the dominant component at approximately 55%, followed by Pb (~30%) and Sb (~20%), with trace levels of Cu and Fe. The 9 mm Luger GFL Italy cartridge shows Ba at around 65%, Sb ~15%, Pb ~10%, and negligible amounts of Cu and Zn. The 7.62×39 mm SMI Italy cartridge presents a more balanced distribution, with Ba (~45%) and Pb (~35%) as the major constituents, and Sb and Cu contributing ~10–15% combined.

In the case of the 5.56×45 mm cartridge from FNB Belgium, Pb is the most abundant element (~65%), with Ba at ~25% and Sb around 8%, while Cu and Al are minor components. The 7.62×39 mm and 7.62×51 mm Egyptian cartridges exhibit a relatively even distribution of Ba and Pb (both ~35–40%), with Sb (~10–15%) and Cu contributing moderate levels (~10–15%), and trace amounts of Zn.

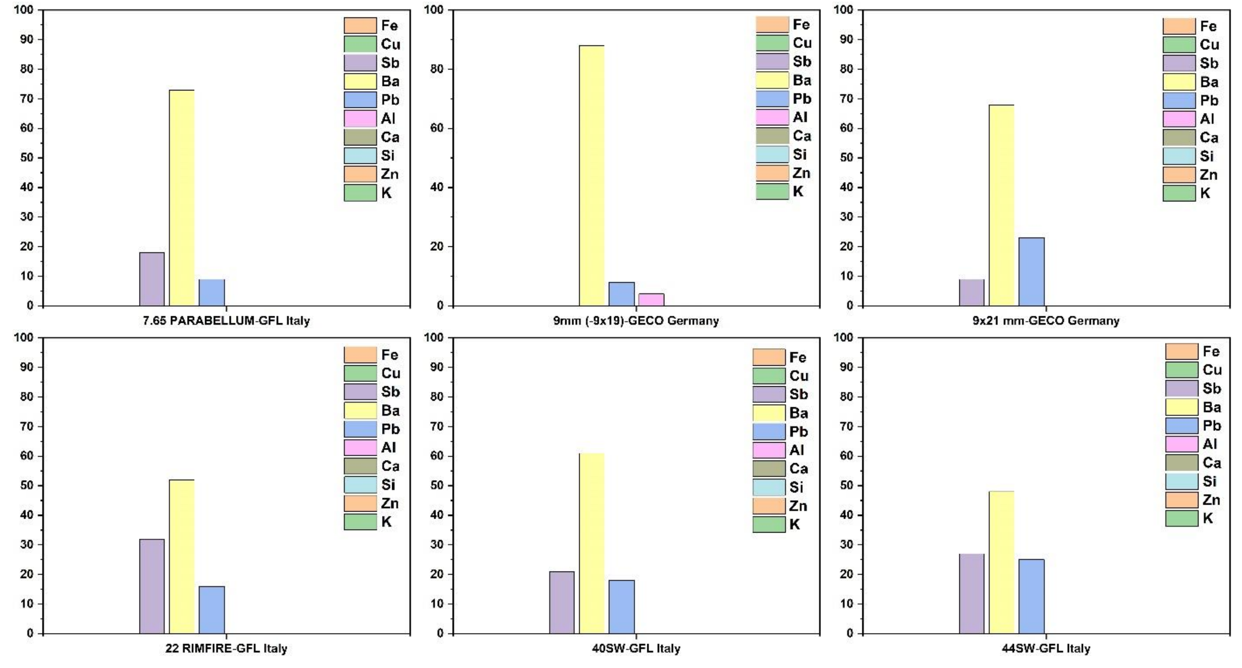

Fig. 6: Comparative elemental profile composition of GSR from GECO Germany and GFL Italy cartridges, showing three detected elements

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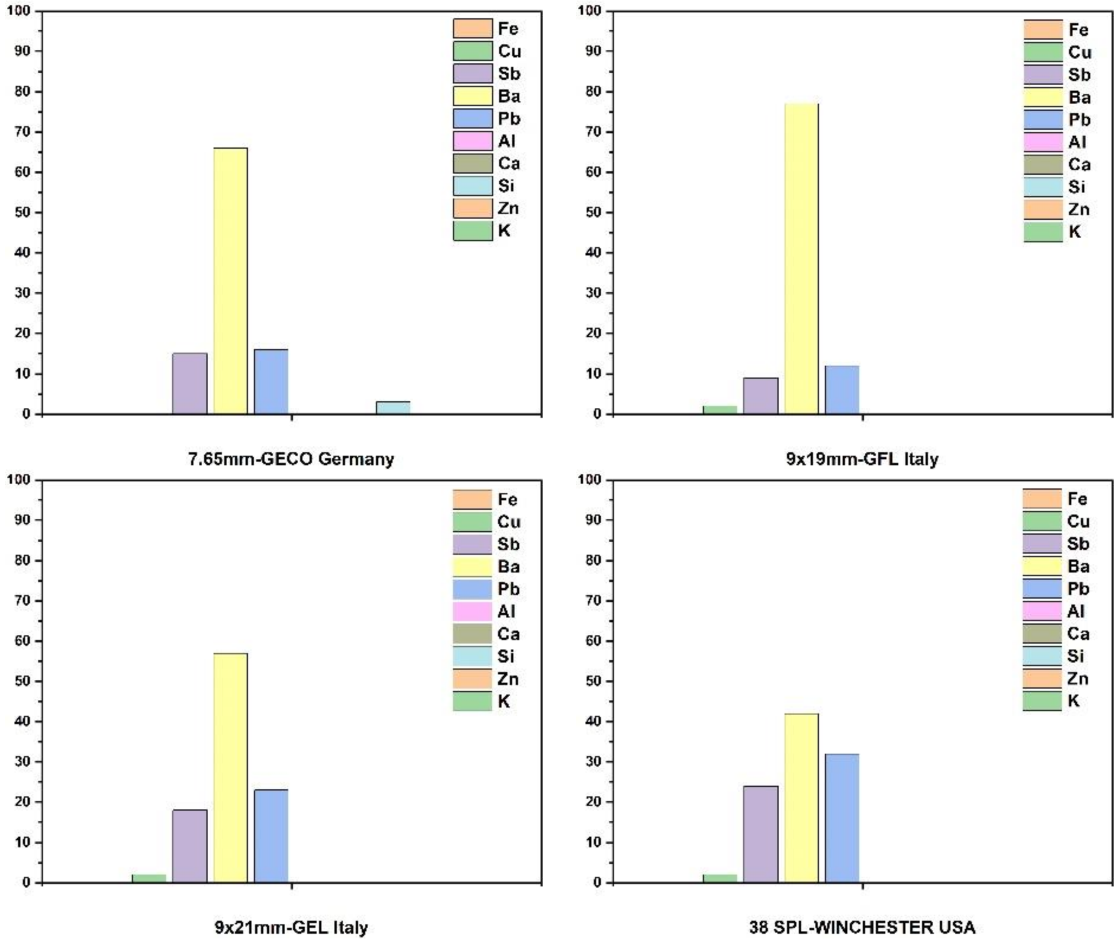
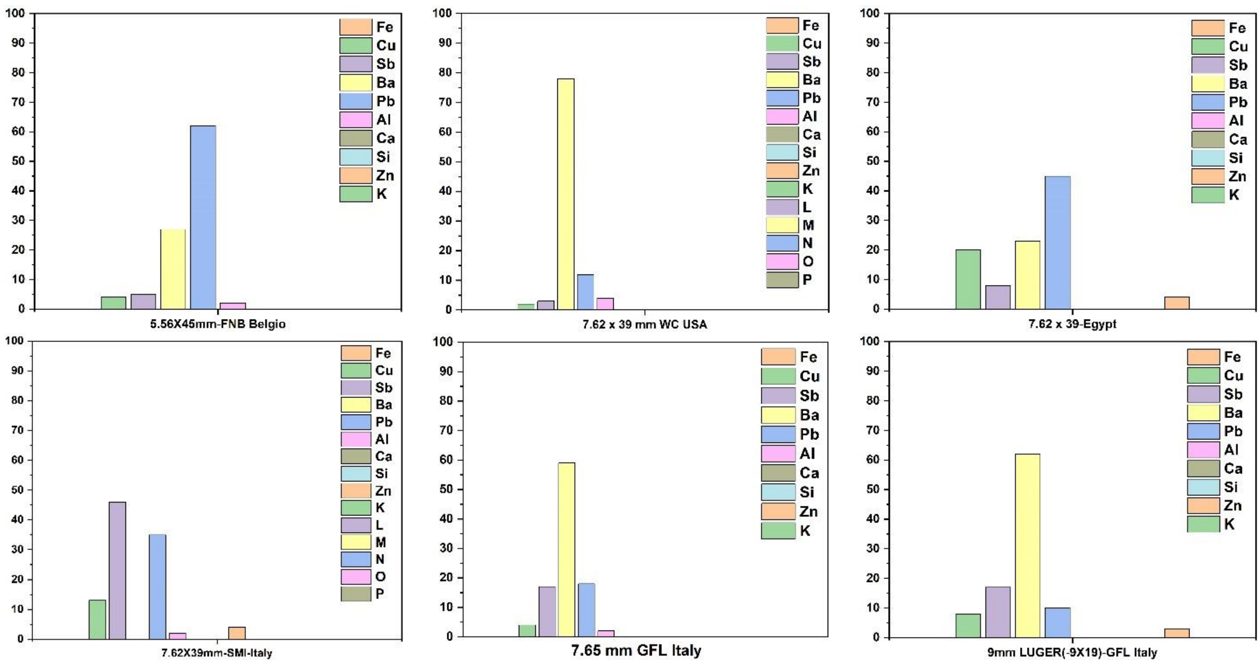


Fig. 7: Elemental profile composition of GSR from GECO, GFL, and WINCHESTER cartridges based on four detected elements



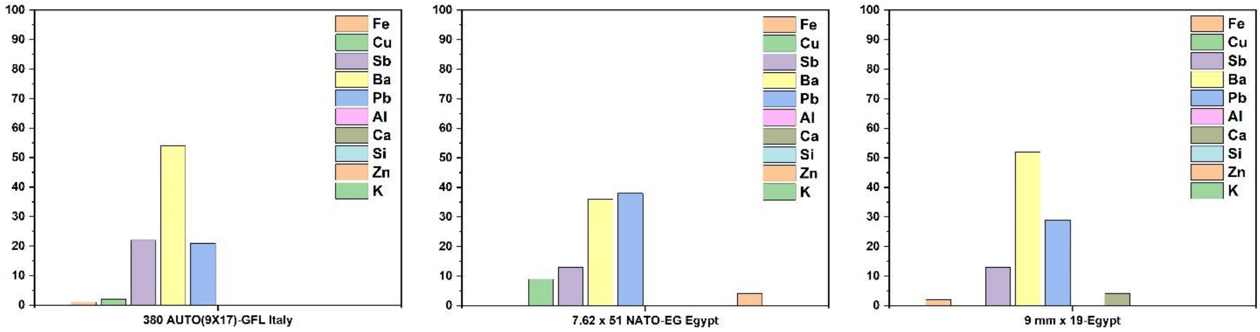


Fig. 8: Elemental profile composition of GSR from international cartridges based on five detected elements

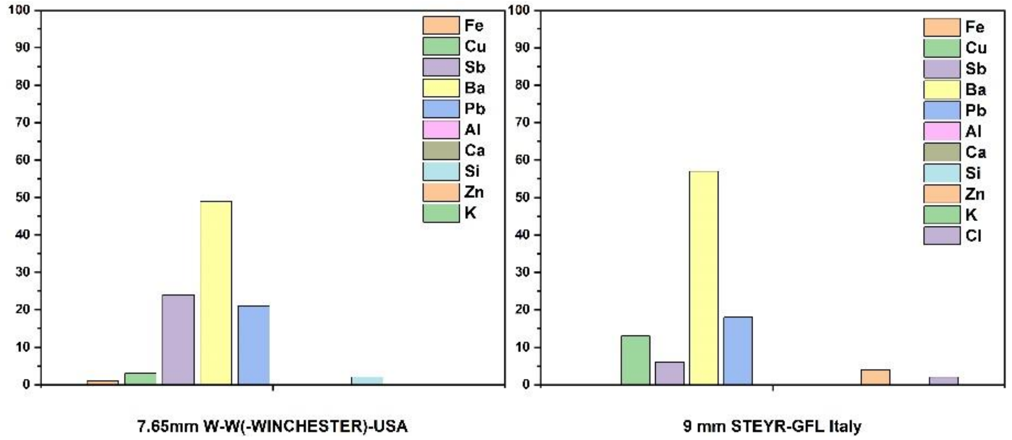


Fig. 9: Elemental profile Composition of GSR from 9 mm STEYR (GFL Italy) and 7.65 mm WINCHESTER USA cartridges based on five detected elements

The 9 mm Egyptian cartridge has a dominant Ba peak (~55%), followed by Pb (~30%) and Sb (~10%), with Ca and Fe present in low concentrations. For the 7.65 mm GFL Italy cartridge, Ba (~60%) again dominates, with Sb (~20%) and Pb (~15%), and minimal contributions from Cu and Al. Finally, the 7.62×39 mm WC USA cartridge reveals a highly concentrated Ba content (~75%), with low-to-moderate levels of Pb (~15%) and Sb (~10%), and trace levels of Al and Cu.

Figure 9 compares the elemental composition of GSR from two cartridge types: 9 mm STEYR manufactured by GFL Italy and 7.65 mm W-W (WINCHESTER) manufactured in the USA. In the GFL Italy cartridge, Ba is the dominant element, contributing approximately 55% of the total residue mass, followed by Pb at around 18%, and Cu at roughly 13%. Smaller quantities of Sb and Zn are present at approximately 6% and 4%, respectively, with Cl contributing a minor amount under 2%. For the 7.65 mm WINCHESTER cartridge, Ba also dominates the elemental profile at approximately 48%, followed by Sb (~25%), lead (~20%), and Cu (~3%), with Si and Fe present in trace amounts below 2%.

Figure 10 displays the elemental composition, by weight percentage, of GSR collected from a 5.46×45 mm cartridge manufactured in Egypt. Among the seven detected elements, five, Cu, Sb, Ba, Pb, and Zn, are the most prominent and are considered primary contributors to the residue profile. Pb is the dominant element, constituting approximately 38% of the total GSR mass, followed by Ba at around 28% and Cu at approximately 16%. Sb contributes about 14%, and Zn appears in smaller quantities, near 4%. Trace levels of K and Cl are also present, each under 3%. These results suggest a conventional primer composition rich in Pb and Ba, with Sb and Cu indicating complex combustion byproducts.

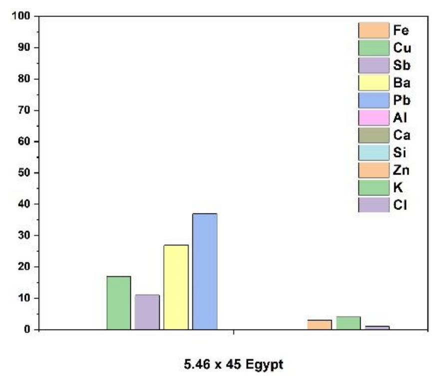


Fig. 10: Elemental profile of GSR from a 5.46×45 mm Egyptian cartridge based on five primary elements

Conclusion

This study presents a comprehensive and qualitative evaluation of inorganic GSR profiles from a diverse range of international ammunition types using high-resolution SEM/EDX. Residues were collected from post-discharge cartridge cases manufactured in the United States, Germany, Italy, Belgium, and Egypt, and the results revealed notable inter-brand and international variations in both elemental composition and particle morphology. These variations enabled effective forensic differentiation among ammunition types based on their distinct primer formulations and manufacturing characteristics.

Across the analyzed cartridges, Ba consistently appeared as a dominant component in primer residue. For example, the 9 mm GFL Italy, 9 mm GECO Germany, and 7.65 mm WINCHESTER USA cartridges exhibited Ba contents exceeding 60%, highlighting the prevalence of barium nitrate in their primer formulations. In contrast, Pb concentration varied widely, ranging from below 10% in cartridges such as the 9 mm Luger GFL Italy and 7.65 mm GECO Germany to above 70% in the 5.56 × 45 mm FNB Belgium, .22 Rimfire USA, and 5.46 × 45 mm Egypt cartridges, emphasizing the continued use of lead styphnate in conventional primers. Sb content also showed significant variation, with some cartridges such as the 7.65 mm WINCHESTER USA and 40 SW GFL Italy containing over 20% Sb, whereas others like the 9 mm GECO Germany and 9 mm Luger GFL Italy presented less than 10%. Cu content, although generally minor, reached notable concentrations in the 9 mm Steyr GFL Italy (~14%) and 5.46×45 mm Egypt (~16%), indicating contributions from the cartridge case or projectile.

Moreover, trace elements such as Zn, Si, K, Ca, Fe, and Cl were observed at concentrations ranging from 1% to 5%, varying depending on manufacturer's origin and primer composition. Notably, Egyptian-manufactured cartridges such as the 7.62×51 mm NATO-EG and 5.46 × 45 mm displayed broader multi-elemental profiles, with Pb and Ba consistently sharing major weight percentages (~35–40%) and supporting the reproducibility of their primer formulation. The observed elemental profile distinctions support the effectiveness of elemental profiling in differentiating ammunition sources. When considered together, the distribution patterns of Ba–Pb–Sb–Cu—combined with trace elemental signatures serve as reliable forensic indicators for cartridge classification, origin attribution, and case reconstruction.

The findings affirm the reliability of SEM/EDX as a highly sensitive and selective microanalytical technique for GSR investigations, capable of delivering detailed, material-specific fingerprints for forensic ammunition source attribution. The robust reproducibility and high-resolution capabilities of the method make it particularly well-suited for comparative studies, evidentiary support, and post-firing reconstructions. Future research could benefit from incorporating chemometric and machine learning models for automated classification of GSR profiles, as well as broadening the scope of ammunition types to include non-toxic primer compositions and emerging "green" alternatives, thereby aligning forensic science with evolving environmental and regulatory standards.

Limitations of this study include its qualitative focus, modest sample size, and controlled-range firing conditions, which may not capture all potential environmental contributions to elemental profiles. Future work should expand to larger datasets, include non-toxic “green” primers, and apply chemometric or machine learning techniques to the database for automated classification.

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Authors Contributions

All authors equally contributed in this work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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