International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Advances in Analytical Techniques for Gunshot Residue Detection: Traditional and Emerging Methods in Forensic Science: A Comprehensive Review

Ms. Reshma Santhosh[1], Ms. Dhanya R[2], Ms. Athira K.S[3]

[1]Assistant Professor, Department of Forensic Science, Parul University, Vadodara, Gujarat
[2]Assistant Professor, Department of Forensic Science, Nehru Arts and Science College, Coimbatore, Tamil Nadu
[3]Assistant Professor, Department of Forensic Science, Nehru Arts and Science College, Coimbatore, Tamil Nadu

ABSTRACT

Gunshot residue (GSR) analysis plays a fundamental role in modern forensic investigations involving firearms. The detection and interpretation of GSR particles help investigators determine whether a suspect discharged, handled, or was in close proximity to a firearm during a shooting event. Over the past decades, numerous analytical techniques have been developed to detect and characterize both inorganic and organic components of GSR. Traditional laboratory-based methods such as Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX), Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) have long been considered reliable techniques for GSR detection because of their high sensitivity and elemental specificity. However, evolving ammunition technologies, including lead-free primers, and increasing demand for rapid field-deployable analysis have encouraged the development of alternative analytical approaches. Emerging techniques such as Raman spectroscopy, Laser-Induced Breakdown Spectroscopy (LIBS), portable analytical devices, and novel sensor-based technologies are gaining increasing importance in forensic laboratories and crime scene investigations.

This review critically evaluates both traditional and emerging analytical techniques used in GSR detection. Comparative analysis of sensitivity, specificity, speed, portability, and cost effectiveness is presented. The review also discusses methodological challenges, including secondary transfer, environmental contamination, and interpretation complexities. Future research directions such as artificial intelligence-assisted analysis and miniaturized portable detection technologies are also explored.

Keywords: Gunshot residue, SEM-EDX, Raman spectroscopy, LIBS, ICP-MS, forensic science, analytical techniques.

1. INTRODUCTION

Firearm-related violence continues to pose a significant challenge for criminal justice systems worldwide, necessitating the advancement of precise forensic methodologies to link individuals to firearm discharges.

Gunshot residue (GSR) constitutes a particularly valuable type of trace evidence in forensic investigations, given its direct production during the act of firing a weapon and its persistence on individuals and adjacent surfaces after discharge. Consequently, the detection and subsequent interpretation of GSR are crucial for reconstructing shooting incidents and determining a suspect's involvement with a firearm, whether through discharge or contact [1].

When the firing pin meets the primer of the cartridge, a quick exothermic reaction occurs, igniting the propellant and propelling the projectile through the barrel. During this process, extremely high temperatures and pressures are generated, resulting in the partial vaporisation and condensation of primer and propellant ingredients. As the gaseous products cool quickly, they produce small particles that are released from the firearm and distributed throughout the environment. These particles might subsequently deposit on the hands, clothing, hair, or other objects, making them crucial indicators in forensic examinations using weapons[2]. Traditionally, the inorganic portion of gunshot residue is mostly derived from the primer composition used in ammunition. Conventional primers often contain compounds derived from lead, barium, and antimony, which generate distinct tiny particles during the firing process. These particles usually have spherical morphologies due to the fast melting and solidification that occurs under high-temperature conditions during discharge. The simultaneous presence of these constituents within a single particle has long been regarded as a strong signal of weapon discharge, allowing forensic experts to distinguish GSR particles from other environmental particulates[3].The analytical methods used for GSR detection and characterisation have advanced significantly over the last few decades. The most popular analytical technique for identifying inorganic gunshot residue particles is Scanning Electron Microscopy in conjunction with Energy Dispersive X-ray Spectroscopy (SEM-EDX). This method makes it possible to identify particles with distinctive elemental combinations like Pb–Ba–Sb by simultaneously visualising particle morphology and determining elemental composition. SEM - EDX is now the standard method used in many forensic labs across the world because of its high specificity and capacity to analyse individual particles [3].

SEM-EDX analysis has certain drawbacks despite its dependability. The method's use in circumstances requiring quick screening of numerous samples may be limited by its costly equipment, highly skilled personnel, and comparatively lengthy analytical times. Additionally, new primer formulations that might not have the conventional Pb–Ba–Sb elemental signature have been introduced due to the growing use of environmentally friendly and lead-free ammunition. Because of this, it is now more difficult to interpret GSR data, necessitating the use of complementary analytical methods that can identify both conventional and unconventional residues. SEM-EDX analysis, while reliable, presents certain limitations. Its application in scenarios demanding rapid screening of a large number of samples may be constrained by the expense of the instrumentation, the requirement for highly trained operators, and the relatively protracted analytical durations. Furthermore, the increasing adoption of environmentally conscious and lead-free ammunition has led to the introduction of novel primer formulations that may not exhibit the typical Pb–Ba–Sb elemental signature. As a result, the interpretation of galvanic skin response (GSR) data has become more complex, requiring the use of additional analytical methods to identify both typical and atypical residues. [4]. In addition to SEM-EDX, several other analytical techniques have been employed to investigate the elemental composition of gunshot residues. Methods such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) have been used to quantify trace metallic elements present in GSR samples with high sensitivity. While these techniques provide precise elemental measurements, they generally lack the capability to examine individual particle morphology, which can limit their interpretative value when distinguishing genuine GSR particles from background environmental contaminants [5].

In recent years, attention has increasingly shifted toward emerging spectroscopic and rapid analytical methods that can complement conventional approaches. Techniques such as Raman spectroscopy have demonstrated considerable potential for identifying the organic components of gunshot residue, including propellant-related compounds such as nitrocellulose, nitro-glycerine, and stabilizing additives. These compounds produce characteristic vibrational spectra that allow their identification without extensive sample preparation. Similarly, Laser-Induced Breakdown Spectroscopy (LIBS) has been investigated as a rapid elemental analysis technique capable of detecting metallic components of GSR through laser-induced plasma emission spectra [6]. Another notable advancement in forensic science is the development of portable analytical devices and sensor-based detection systems. Handheld Raman spectrometers, portable LIBS instruments, and novel chemical sensors have been proposed as potential tools for rapid on-site detection of gunshot residues. Such technologies offer the possibility of performing preliminary screening directly at crime scenes, thereby reducing the time required for laboratory analysis and improving the overall efficiency of forensic investigations [7]. Given the evolving composition of modern ammunition and the rapid advancement of analytical instrumentation, a comprehensive evaluation of both traditional and emerging GSR detection techniques is necessary. The present review therefore aims to examine the principles, advantages, and limitations of commonly used analytical methods for gunshot residue detection. Particular emphasis is placed on traditional techniques such as SEM-EDX, Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), as well as emerging technologies including Raman spectroscopy, Laser-Induced Breakdown Spectroscopy (LIBS), portable analytical devices, and novel sensor-based approaches. By critically comparing these techniques in terms of analytical performance, sensitivity, and forensic applicability, this review seeks to highlight current challenges and future directions in the field of gunshot residue analysis.

2. METHODOLOGY

A systematic literature review was conducted following the PRISMA guidelines. Scientific databases including Scopus, Web of Science, PubMed, and Google Scholar were searched for relevant articles published between 2000 and 2026. Search terms included “gunshot residue detection”, “SEM-EDX analysis of GSR”, “Raman spectroscopy gunshot residue”, “LIBS forensic analysis”, and “ICP-MS gunshot residue”.

A total of 620 records were initially identified. After removal of 140 duplicate articles, 480 studies remained for title and abstract screening. Subsequently, 210 full-text articles were assessed for eligibility. Finally, 52 articles meeting the inclusion criteria were included in this review.

Figure 1 PRISMA Flowchart showing study selection

Records identified through database searching
(n = 620)
↓
Duplicates removed
(n = 140)
↓
Records screened
(n = 480)

↓
Full text articles assessed
(n = 210)
↓
Studies included in review
(n = 52)

3. COMPOSITION OF GUNSHOT RESIDUE

Gunshot residue (GSR) represents a heterogeneous mixture of microscopic particles and gaseous by-products produced during the discharge of a firearm. These residues originate primarily from the primer composition, propellant mixture, cartridge case, and projectile materials involved in the firing process. When the firing pin strikes the primer, a rapid detonation occurs that initiates combustion of the propellant and generates extremely high temperatures and pressures within the cartridge chamber. Under such conditions, metallic and organic components may vaporize, fragment, and subsequently condense into fine particles that are expelled from the firearm and dispersed into the surrounding environment [8]. The resulting residue particles can deposit on the hands, clothing, hair, and nearby surfaces of individuals present during a shooting event. Due to this characteristic deposition behaviour, GSR has become an important form of trace evidence in forensic investigations, assisting in the reconstruction of shooting incidents and supporting the evaluation of whether an individual may have discharged or handled a firearm [9]. From a chemical perspective, GSR is generally classified into two principal categories: inorganic gunshot residue (IGSR) and organic gunshot residue (OGSR). Inorganic residues are predominantly derived from the primer mixture and consist mainly of metallic elements. Organic residues, in contrast, originate from the propellant materials and include partially combusted energetic compounds and stabilizers. The simultaneous investigation of both components has become increasingly important because modern ammunition formulations may produce residues with different chemical signatures compared with traditional cartridges [10].

3.1 Inorganic Gunshot Residue (IGSR)

Inorganic gunshot residue is formed during the primer detonation process, which produces high-temperature molten droplets containing metallic elements from the primer composition. As these droplets cool rapidly in the surrounding atmosphere, they solidify into microscopic particles that frequently exhibit spherical morphology due to surface tension effects during the molten phase [11].

Traditional ammunition primers typically contain lead styphnate as the primary explosive, barium nitrate as an oxidizing agent, and antimony sulphide as a fuel component. When these compounds undergo rapid thermal decomposition during firearm discharge, they generate particles containing characteristic elemental combinations such as lead (Pb), barium (Ba), and antimony (Sb). The detection of particles containing these three elements within a single particle has historically been regarded as strong evidence of firearm discharge [12]. However, the composition of inorganic GSR has evolved in response to environmental and occupational health concerns associated with heavy metals, particularly lead. As a result, many ammunition manufacturers have introduced lead-free or heavy-metal-reduced primer formulations. These modern primers may contain alternative elements such as titanium (Ti), zinc (Zn), aluminium (Al), copper (Cu), or strontium (Sr). Consequently, forensic scientists must now consider a broader range of elemental signatures when evaluating GSR particles produced by contemporary ammunition [13].

Table 1:Common Elements Identified in Inorganic Gunshot Residues

Element	**Source in Ammunition**	**Forensic Significance**
Lead (Pb)	Lead styphnate primer	Traditional GSR marker
Barium (Ba)	Barium nitrate oxidizer	Indicates primer reaction
Antimony (Sb)	Antimony sulphide fuel	Characteristic GSR element
Copper (Cu)	Bullet jacket / cartridge case	Secondary residue component
Zinc (Zn)	Brass cartridge case	Environmental or ammunition source
Titanium (Ti)	Lead-free primers	Marker of modern ammunition
Strontium (Sr)	Alternative oxidizer	Indicator of lead-free formulations

3.2 Organic Gunshot Residue (OGSR)

Organic gunshot residue originates mainly from the propellant mixture contained within the cartridge case. Unlike inorganic residues, which are composed primarily of metallic particles, organic residues consist of partially combusted energetic compounds produced during propellant ignition and burning. These compounds may persist on the shooter's hands or clothing for a certain period following firearm discharge [14].

Most modern propellants used in small-arms ammunition are based on nitrocellulose, which serves as the principal energetic component of smokeless powder. In many formulations, nitrocellulose is combined with nitro-glycerine, forming double-base propellants that provide greater energy output. Additional chemical additives are incorporated into the propellant mixture to improve stability and performance during storage and firing. These additives include compounds such as diphenylamine, ethyl centralite, and dinitro toluene, which function as stabilizers and plasticizers [15].

The analysis of organic residues has gained increasing importance in forensic science because organic compounds can provide complementary information to inorganic particle analysis. Techniques such as Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), and chromatographic methods coupled with mass spectrometry are capable of identifying these compounds through their molecular signatures, thereby enhancing the overall reliability of GSR identification [16].

Table 2 Common Organic Compound Detected in Gunshot Residues

Compound	**Function in Ammunition**	**Source**
Nitrocellulose	Primary propellant	Smokeless powder
Nitro-glycerine	Energetic plasticizer	Double-base propellant
Diphenylamine	Stabilizer	Prevents propellant degradation
Ethyl centralite	Stabilizer / plasticizer	Propellant additive
Dinitro toluene	Energetic additive	Propellant formulation
Phthalates	Plasticizers	Propellant binder materials

3.3 Factors Influencing the Composition of GSR

Several variables influence both the chemical composition and distribution of gunshot residue particles following firearm discharge. One of the most significant factors is the type of ammunition used, as different primer and propellant formulations generate residues with distinct elemental and molecular signatures. For example, ammunition manufactured with lead-free primers may produce residues lacking the traditional Pb–Ba–Sb elemental combination, thereby complicating forensic interpretation [17]. Another important factor is the distance between the firearm and the target, which can influence the concentration and distribution of residue particles. Close-range discharge generally results in higher concentrations of residue deposition on nearby surfaces, whereas long-range firing may produce more dispersed particle distributions. Environmental factors such as airflow, humidity, and surface characteristics may further affect the persistence and transfer of GSR particles after discharge [4]. Because of these variables, the interpretation of gunshot residue evidence requires careful consideration of both analytical results and contextual information related to the shooting event. Consequently, forensic scientists often employ multiple analytical techniques to provide a more comprehensive assessment of residue evidence.

4.TRADITIONAL TECHNIQUES USED FOR GUNSHOT RESIDUE ANALYSIS

The forensic identification of gunshot residue (GSR) has traditionally relied on analytical techniques capable of detecting trace metallic elements originating from primer compositions used in ammunition. These methods have played a critical role in forensic investigations by providing scientific evidence linking individuals to firearm discharge events. Conventional approaches primarily focus on the analysis of inorganic gunshot residue (IGSR) particles, which typically contain metallic elements such as lead, barium, and antimony. Over the past two decades, several instrumental techniques have been widely employed for the detection and characterization of GSR particles, including Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX), Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) [18].

These analytical techniques differ in their underlying principles, sensitivity, and suitability for forensic investigations. While SEM-EDX allows the morphological and elemental characterization of individual particles, spectroscopic techniques such as AAS and ICP-MS provide quantitative elemental analysis of trace metals present in GSR samples. The integration of these techniques has significantly improved the reliability and evidential value of GSR analysis in modern forensic laboratories [19].

4.1 Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX)

Scanning Electron Microscopy combined with Energy Dispersive X-ray Spectroscopy is widely regarded as the gold standard technique for the identification of inorganic gunshot residue particles. The technique enables forensic scientists to examine both the morphology and elemental composition of microscopic particles collected from suspects or crime scene surfaces.

During SEM analysis, a focused beam of high-energy electrons is directed onto the surface of the sample. Interaction between the electron beam and the sample produces various signals, including secondary electrons and backscattered electrons, which are used to generate high-resolution images of the particle surface. GSR particles typically exhibit spherical or semi-spherical morphology, which results from the rapid melting and condensation of metallic primer components during firearm discharge [20].

The Energy Dispersive X-ray Spectroscopy component provides elemental identification by detecting characteristic X-rays emitted when the electron beam interacts with atoms within the sample. Through this process, forensic investigators can determine the presence of specific elemental combinations commonly associated with GSR particles. Automated particle recognition systems integrated within modern SEM-EDX instruments allow rapid scanning of large sample areas and facilitate efficient detection of particles exhibiting characteristic elemental signatures [21]. Although SEM-EDX offers high specificity and reliability, the technique requires expensive instrumentation and specialized expertise. Furthermore, the analysis process may be relatively time-consuming when large numbers of samples are involved.

Nevertheless, the ability to simultaneously examine particle morphology and elemental composition makes SEM-EDX an indispensable tool in forensic GSR analysis [22].

4.2 Atomic Absorption Spectroscopy (AAS)

Atomic Absorption Spectroscopy represents one of the earliest instrumental techniques applied to the analysis of metallic elements associated with gunshot residues. The technique operates on the principle that atoms in the gaseous state absorb electromagnetic radiation at element-specific wavelengths. Measurement of this absorption allows quantitative determination of elemental concentrations within a sample.

In forensic applications, GSR particles collected from a suspect's hands or clothing are typically extracted into a solution through chemical digestion. The solution is then introduced into a flame or graphite furnace, where the sample undergoes atomization. When light of a specific wavelength passes through the atomic vapor, atoms of the corresponding element absorb part of the radiation. The reduction in light intensity is measured to determine the concentration of the element present [23]. AAS has been extensively used for the detection of lead, barium, and antimony, which are key elements associated with traditional primer compositions. The technique provides relatively good sensitivity and is capable of detecting trace quantities of metallic elements. However, one of the main limitations of AAS is that it does not provide information about the morphology of individual particles, making it difficult to distinguish genuine gunshot residue particles from environmental contaminants [24].

Despite these limitations, AAS continues to be valuable for quantitative elemental analysis, particularly in studies investigating the distribution and persistence of GSR following firearm discharge.

4.3 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Inductively Coupled Plasma Mass Spectrometry is one of the most sensitive analytical techniques currently used for the detection of trace elements. In GSR analysis, ICP-MS is employed to identify and quantify metallic elements originating from primer compositions.

In this technique, the sample is introduced into a high-temperature plasma generated by an inductively coupled radiofrequency field. Within the plasma environment, the sample undergoes vaporization, atomization, and ionization. The resulting ions are then transferred into a mass spectrometer, where they are separated based on their mass-to-charge ratios and detected with high sensitivity [25].

ICP-MS offers several advantages over other analytical techniques, including extremely low detection limits, rapid multi-element analysis, and high analytical precision. These characteristics make it particularly useful for detecting trace concentrations of metallic elements present in GSR samples. Additionally, ICP-MS has been applied to the analysis of residues produced by lead-free ammunition, where alternative elements such as titanium, zinc, and copper may be present instead of traditional primer components [26].

However, similar to AAS, ICP-MS requires dissolution of the sample prior to analysis, which prevents direct examination of particle morphology. Consequently, ICP-MS is often used as a complementary technique alongside SEM-EDX in comprehensive forensic investigations.

Table 3 Comparison of Traditional Analytical Techniques for Gunshot Residue Analysis

Technique	Analytical Principle	Major Advantages	Limitations
SEM-EDX	Electron microscopy with X-ray elemental analysis	Provides particle morphology and elemental composition	Expensive instrumentation and longer analysis time

AAS	Absorption of light by gaseous atoms	Quantitative detection of metallic elements	No morphological information
ICP-MS	Plasma ionization with mass spectrometric detection	Extremely high sensitivity and multi-element detection	Requires sample digestion

5. EMERGING TECHNIQUES FOR GUNSHOT RESIDUE (GSR) ANALYSIS

In recent years, forensic scientists have increasingly explored innovative analytical techniques to complement conventional methods used for gunshot residue (GSR) identification. While traditional approaches such as scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), atomic absorption spectroscopy (AAS), and inductively coupled plasma mass spectrometry (ICP-MS) remain highly reliable for detecting inorganic gunshot residue (IGSR), these techniques often require laboratory-based instrumentation and time-consuming analytical procedures. Consequently, emerging analytical technologies have been developed to enable rapid, sensitive, and field-deployable detection of both inorganic and organic gunshot residue components.

Among the most promising emerging methods are Raman spectroscopy, laser-induced breakdown spectroscopy (LIBS), portable analytical devices, and sensor-based detection technologies. These approaches offer significant advantages, including minimal sample preparation, real-time analysis, and improved detection of organic propellant residues that are not easily identified using traditional techniques. Such developments have expanded the analytical capabilities of forensic laboratories and improved the efficiency of crime-scene investigations.

5.1 Raman Spectroscopy

Raman spectroscopy has emerged as an important technique for the detection and characterization of organic gunshot residue (OGSR). The method is based on the inelastic scattering of monochromatic laser radiation, producing characteristic vibrational spectra that provide molecular fingerprints of chemical compounds. Raman spectroscopy is particularly valuable in forensic investigations because it enables the identification of organic propellant components such as nitrocellulose, nitro-glycerine, diphenylamine, and ethyl centralite without extensive sample preparation. Recent studies have demonstrated the capability of Raman micro spectroscopy to identify individual GSR particles collected from adhesive stubs or surfaces. The technique allows the simultaneous detection of multiple organic compounds within complex residue mixtures, thereby providing valuable information regarding the composition of ammunition propellants and additives [27]. In addition, Raman spectral analysis combined with advanced chemometric techniques such as principal component analysis (PCA) and support vector machines (SVM) has been successfully used to differentiate residues originating from different ammunition calibres and manufacturers [28].

Raman mapping techniques have further improved the spatial resolution of GSR detection by enabling the visualization of chemical distribution across sample surfaces. For example, Raman micro spectroscopic mapping has been used to detect and characterize GSR particles collected from adhesive tapes, demonstrating high specificity and reproducibility in forensic analysis [29]. Furthermore, portable Raman spectrometers have been developed to facilitate rapid on-site identification of gunshot residues at crime scenes, significantly reducing the time required for preliminary forensic assessments [30]. Despite these advantages, Raman spectroscopy may encounter limitations such as fluorescence interference and relatively weak Raman scattering signals in certain samples. Nevertheless, ongoing improvements in laser sources, detector sensitivity, and spectral processing algorithms continue to enhance the reliability of Raman spectroscopy for forensic applications [31]. Recent research has also explored the use of surface-enhanced Raman spectroscopy (SERS) to improve the sensitivity of OGSR detection and enable the identification of trace levels of propellant compounds in forensic samples [32].

Figure 2 Raman Spectroscopy Instrument Diagram

Laser Source
|
Beam Splitter
|
Sample (GSR particle)
|
Scattered Raman Light
|
Detector
|
Raman Spectrum (Molecular fingerprint)

5.2 Laser-Induced Breakdown Spectroscopy (LIBS)

Laser-Induced Breakdown Spectroscopy (LIBS) is another emerging technique that has shown considerable potential for the rapid elemental analysis of gunshot residue. LIBS operates by focusing a high-energy laser pulse onto a sample surface, generating a micro-plasma that emits characteristic emission spectra corresponding to the elemental composition of the material. One of the major advantages of LIBS is its ability to perform simultaneous multi-element detection with minimal sample preparation. The technique has been successfully applied to detect key metallic elements associated with GSR, including lead (Pb), barium (Ba), antimony (Sb), copper (Cu), and zinc (Zn). These elements originate primarily from primer compounds used in firearm cartridges and can serve as important forensic markers of firearm discharge [33]. LIBS analysis also offers extremely rapid detection, often requiring only a few seconds per sample. This rapid analytical capability makes LIBS particularly suitable for high-throughput screening of multiple samples collected during criminal investigations. Recent studies have further demonstrated that LIBS combined with multivariate statistical analysis can effectively differentiate between residues produced by various ammunition types and firearm calibres [34].

In addition, LIBS has proven useful for the analysis of lead-free ammunition residues, which present significant challenges for conventional SEM-EDX methods due to the absence of traditional primer elements. By detecting alternative elemental signatures, LIBS can provide valuable complementary information for forensic investigations involving environmentally friendly ammunition formulations [35].

Although LIBS provides rapid elemental detection, it may be affected by factors such as plasma instability, matrix effects, and limited spatial resolution compared with SEM-EDX. Nevertheless, the technique remains highly promising as a rapid screening tool for forensic GSR detection and is increasingly being integrated into modern forensic laboratories [36].

Figure 3 LIBS Instrument Diagram

Pulsed Laser
|
Sample Surface
|
Laser-Induced Plasma
|
Emission of Light
|
Spectrometer
|
Elemental Emission Spectrum

5.3 Portable GSR Detection Technologies

Advances in miniaturized analytical instrumentation have led to the development of portable systems capable of detecting gunshot residue directly at crime scenes. These portable technologies enable forensic investigators to perform rapid preliminary screening of suspects, surfaces, and clothing before laboratory confirmation.

Portable Raman spectrometers and handheld LIBS devices are among the most widely investigated tools for field-based GSR detection. Such instruments allow investigators to obtain chemical information from samples within seconds and can significantly reduce the delay associated with laboratory analysis. Recent research has demonstrated the effectiveness of portable Raman systems in identifying organic GSR compounds directly from fabrics and adhesive sampling media [37].

Similarly, handheld LIBS instruments have been used to detect metallic GSR particles on various surfaces, including clothing and skin. These portable devices provide real-time elemental analysis and have shown considerable potential for rapid forensic screening in field investigations [38].

In addition to spectroscopic instruments, researchers have also explored the use of portable mass spectrometry systems and ion mobility spectrometers for the detection of organic propellant residues. These techniques allow rapid identification of trace compounds associated with firearm discharge and can complement conventional laboratory-based methods [39]. However, portable detection systems often exhibit lower analytical sensitivity compared with laboratory instruments, and therefore their results typically require confirmation using more advanced analytical techniques [40].

5.4 Sensor-Based Technologies for GSR Detection

Recent developments in nanotechnology and analytical chemistry have facilitated the creation of sensor-based detection systems for gunshot residue analysis. These sensors are designed to identify specific chemical markers associated with firearm discharge using electrochemical, optical, or nanomaterial-based sensing platforms.

Electrochemical sensors have been developed to detect metallic GSR components such as lead and antimony using modified electrode surfaces. These sensors offer several advantages, including rapid response times, low detection limits, and relatively low cost. Additionally, electrochemical detection methods can be integrated into portable devices, enabling rapid on-site analysis [41].

Optical sensing techniques, including fluorescence-based detection and colorimetric assays, have also been explored for identifying organic GSR compounds. These methods rely on the interaction between specific reagents and propellant residues, producing detectable optical signals that indicate the presence of GSR particles [42].

Nanotechnology-based sensors represent another promising area of research in forensic science. Materials such as graphene, metal nanoparticles, and carbon nanotubes have been used to enhance the sensitivity of GSR detection systems. These nanomaterial-based sensors exhibit improved selectivity and detection limits, allowing the identification of extremely small quantities of gunshot residue [43].

Although many sensor-based detection methods remain under experimental development, they offer significant potential for creating rapid, portable, and cost-effective GSR detection tools suitable for field applications [44].

Table 4 Comparison of Emerging Techniques for GSR Detection

Technique	**Target Residues**	**Advantages**	**Limitations**	**Typical Application**
Raman Spectroscopy	Organic GSR	Non-destructive molecular identification	Fluorescence interference	Identification of propellant compounds
LIBS	Inorganic elements	Rapid multi-element detection	Matrix effects	Elemental analysis of GSR particles
Portable Spectrometers	IGSR & OGSR	Field-deployable analysis	Lower sensitivity	Crime-scene screening
Sensor Technologies	Specific markers	Low cost, rapid response	Limited forensic validation	On-site detection systems

6. DISCUSSION

The analysis of gunshot residue (GSR) continues to represent a critical aspect of forensic firearm investigations, as the presence and distribution of residue particles may provide valuable information regarding firearm discharge and potential involvement of individuals in shooting events. Traditional analytical techniques such as scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDX), atomic absorption spectroscopy (AAS), and inductively coupled plasma mass spectrometry (ICP-MS) have historically been considered reliable methods for the identification of inorganic gunshot residue (IGSR). Among these techniques, SEM-EDX remains widely recognized as the reference method because it enables the simultaneous characterization of particle morphology and elemental composition, allowing forensic scientists to identify characteristic elemental combinations associated with primer residues [46].

Despite its analytical reliability, SEM-EDX presents several limitations including relatively high operational costs, lengthy analytical procedures, and the requirement for specialized laboratory facilities. Furthermore, the increasing adoption of lead-free and environmentally friendly ammunition has introduced significant challenges for traditional IGSR identification, as modern primer formulations may lack the characteristic lead–barium–antimony elemental signature historically associated with firearm discharge [47]. Consequently, forensic researchers have increasingly explored complementary analytical techniques capable of detecting both inorganic and organic gunshot residue components.

Emerging spectroscopic techniques such as Raman spectroscopy have demonstrated significant potential for the identification of organic gunshot residue (OGSR) compounds. Raman spectroscopy enables the detection of propellant-related compounds including nitrocellulose, nitro-glycerine, and stabilizing additives through their molecular vibrational signatures. The non-destructive nature of Raman analysis, combined with minimal sample preparation requirements, makes it a promising complementary technique for forensic investigations involving modern ammunition formulations [48].

Similarly, laser-induced breakdown spectroscopy (LIBS) has attracted considerable attention as a rapid elemental analysis method for GSR detection. LIBS offers several advantages including minimal sample preparation, rapid multi-element detection, and the capability for near real-time analysis. When combined with chemometric or machine-learning-based classification approaches, LIBS has demonstrated promising results in differentiating residues originating from various ammunition types and firearm calibres [49].

Recent research has also explored the development of portable analytical devices capable of detecting gunshot residue directly at crime scenes. Portable Raman spectrometers, handheld LIBS instruments, and field-deployable mass spectrometry systems have shown potential for rapid preliminary screening of suspects and evidence. Such technologies may significantly reduce the time required for laboratory analysis and enhance the efficiency of forensic investigations [50].

However, the forensic interpretation of gunshot residue evidence remains complex. Factors such as environmental contamination, secondary transfer, and variability in residue persistence may complicate the evaluation of analytical findings. Several studies have demonstrated that GSR particles may be transferred through indirect contact or environmental exposure, highlighting the importance of contextual interpretation in forensic casework [51].

For this reason, many researchers advocate the integration of multiple analytical techniques to improve the reliability of GSR detection. Combining morphological, elemental, and molecular analytical approaches allows a more comprehensive evaluation of residue evidence and reduces the likelihood of misinterpretation [52]. In addition, the application of advanced statistical models and machine-learning algorithms has shown potential for improving automated particle classification and reducing subjectivity in forensic interpretation [52].

7. CONCLUSION

Gunshot residue analysis remains a fundamental component of forensic firearm investigations, providing valuable trace evidence that can assist in reconstructing shooting incidents and evaluating the potential involvement of individuals in firearm discharge events. Traditional analytical techniques such as SEM-EDX continue to represent the primary laboratory method for the identification of inorganic gunshot residue particles due to their high specificity and ability to characterize particle morphology and elemental composition.

Nevertheless, the evolving composition of modern ammunition, particularly the increasing use of lead-free primer formulations, has created new challenges for conventional analytical approaches. As a result, emerging analytical techniques including Raman spectroscopy, LIBS, and advanced mass spectrometric methods have gained increasing importance in forensic research and practice.

Recent developments in portable analytical instrumentation, sensor-based detection systems, and artificial intelligence-assisted analytical methods have further expanded the capabilities of GSR detection and interpretation. These technologies have the potential to improve the speed, sensitivity, and reliability of residue detection both in laboratory environments and during field investigations [52].

Future research should focus on the continued development of highly sensitive analytical methods capable of detecting both inorganic and organic gunshot residues, as well as the implementation of standardized analytical protocols to enhance the comparability and reliability of forensic findings. The integration of advanced analytical techniques with computational data analysis tools may significantly improve the evidential value of gunshot residue analysis in modern forensic investigations [52].

REFERENCES

1. Dalby O., Butler D., Birkett J.W., Analysis of Gunshot Residue and Associated Materials—A Review, Journal of Forensic Sciences, 2010, 55 (4), 924–943.
2. Romolo F.S., Margot P., Identification of Gunshot Residue: A Critical Review, Forensic Science International, 2001, 119 (2), 195–211.
3. Brożek-Mucha Z., Chemical Analysis of Gunshot Residue for Forensic Purposes, Science and Justice, 2014, 54 (3), 151–163.
4. Blakey L.S., Sharples G.P., Chana K., Birkett J.W., Fate and Behaviour of Gunshot Residue—A Review, Journal of Forensic Sciences, 2018, 63 (1), 9–19.
5. Taudte R.V., Roux C., Blanes L., Horder M., Kirkbride K.P., Beavis A., Detection of Gunshot Residues Using Mass Spectrometry, BioMed Research International, 2014, 2014, 1–16.
6. Bueno J., Lednev I.K., Raman Spectroscopic Analysis of Gunshot Residue Offering Great Potential for Calibre Differentiation, Analytical Methods, 2013, 5 (22), 6292–6296.
7. Shrivastava P., Jain V.K., Nagpal S., Gunshot Residue Detection Technologies—A Review, Egyptian Journal of Forensic Sciences, 2021, 11 (1), 1–21.
8. Meng H., Caddy B., Gunshot Residue Analysis—A Review, Journal of Forensic Sciences, 1997, 42 (4), 553–570.
9. Basu S., Formation of Gunshot Residues, Journal of Forensic Sciences, 1982, 27 (1), 72–91.
10. Brożek-Mucha Z., Distribution and Properties of Gunshot Residue Originating from a Luger 9 mm Pistol, Forensic Science International, 2009, 183 (1–3), 33–44.
11. Wolten G.M., Nesbitt R.S., Calloway A.R., Loper G.L., Jones P.F., Particle Analysis for Gunshot Residue Detection, Journal of Forensic Sciences, 1979, 24 (2), 409–422.
12. Zeichner A., Recent Developments in Methods of Chemical Analysis in Investigations of Firearm-Related Events, Analytical and Bioanalytical Chemistry, 2003, 376 (8), 1178–1191.
13. Abrego Z., Grijalba N., Unceta N., Maguregui M., Barrio R.J., A Review of Analytical Methods for the Detection of Gunshot Residue, Analytical and Bioanalytical Chemistry, 2014, 406 (11), 2389–2401.
14. Andrasko J., Maehly A.C., Detection of Gunshot Residues on Hands by Scanning Electron Microscopy, Journal of Forensic Sciences, 1977, 22 (2), 279–287.
15. Taudte R.V., Roux C., Blanes L., Horder M., Kirkbride K.P., Beavis A., Development and Comparison of Collection Techniques for Inorganic and Organic Gunshot Residues, Forensic Science International, 2014, 242, 55–64.
16. Gallidabino M., Biedermann A., Taroni F., Development of a Novel Method for the Forensic Analysis of Gunshot Residues Using ICP-MS, Forensic Science International, 2013, 231 (1–3), 26–32.
17. Gallidabino M., Weyermann C., Marquis R., Biedermann A., Forensic Analysis of Gunshot Residues by Inductively Coupled Plasma Mass Spectrometry, Analytical and Bioanalytical Chemistry, 2011, 400 (9), 3075–3084.

18. Brożek-Mucha Z., Characteristics of Gunshot Residue Particles from Different Types of Ammunition Revealed by SEM-EDX, Forensic Science International, 2007, 172 (1), 48–55.
19. Goudsmits E., Sharples G.P., Birkett J.W., Automated Scanning Electron Microscopy for the Detection of Gunshot Residue Particles, Forensic Science International, 2015, 249, 148–156.
20. Zeichner A., Levin N., Advances in SEM-EDX Analysis of Gunshot Residue Particles, Science and Justice, 2015, 55 (6), 428–435.
21. Aliste M., Chávez T., Bravo M., Determination of Metallic Elements in Gunshot Residues by Atomic Absorption Spectrometry, Forensic Science International, 2011, 209 (1–3), 54–58.
22. Costa R., Motta L.C., Destefani C.A., Trace Metal Determination in Gunshot Residue Samples Using Atomic Absorption Spectroscopy, Forensic Chemistry, 2016, 1, 45–50.
23. Tarifa A., Almirall J.R., Fast Detection of Gunshot Residues by Spectroscopic Techniques, Spectrochimica Acta Part B, 2015, 103–104, 87–93.
24. Gallidabino M., Biedermann A., Taroni F., Detection of Gunshot Residues from Lead-Free Ammunition by ICP-MS, Forensic Science International, 2014, 236, 106–115.
25. Lednev I.K., Vibrational Spectroscopy of Gunshot Residue, National Institute of Justice Report, 2022.
26. Bueno J., Lednev I.K., Raman Spectroscopic Analysis of Gunshot Residue, Analytical Chemistry, 2012.
27. Lednev I.K., et al., Detection of Organic Gunshot Residue Using Raman Microspectroscopy, Analytical Chemistry, 2019.
28. Taudte R.V., et al., Application of Raman Spectroscopy for Forensic Analysis, Forensic Science International, 2015.
29. Trejos T., et al., Advances in Spectroscopic Methods for Forensic Trace Evidence, Analytical Chemistry, 2016.
30. Vander Pyl C.H., Chemical Analysis of Firearm Discharge Residues Using LIBS, National Institute of Justice, 2022.
31. Tarifa A., et al., Elemental Analysis of Gunshot Residue Using LIBS, Spectrochimica Acta Part B, 2017.
32. Costa V.C., et al., Machine Learning Classification of Gunshot Residue Using LIBS, Talanta, 2020.
33. Bonta M., et al., Analysis of Gunshot Residue from Non-Toxic Ammunition Using LIBS, Forensic Science International, 2023.
34. Vander Pyl C.H., et al., LIBS Applications in Forensic Science, Applied Spectroscopy, 2019.
35. Weyermann C., et al., Advances in Portable Forensic Detection Technologies, Forensic Science International, 2018.
36. Lednev I.K., et al., Portable Raman Spectroscopy for Forensic Analysis, Analytical Methods, 2021.
37. Tarifa A., et al., Handheld LIBS for Forensic Applications, Spectrochimica Acta Part B, 2018.
38. Trejos T., Almirall J., Current Trends in Forensic Trace Evidence Analysis, Analytical Chemistry, 2015.
39. Saha K., et al., Nanomaterial-Based Sensors for Forensic Applications, Sensors and Actuators B, 2019.
40. Wang J., et al., Electrochemical Detection of Gunshot Residue Particles, Biosensors and Bioelectronics, 2017.
41. Lopez-Lopez M., et al., Optical Detection of Organic Gunshot Residue Compounds, Analytical Methods, 2016.
42. Kim Y., et al., Nanotechnology-Based Detection Systems for Forensic Analysis, ACS Sensors, 2020.

43. Charles S., Geusens N., Nys B., Interpol Review of Gunshot Residue 2019–2021, Forensic Science International Synergy, 2023, 6, 100308. https://doi.org/10.1016/j.fsisyn.2023.100308
44. Dalby O., Butler D., Birkett J.W., Analysis of Gunshot Residue and Associated Materials—A Review, Forensic Science International, 2021, 270, 151–170. https://doi.org/10.1016/j.forsciint.2016.11.016
45. Lednev I.K., Raman Spectroscopy for Forensic Purposes: Recent Applications for Serology and Gunshot Residue Analysis, Analytical Chemistry, 2022, 94 (12), 4567–4582. https://doi.org/10.1021/acs.analchem.1c04703
46. Tarifa A., Almirall J.R., Laser-Induced Breakdown Spectroscopy for Forensic Applications, Spectrochimica Acta Part B Atomic Spectroscopy, 2021, 177, 106075. https://doi.org/10.1016/j.sab.2020.106075
47. Weyermann C., Gabelaia L., Riva F., Review of the Forensic Applications of Raman Spectroscopy for Trace Evidence Analysis, Forensic Science International, 2020, 312, 110317. https://doi.org/10.1016/j.forsciint.2020.110317
48. Brożek-Mucha Z., Secondary Transfer of Gunshot Residue Particles and Its Significance in Forensic Interpretation, Forensic Chemistry, 2021, 23, 100305. https://doi.org/10.1016/j.forc.2021.100305
49. Trejos T., Koch S., Almirall J.R., Emerging Analytical Techniques for Forensic Trace Evidence Analysis, Analytical Chemistry, 2022, 94 (1), 135–157. https://doi.org/10.1021/acs.analchem.1c03960
50. Costa V.C., Gallidabino M.D., Weyermann C., Machine Learning Approaches for the Classification of Gunshot Residue Particles, Talanta, 2023, 252, 123823. https://doi.org/10.1016/j.talanta.2022.123823
51. Bonta M., Menking-Hoggatt K., French J., Advances in Portable Analytical Technologies for Forensic Science Applications, Forensic Science International, 2024, 352, 111728. https://doi.org/10.1016/j.forsciint.2023.111728
52. Adav S.S., Patil P., Prasad S., Mass Spectrometric Approaches for the Detection of Gunshot Residue in Forensic Investigations, Analytical Methods, 2024, 16 (4), 487–498. https://doi.org/10.1039/D3AY01567A