

Article

From Locard to Court: The Scientific Foundations and Legal Admissibility of Firearm Evidence in Court

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Abstract

Background/Objectives: Despite its central role in murder investigations, firearm evidence remains one of the most scientifically contested and legally scrutinised forms of forensic proof. International critiques have highlighted limitations in foundational validity, examiner subjectivity, and individualisation claims within firearm and toolmark analysis, underscoring the importance of examining these issues within the South African context. Despite its central role in murder investigations, firearm evidence remains one of the most scientifically contested and legally scrutinised forms of forensic proof. Firearm evidence remains central to murder investigations; however, ongoing scientific and legal debates continue to raise concerns about its reliability, interpretation, and admissibility. **Materials and Methods:** A qualitative case study approach was used to examine the scientific basis, forensic integrity, and legal admissibility of firearm evidence. Semi-structured interviews were conducted with 39 purposively selected participants, including detectives, crime scene experts, and ballistics specialists. Participants were drawn from Tshwane-based police stations with high murder rates, using a combination of purposive, random, and systematic sampling techniques. Guided by interpretivist and constructivist paradigms, thematic and content analysis were applied building inductively on the empirical findings and informed by contemporary international debates. The study developed the Triadic Model of Forensic Investigation: Science, Integrity, and Law, integrating scientific, procedural, and legal dimensions of firearm evidence. **Results:** The study examined the Locard Exchange Principle as the scientific foundation of firearm evidence and found varying levels of practitioner understanding. Although some participants demonstrated foundational knowledge of forensic concepts such as identification and individualisation, terminology and conceptual understanding varied substantially across professional groups. Understanding of chain-of-custody requirements and legal admissibility criteria was uneven, with notable gaps among some practitioner groups. These inconsistencies, particularly among Investigating Officers, have significant implications for evidentiary integrity and courtroom reliability, especially in contexts where courts increasingly scrutinise categorical claims of firearm source attribution. **Conclusions:** The results highlight the importance of aligning professional practice, forensic education, and evolving scientific and legal standards to support reliable and legally admissible firearm evidence. The Triadic Model provides a coherent evaluative structure for strengthening the reliability, interpretive accuracy, and legal defensibility of firearm evidence. The study emphasises the value of interdisciplinary collaboration and closer alignment between forensic science, operational practice, and evolving judicial standards.



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1. Introduction

Murder investigations involving firearms sit at the intersection of forensic science, procedural rigour, and legal scrutiny, rendering firearm-related evidence particularly vulnerable to scientific and evidentiary challenges [1]. Despite significant advances in forensic technologies, firearm and toolmark evidence remains one of the most contested forms of forensic proof, attracting sustained scientific critique and increasing judicial scrutiny in both domestic and international contexts [2].

In recent years, debates within forensic science have intensified regarding the foundational validity, reliability, and interpretive limits of firearm and toolmark identification. International research has highlighted concerns relating to examiner subjectivity, reproducibility, error rates, and the absence of standardised criteria for source attribution, issues that have direct implications for the admissibility and weight of firearm evidence in court [3–5]. Within this broader forensic context, firearm-related evidence occupies a particularly contested position due to its interpretive and methodological complexity. Conclusions often depend on expert judgment and pattern interpretation rather than fully validated quantitative comparison frameworks. Although firearm and toolmark identification has a long history of courtroom use, contemporary forensic scholarship increasingly challenges the scientific foundations underlying traditional comparison practices, particularly categorical claims of individualisation [6,7]. At the same time, courts have begun to place greater emphasis on methodological transparency, qualification of conclusions, and explicit communication of uncertainty, reflecting evolving evidentiary standards for expert testimony [8]. Despite this growing body of international literature, limited empirical research has examined how forensic practitioners themselves conceptualise the scientific foundations, procedural integrity, and legal admissibility of firearm evidence, particularly within the South African context. Available studies indicate that practitioner understanding of core forensic concepts such as Locard's Exchange Principle, the distinction between identification and individualisation, and evidentiary continuity directly influences investigative reliability, evidentiary interpretation, and judicial decision-making [7,9]. Yet these issues remain empirically under-examined in local forensic and investigative practice.

Against this backdrop, this study addresses a critical knowledge and practice gap by examining practitioners' conceptual understanding of firearm evidence across scientific, procedural, and legal dimensions. Specifically, the study investigates how these understandings shape the generation, interpretation, and courtroom presentation of firearm evidence in murder investigations.

To address these gaps, the study introduces the "Triadic Model of Forensic Investigation: Science, Integrity, and Law," a framework that integrates foundational scientific principles, procedural requirements, and legal standards governing evidence interpretation and admissibility. By bridging these domains, the model provides a structured and theoretically grounded lens for evaluating the lifecycle of firearm evidence from its creation and transfer to its forensic processing and judicial scrutiny. This model offers a structured framework for examining and enhancing the scientific foundation, procedural integrity, and legal admissibility of forensic evidence. This article is organised as follows: next, the literature review on the scientific basis, forensic integrity, and legal admissibility of firearm evidence in murder investigations is presented, followed by a description of the qualitative

case study approach employed to examine these dimensions within Gauteng. Thereafter, the article outlines the research methodology, presents the findings and discussion, and concludes with recommended strategies for enhancing the use of firearm evidence in murder investigations.

The literature review examines the scientific foundations, forensic integrity, and legal admissibility of firearm evidence. Following a thematic approach, it draws on forensic science literature, legal analyses, and empirical studies to examine how firearm evidence informs both investigative processes and judicial outcomes. By synthesising findings from multiple disciplines, this review identified three interrelated domains that consistently emerged as foundational to effective forensic investigation: scientific foundation, forensic integrity, and legal admissibility of firearm evidence [10].

Scientific Foundations: Locard's Exchange Principle, commonly expressed as "every contact leaves a trace", provides the theoretical foundation for forensic interpretation of physical evidence. Although widely accepted, contemporary forensic scholarship increasingly interrogates how this principle is operationalised in practice, particularly in complex crime scenes where trace transfer, persistence, and interpretation are not always straightforward [7,11]. This framework remains central to modern criminalistics, where advances in analytical chemistry have refined the detection and characterisation of trace transfers across materials, including gunshot residue (GSR), fibres, glass, and related microtraces [7].

Within firearm and toolmark analysis, Locard's Exchange Principle underpins the assumption that mechanical interactions generate traceable marks. However, the inferential strength of these marks and the degree to which they support individual source attribution has become a central point of scientific debate [7,12–16].

While empirical research attributes firearm-related toolmark variation to manufacturing processes and wear, the extent to which such variations reliably support individual source attribution remains contested. Variability and surface topography form the basis of comparison, yet translating these features into scientifically defensible conclusions raises significant methodological challenges [7,17–19].

However, major scientific reviews including the National Academy of Sciences [2] and the President's Council of Advisors on Science and Technology [20] have challenged the empirical basis for traditional toolmark identification, arguing that the discipline lacks foundational validity, standardised comparison criteria, and adequate error rate research. These critiques highlight the need for greater empirical rigour, reproducible methodologies, and validated comparison protocols to support firearm/toolmark conclusions. These scientific criticisms have stimulated substantial methodological advancements. The U.S. National Institute of Standards and Technology (NIST) report a shift toward quantitative, instrument-based analysis, including 3D topographical imaging, computational similarity scoring, confocal microscopy, and micro computed tomography. These approaches aim to reduce examiner subjectivity and enhance reproducibility by using measurable, statistically defensible criteria rather than purely subjective visual comparison [19,21]. Judicial analyses likewise reflect these ongoing scientific debates. Reviews compiled in the NIJ Post PCAST Judicial Database show that courts increasingly reference NAS and PCAST critiques, limiting categorical individualisation claims and requiring examiners to qualify their conclusions. At the same time, emerging validation studies suggest improved accuracy and reproducibility when modern, standardised methods are used, indicating that the discipline may be evolving toward greater empirical robustness [22].

The literature indicates that firearm/toolmark identification remains scientifically significant but contested. The field is transitioning from subjective comparison microscopy toward more standardised, quantitative, and empirically grounded methodologies, with direct implications for forensic integrity and legal admissibility. Forensic integrity in firearm ex-

amination extends beyond technical procedures and encompasses the conceptual, methodological, and procedural soundness of conclusions drawn from firearm-related evidence. Contemporary forensic scholarship increasingly focuses on how firearm evidence is interpreted, framed, and constrained to ensure that conclusions remain scientifically defensible and legally credible, particularly where expert judgment plays a central role.

Within forensic discourse, individualisation refers to the assertion that a particular firearm is the sole source of a questioned mark, an inference that remains scientifically contentious due to the absence of universally accepted criteria and statistically validated thresholds. Digital comparison systems such as the Integrated Ballistics Identification System (IBIS) support the organisation and correlation of ballistic signatures but do not, in themselves, provide scientifically validated criteria for individual source attribution without further empirical justification [23]. However, the scientific community has raised concerns about the reliability of individualisation claims. The National Academy of Sciences [2] and the President's Council of Advisors on Science and Technology [20] have criticised traditional firearm identification methods for lacking foundational validity and repeatability, urging more empirical studies and standardisation [9]. Kaye [6] further distinguishes between identification and individualisation, arguing that while identification is widely accepted, individualisation requires a higher burden of proof and should be approached with caution in legal contexts. While identification conclusions tend to be stable overall, claims of individualisation need much more robust supporting evidence. Hicklin [5] highlight notable variability among examiners and limitations in methods, suggesting caution when claiming same source conclusions [5]. Identification is generally recognised as a classification process; however, individualisation asserting that a specific firearm created a particular mark demands considerably stronger empirical backing. Recent research on toolmarks shows that relying solely on subjective examiner judgments is inadequate, and that individualisation should be based on validated statistical methods. The Scientific Working Group for Firearms and Toolmarks (SWGgun) also emphasised the importance of applying rigorous scientific methods such as hypothesis testing, controlled experimentation, and peer-reviewed validation to support individualisation claims.

However, sustained scientific scrutiny has further highlighted the limitations of subjective comparison procedures traditionally used in firearm examination. Contemporary debates increasingly stress the need for probabilistic or statistical approaches to strengthen the empirical foundation for individualisation conclusions, particularly in light of demonstrated examiner variability [5].

Policy developments also reflect these scientific concerns. The U.S. Department of Justice's Uniform Language for Testimony and Reports (ULTR, [24]) explicitly prohibits firearm examiners from asserting uniqueness, zero error rates, or infallibility. Instead, examiners must express conclusions in qualified and scientifically defensible terms, such as "identification," "inconclusive," or "elimination".

The *Abruquah v. State* [25] ruling by the Maryland Supreme Court offers a further illustration of this shift: although firearm evidence was deemed admissible, the Court prohibited unqualified source attribution testimony, requiring experts to frame their conclusions as "consistent with," rather than categorically identifying a firearm as the unique source.

In terms of scientific evidence, Lyle [26] outlines relevance and reliability as the key standards that guide its acceptance in court. Rather than merely reaffirming relevance and reliability as admissibility thresholds, contemporary judicial scrutiny increasingly interrogates how scientific limitations, uncertainty, and examiner discretion are communicated within expert testimony [27,28]. This means that scientific testimony must be based on principles that have gained general acceptance within the scientific community, ensuring

that only well-established methods are presented in court. In South Africa, the reliability of firearm evidence is often tested through cross-examination rather than through a formal admissibility standard. The reason is that the country does not yet apply a Daubert-like framework, a legal standard used to assess the admissibility of expert scientific evidence based on its relevance, reliability, and methodological validity. This lack places significant responsibility on forensic practitioners and legal professionals to ensure that the evidence presented is scientifically sound and legally defensible [9].

Recent literature emphasises that scientific rigour alone is insufficient to guarantee forensic integrity. Adequate proficiency testing, inter-laboratory validation, structured decision-making frameworks, and continuous training highlighted by organisations such as NIST and OSAC are essential for ensuring the accuracy and reproducibility of firearm examinations [19,29]. Without such procedural safeguards, even scientifically defensible techniques risk producing inconsistent or unreliable results due to practitioner variability or inadequate documentation. Thus, forensic integrity emerges as a critical dimension connecting scientific foundation to legal admissibility. Conceptual gaps, inconsistent terminology, and procedural weaknesses undermine the reliability of firearm evidence and may jeopardise its credibility during judicial evaluation.

Legal Admissibility of Firearm Evidence: Contemporary legal scrutiny increasingly shifts away from restating threshold admissibility criteria toward interrogating how scientific uncertainty, methodological limitations, and expert discretion are articulated, constrained, and justified within judicial decision-making [30].

Rondinelli [31] notes that the materiality of evidence is shaped by how the parties define the case, how the offence is described in the criminal code, and how the charge is framed in the indictment or information. Recent scholarship similarly emphasises that the *materiality* of forensic evidence depends on its connection to legally defined issues in dispute, the statutory elements of the offence, and the way prosecutors and defence counsel structure the narrative of the case [27]. While forensic science aspires to reproducibility, peer review, and methodological validation, courts increasingly scrutinise whether these standards are meaningfully satisfied in practice, particularly within pattern-comparison disciplines such as firearm examination [14].

Literature [32,33] stresses the importance of maintaining a transparent chain of custody from the crime scene to the courtroom. Maintaining the integrity of evidence via a proper chain of custody is another essential element of forensic science [14]. The admissibility of forensic evidence relies on establishing an unbroken chain of custody. Recent research highlights that maintaining a continuous and well-documented custody trail is crucial for ensuring the authenticity and legal admissibility of forensic exhibits [34–36].

Rather than treating chain of custody as a procedural checklist, contemporary legal and forensic scholarship conceptualises evidentiary continuity as a point of vulnerability, where gaps, inconsistencies, or inadequate documentation risk undermining judicial confidence in otherwise probative evidence.

The presentation of physical evidence in court requires careful adherence to legal standards to ensure its admissibility and relevance [37]. Marais [38] and Van Rooyen [39] recognise that tangible evidence must be identified and authenticated through oral testimony by a witness with direct knowledge of its collection or handling.

Modern admissibility discourse frames authentication not as a routine formality, but as part of the judiciary's broader gatekeeping responsibility to ensure that evidence presented to fact-finders is both reliable and contextually intelligible.

Rule 901 of the Federal Rules of Evidence requires testimony sufficient to support a finding that the item is what its proponent claims [40]. Comparable principles emerge

across jurisdictional guidance, emphasising that evidentiary authentication functions as a safeguard against unverified or misleading forensic assertions [29].

According to Zeffertt and Paizes [41], relevance functions as a threshold criterion for admissibility, while Schwikkard and Van der Merwe [42] emphasise that admissibility is binary but evidentiary weight may vary depending on circumstances. Courts therefore assume responsibility not merely for admitting forensic evidence, but for critically evaluating its probative force and epistemic limitations.

Within an adversarial justice system, forensic experts are subject to intensive scrutiny through cross-examination and must establish credibility through both qualifications and the transparent application of reliable methodologies. Contemporary legal commentary highlights the judiciary's strengthened gatekeeping role, requiring judges to assess whether expert opinion is grounded in recognised specialised knowledge and applied through sound reasoning [4,43,44].

Beyond national operational requirements, contemporary international case law demonstrates heightened judicial scrutiny of firearm and toolmark evidence. Courts in multiple jurisdictions increasingly demand that firearm evidence meet rigorous reliability thresholds, drawing extensively on scientific critiques such as those documented in the NAS [2] and PCAST [20] reports. These reports highlighted methodological limitations, insufficient error rate data, and a lack of standardised comparison criteria issues that now inform judicial evaluations of expert testimony.

In the United States, the admissibility of firearm evidence is guided by either the Frye standard (general acceptance) or the Daubert standard, which examines testability, peer review, error rates, and methodological standards. Judicial analyses published in *Judicature* reveal that more than half of recent court decisions explicitly reference NAS and PCAST critiques when limiting expert conclusions [22]. In *United States v. Glynn* [45], firearm examiner testimony was restricted to statements that a match was “more likely than not,” reflecting judicial caution toward categorical source attribution. In *People v. Kirschke* [46], the court condemned a categorical individualisation claim as scientifically unsupportable. Similarly, *Abruquah v. State* [25] upheld admissibility but prohibited unqualified source identification testimony, requiring experts to express conclusions using qualified language such as “consistent with”.

Amendments to Federal Rule of Evidence 702 [40] have strengthened judicial gatekeeping obligations, requiring judges to ensure that experts apply reliable methods and do not overstate their conclusions. These amendments reinforce the growing legal consensus that expert testimony must be grounded in validated scientific principles and communicated with accuracy and transparency.

Internationally, similar developments are evident.

- Canada applies the Mohan test but increasingly references U.S. rulings (including *Glynn* and *Abruquah*) when assessing the reliability of pattern comparison evidence.
- The United Kingdom's Criminal Practice Directions emphasise that expert evidence must be grounded in sound scientific methodology.
- Australian commentary similarly reflects concerns paralleling NAS/PCAST, emphasising reliability, relevance, and cautious expression of uncertainty.

Policy reforms complement judicial developments across jurisdictions. The U.S. Department of Justice's ULTR [24] prohibits firearm examiners from asserting uniqueness or zero error rates and mandates that conclusions be expressed in qualified terms. These policy shifts align with scientific critiques concerning reproducibility, examiner variability, and methodological limitations identified in the foundational forensic science literature.

International jurisprudence demonstrates a converging expectation: firearm evidence must be expressed with caution, supported by empirical research, and presented through

transparent, scientifically defensible methodologies. This legal landscape underscores the need for integrated frameworks such as the Triadic Model proposed in this study that link scientific foundations, forensic integrity, and admissibility standards into a cohesive evaluative structure.

This study is grounded in the Locard Exchange Principle, which asserts that every interaction leaves behind trace evidence. In firearm-related investigations, this principle supports the forensic examination of bullets, cartridge cases, gunshot residue, and the firearm itself. The evidentiary significance of trace transfers lies not in their mere presence, but in the inferential processes through which those traces are interpreted, evaluated, and presented within scientific and legal contexts. These exchanges are vital for reconstructing events and establishing connections. The Locard Exchange Principle highlights the vital role of careful evidence collection, preservation, and analysis in firearm investigations. Mistek [7] points out that Locard's principle remains central to modern forensic science, with ongoing advances in trace evidence detection depending on the meticulous recovery and preservation of microscopic transfers during crimes. However, the probative value of trace evidence depends on the reliability of its interpretation and the integrity of the processes through which it is analysed and conveyed. Mistek [7] points out that Locard's principle remains central to modern forensic science, with ongoing advances in trace evidence detection depending on the meticulous recovery and preservation of microscopic transfers during crimes. Current forensic standards also emphasise that maintaining the integrity of transferred traces from collection to courtroom presentation is crucial to their probative value [29].

Contemporary scholarship, however, emphasises that Locard's principle extends far beyond the simplified maxim that "every contact leaves a trace." Modern forensic science recognises the principle as encompassing not only the physical transfer of material but also the interpretive processes through which meaning is assigned to those traces during analysis and court presentation [7]. This expanded understanding transforms Locard's principle from a purely physical proposition into a conceptual foundation for examining the scientific, procedural, and legal dimensions of firearm evidence. Viewed in this way, Locard's Exchange Principle provides more than a physical explanation for trace transfer; it functions as a conceptual scaffold for evaluating how scientific inference, procedural integrity, and legal reasoning interact in the production of forensic knowledge. The present study builds on this insight by structuring these interactions within a triadic analytical framework, enabling systematic examination of how weaknesses in any one domain may compromise the credibility and admissibility of firearm evidence.

1.1. Locard's Principle as a Scientific Foundation

In the context of firearm investigations, Locard's principle underpins the scientific inference that mechanical interactions during chambering, firing, and ejection leave identifiable striations, impressions, and particulate traces. These transfers form the basis for comparison microscopy and the identification of class and individual characteristics on bullets, cartridge cases, and gunshot residue [7]. However, major scientific reviews such as those by the National Academy of Sciences [2] and PCAST [20] have shown that the interpretation of such traces is not purely mechanical or objective. Rather, the reliability of these transfers and the conclusions drawn from them depends on the scientific validity of toolmark comparison methods, the reproducibility of examiner decisions, and the degree to which transfer patterns can be empirically verified. Locard's principle therefore provides not only a rationale for why trace evidence exists, but also a framework for interrogating how the scientific merit of firearm/toolmark analysis is constructed, tested, and challenged.

1.2. Locard's Principle and Forensic Integrity

Locard's principle also anchors the domain of forensic integrity by emphasising the necessity of proper evidence recovery, preservation, documentation, and handling. A trace is not inherently meaningful unless it is interpreted within a reliable chain of custody and examined using robust forensic procedures. Misunderstanding or misapplying foundational concepts such as confusing identification with individualisation or mishandling trace transfers can compromise the interpretive value of the traces that Locard's principle predicts. The literature highlights persistent conceptual ambiguity among practitioners regarding Locard's principle, the meaning of "individualisation," and the conditions under which trace transfers can be reliably linked to specific objects or individuals [6,7]. These inconsistencies directly impact the integrity of forensic reasoning and the credibility of resulting conclusions. Locard's principle therefore functions as a conceptual bridge linking physical evidence to practitioner competence, methodological rigour, and procedural soundness.

1.3. Locard's Principle and Legal Admissibility

Locard's principle further shapes legal admissibility because courts evaluate not merely the existence of a trace, but the persuasiveness, scientific credibility, and methodological transparency of the interpretation derived from that trace. Courts increasingly scrutinise the scientific foundations of ballistic evidence, requiring examiners to justify the reliability of their interpretations and avoid overstated claims [6,32]. This judicial scrutiny aligns with critiques raised in NAS [2] and PCAST [20], which emphasise the need for empirically grounded and reproducible interpretations of trace evidence. Accordingly, Locard's principle serves as a legal as well as scientific lens, guiding the evaluation of whether the movement from physical trace to forensic interpretation to courtroom testimony is logically coherent, scientifically credible, and procedurally defensible. The admissibility of firearm evidence ultimately hinges on whether the interpretive steps connecting trace transfer, evidence identification, and expert testimony meet the standards of transparency, reliability, and methodological validity expected in modern courts.

2. Materials and Methods

Research Design: This study employed a qualitative case study design to investigate how practitioners understand and apply the scientific foundations, forensic integrity requirements, and legal admissibility standards relating to firearm evidence in murder investigations in Gauteng. This approach facilitated in-depth exploration of practitioner reasoning, evidentiary judgment, and decision-making within real investigative contexts. A qualitative design was selected because it allows rich, contextualised insights into professional knowledge and interpretive practices that cannot be meaningfully captured through quantitative approaches.

The study was grounded in an interpretivist epistemology, which assumes that meaning is socially constructed through training, institutional norms, and real-world practice. A constructivist paradigm further guided the inquiry, recognising that practitioners actively construct understanding through their interactions with evidence, colleagues, and legal actors.

Study Setting: Although the study focused broadly on Gauteng Province, data collection was intentionally limited to Tshwane-based police stations to ensure logistical feasibility and consistent field access. Tshwane policing areas are organised into six clusters, and crime statistics from the preceding year were reviewed to identify stations that had experienced an increase in murder cases. One station from each cluster was then selected

to participate. This ensured that the selected sites were operationally relevant and reflected environments where firearm related murders were increasingly prevalent.

Sampling and Participants: A combination of purposive, simple random, and systematic sampling was utilised. Simple random sampling was used to select police stations: the names of eligible stations were written on separate slips, placed in a container, and one station per cluster was drawn at random. Purposive sampling ensured inclusion of practitioners directly involved in firearm-related murder investigations. From the selected stations, a list of detectives was obtained, and systematic sampling selecting every third name was used to identify investigating officers who met the inclusion criteria. Crime-scene specialists who routinely attend murder scenes within the selected clusters were invited to participate, as were ballistics experts responsible for firearm examinations. Purposive sampling targeted three professional categories central to the lifecycle of firearm evidence:

- Investigating Officers (I/Os)
- Crime Scene Experts (CS Experts)
- Ballistics Experts

These groups were intentionally selected because they represent distinct but interconnected stages in the handling, interpretation, and courtroom presentation of firearm evidence. A total of 39 participants took part in the study: 11 Investigating Officers, 15 Crime Scene Experts, and 13 Ballistics specialists. This sample size allowed for thematic saturation, which was reached when no new ideas emerged across interviews.

Data Collection Procedures: Data were collected through semi-structured interviews designed to encourage detailed accounts of participants' experiences. The interviews explored three domains: the scientific basis of firearm and ballistic evidence; issues relating to forensic integrity, including documentation, contamination prevention, and chain-of-custody practices; and the legal considerations governing admissibility and the evaluation of firearm evidence in court. All interviews were audio-recorded with consent and transcribed verbatim. Field notes were also taken to capture contextual details, nonverbal cues, and emerging insights during interviews. The interview guide was derived directly from the study's three analytical domains and reviewed by two independent forensic science academics to enhance content validity. It was also pilot tested with two practitioners not included in the final sample. Example guiding questions addressed:

- Understanding of Locard's Exchange Principle
- Interpretation of identification vs. individualisation
- Chain of custody practices
- Legal admissibility criteria for firearm evidence

This structured and validated interview process ensured that the data collected were comprehensive, contextually grounded, and directly aligned with the study's scientific, procedural, and legal domains.

Data analysis: The study was guided by interpretivist and constructivist perspectives, recognising that participants' explanations are shaped by investigative environments, organisational cultures, and courtroom expectations. A combination of thematic analysis and content analysis was applied to the transcripts and field notes. Open coding was used to identify recurring patterns, which were then consolidated into themes reflecting scientific foundations, forensic integrity, and legal admissibility. To enhance dependability and confirmability, coding decisions were reviewed with an independent qualitative specialist, and discrepancies were resolved through discussion. A reflexive journal was maintained throughout to minimise researcher bias. Data analysis followed a hybrid thematic and content analytic approach designed to capture both conceptual depth and the specific terminology used by practitioners. The process began with repeated readings of all interview

transcripts to achieve familiarisation and to identify preliminary patterns in the data. Once familiar with the dataset, the researcher undertook open coding, manually assigning codes to meaningful units related to scientific, procedural, and legal concepts [31]. These initial codes were then grouped into broader analytical categories that reflected shared patterns across participant accounts. From these categories, overarching themes were developed to capture convergences and divergences in understanding among Investigating Officers, Crime Scene Experts, and Ballistics Experts. Comparative analysis across these professional groups allowed the researcher to identify both consistent and contrasting interpretations, enhancing the depth and nuance of the findings. To strengthen dependability and confirmability, coding decisions were reviewed with an independent qualitative specialist, and interpretive discrepancies were discussed until consensus was reached. Throughout the analytic process, a reflexive journal was maintained to monitor positionality, document analytic decisions, and minimise the influence of researcher bias.

To enhance dependability and confirmability, coding decisions were reviewed with an independent qualitative specialist, and discrepancies were resolved through discussion. A reflexive journal was maintained throughout to minimise researcher bias.

Trustworthiness and Rigour: Credibility was enhanced by comparing perspectives across detectives, crime-scene personnel, and ballistics experts to identify areas of convergence and divergence. An analytic trail documenting coding decisions, thematic development, and methodological reflections was maintained throughout the process. Peer debriefing further strengthened the credibility and dependability of the analytical interpretations. Transferability was supported through thick description of the study context, participant roles, and operational environments.

Ethical Considerations: Ethical approval for the study was obtained through the relevant university processes, and permission to conduct fieldwork was granted by the South African Police Service. Participation was voluntary, and all individuals received written and verbal information about the purpose of the research, confidentiality protections, and their right to withdraw at any stage. Written consent was obtained from all participants, and anonymity was maintained in all stages of data handling and reporting. All data were securely stored in accordance with institutional ethics requirements.

3. Results

The findings of this study are informed by both a critical synthesis of the literature and qualitative insights derived from interviews with Investigating officers, Crime scene experts, and Ballistics experts (hereinafter referred to as I/Os, CS experts, and Ballistics experts, respectively). The findings of this study are informed by both a critical synthesis of the literature and qualitative insights derived from interviews with Investigating Officers, Crime Scene Experts, and Ballistics Experts. This research examines the scientific foundations, forensic integrity, and legal admissibility of firearm evidence. These themes are explored in detail below and form the basis for the conceptual framework presented later in this section. The findings further integrate cross professional comparisons, thematic patterns, and direct participant expressions, strengthening the analytical depth and alignment with the Triadic Model.

3.1. Scientific Foundation

This theme captures participants' understanding of the foundational scientific rationale underlying trace evidence transfer in firearm-related investigations. Every criminal act, especially violent ones, inevitably leaves behind traces such as prints, marks, or stains which align with Locard's Exchange Principle. In firearm-related investigations, this principle

justifies the forensic analysis of evidence like bullets, cartridge cases, gunshot residue, and the firearm itself [7,14].

Participants' understanding of Locard's Exchange Principle varied substantially. While several Crime Scene and Ballistics Experts referenced trace transfer accurately, many Investigating Officers were unable to explain the principle. Seventeen participants explicitly stated they did not know the principle, noting:

- "I'm not familiar with that principle."
- "I have heard the term but cannot explain it."

Such responses reveal significant conceptual gaps in an area fundamental to interpreting ballistic and trace evidence.

Even participants who attempted explanations often reduced the principle to a basic notion of "something being left behind," without acknowledging contamination control, secondary transfer, persistence, or interpretive limitations. As firearm/toolmark science increasingly moves toward 3D imaging, quantitative comparison methods, and validated measurement systems, practitioners require deeper theoretical knowledge to interpret evidence accurately. Participants' responses suggest limited engagement with concepts such as contamination control, secondary transfer, persistence, and interpretive limitations. These findings align with the Scientific Foundation domain of the Triadic Model by illustrating how variation in theoretical understanding is reflected in practitioner explanations of trace evidence concepts

3.2. Forensic Integrity

This theme explores participants' conceptual understanding of identification and individualisation as components of forensic integrity in firearm investigations. These processes uphold the rigorous scientific and ethical principles that underpin credible forensic work. Participants referred to class characteristics (e.g., calibre, rifling) and individual characteristics (e.g., wear patterns) when describing identification and individualisation processes.

3.2.1. Identification

The study explored participants' conceptual understanding of identification, and six themes emerged from their responses. Participants expressed varied and sometimes inconsistent understandings of the concept of identification. Several Investigating Officers described identification in broad terms as the simple act of "acknowledging or recognising something," reflecting a generalised rather than forensic-specific interpretation. Crime Scene Experts commonly associated identification with fingerprint analysis and suspect matching, explaining that "we identify suspects by lifting and matching fingerprints," which aligns with their routine operational roles at crime scenes. Ballistics Experts, on the other hand, tended to situate identification within a more technical framework, describing it as "comparing items and classifying them based on their features," demonstrating a deeper engagement with object comparison and feature-based classification. Together, these responses illustrate a spectrum ranging from basic recognition to more specialised forensic interpretations, highlighting both interdisciplinary differences and the need for standardised conceptual clarity. Table 1 presents a synthesis of the six emergent themes on participants' conceptual understanding of identification, integrating both frequency and illustrative insights across professional groups.

From Table 1 above, general identification was the most common understanding, reflecting a basic but limited conceptual grasp. Technical identification was less common and found primarily among Ballistics Experts. Ambiguous or incorrect responses highlight the ongoing need for conceptual standardisation and targeted practitioner training.

The analysis of empirical data indicates that, despite varied terminology, several participant responses correspond with general understandings of identification reported in forensic literature [6,9,23]. As shown, general identification was the most expressed theme, indicating a foundational grasp across disciplines. Fingerprint identification was particularly prevalent among Crime Scene Experts, reflecting their routine engagement with this type of evidence. This underscores the influence of operational experience on participants' conceptual frameworks. Themes such as object comparison, scene-based identification, and technical descriptions suggest deeper forensic engagement with both procedural and analytical aspects of forensic work. Some responses reflected engagement with object comparison and technical descriptors beyond general recognition. Technical responses, such as identifying calibre or describing physical attributes, reveal exposure to specialised domains, including ballistics and trace evidence analysis, that are relevant to complex investigations. However, occasional deviations and non-responses, such as "I don't know," highlight the need for ongoing professional development and the use of standardised terminology to ensure consistency in forensic interpretation and reporting.

Table 1. Emergent Themes on Participants' Conceptual Understanding of Identification in Forensic Practice.

Theme	Description	Participants (n)	Participant Groups	Illustrative Response
General Identification	Identification described as recognising or acknowledging an object or person.	18	7 IOs, 3 CS Experts, 8 Ballistics	"It is identifying or recognising something."
Fingerprint-Based Identification	Identification framed through fingerprint analysis and suspect matching.	14	4 IOs, 9 CS Experts, 1 Ballistics	"We identify suspects by comparing fingerprints."
Object Comparison & Classification	Identification via comparison of features and object classification.	5	2 CS Experts, 3 Ballistics	"Comparing items and classifying them based on their features."
Scene-Based Identification	Identification linked to recognising people or objects at a crime scene.	5	2 CS Experts, 3 Ballistics	"We identify people or objects at the scene."
Technical/Descriptive Identification	Identification through technical attributes such as calibre or shape.	2	2 Ballistics	"Describing features like calibre."
Ambiguous/Incorrect Responses	Responses unrelated to identification or participants who did not know.	3	1 IO, 2 Ballistics	"Identification is... knowing something exists?"

3.2.2. Individualisation

Participants described individualisation as the process of associating a specific evidentiary item with a single source based on perceived unique characteristics. This is achieved through comparative analysis. Several participants referred to microscopic features arising from manufacturing processes and wear when describing individualisation [6,9,23].

Participants demonstrated an even wider range of interpretations regarding the concept of individualisation. Several respondents described it accurately as the process of attributing a piece of evidence to a unique source based on distinctive microscopic characteristics. However, others conflated individualisation with suspect identification, suggesting that it involved "singling out" a person rather than distinguishing between evidentiary

items. A number of participants associated individualisation exclusively with fingerprint uniqueness, reflecting a narrow understanding rooted in a single forensic domain. Notably, nine participants were unable to offer any definition at all, indicating limited exposure to or uncertainty about the concept. The variability and conceptual confusion observed among participants suggest differing levels of familiarity with the concept of individualisation.

An analysis of the empirical data revealed that participants had varying understandings of individualisation. First, individualisation was defined by eighteen participants (11 I/Officers, 3 CS experts, and 4 Ballistic experts) as the Identification and Separation of individuals based on unique features. For example, they described individualisation using phrases such as “identifying one item and separating it from others” and “unique features on the specimen.”. and These participants’ responses are in line with the consulted literature [6,9,23].

The second reported understanding concerns individualisation via fingerprint uniqueness. Three CS experts referred to fingerprints as unique identifiers, stating that “fingerprints are unique and belong to one person.” Participants’ emphasis on fingerprints as unique identifiers reflects a broader forensic principle in which distinct physical features are used to individualise evidence. This understanding extends to other forms of forensic analysis, such as firearm examination, where microscopic impression marks, including striations and breech face patterns, are recognised in the literature as reliable indicators for linking ammunition to specific weapons [23].

The third understanding of individualisation relates to practical Forensic examples in Ballistics and Trace Evidence. Ballistics experts provided practical examples of individualisation, using terminology such as “comparing cartridge cases,” “unique marks on bullets,” and “firearm identification through markings.” These responses align with the literature [9,23], indicating a fair operational understanding of individualisation in specialised forensic domains, such as ballistics.

The fourth understanding revealed confusion between individualisation and identification. Some participants, including I/Officers and Ballistics experts, used terminology such as “to single out” and “pinpointing one object or person,” which suggests a conflation of individualisation with identification. These responses reflect a conceptual misunderstanding of forensic terminology.

The fifth theme concerns vague or inaccurate interpretations. Three participants, across CS experts and Ballistics experts, provided responses that diverged from forensic literature. Terminology included “working alone,” “define something in its own version,” and “differentiate evidence by its role in a crime.” These interpretations lack forensic relevance and indicate a fundamental misunderstanding of the concept of individualisation.

The final theme reflects non-responses. Nine participants, comprising three I/O officers and six CS experts, did not respond to the question. In accordance with ethical research practices, the researcher did not compel participation. While ethically sound, the absence of responses may reflect uncertainty or limited knowledge regarding the concept of individualisation.

The empirical data reveals a spectrum of understanding among participants. While several demonstrated conceptual and practical alignment with forensic literature, others exhibited confusion or provided vague interpretations. The prevalence of non-responses and misinterpretations underscores the need for targeted professional development and the standardisation of forensic terminology.

3.2.3. Chain of Custody

Participants described chain of custody as the documentation and transfer process through which physical evidence is managed from recovery to courtroom presentation.

It refers to the continuous, well-documented transfer of physical evidence from the moment of recovery to its presentation in court, ensuring that the item remains authentic, unaltered, and traceable throughout the investigative process. Scholars highlight that any break, ambiguity, or undocumented handover in this sequence can raise questions about contamination, tampering, or integrity, potentially rendering the evidence inadmissible or diminishing its probative value [31,32]. Operational and legal guidelines such as OSAC documentation standards stress the importance of accurate labelling, secure packaging, proper sealing, and detailed recording of every person who handles the exhibit, underscoring that the evidentiary value of physical material depends as much on procedural rigour as on scientific analysis.

Participants' understanding of the chain of custody varied markedly across professional groups. Crime Scene Experts and most Ballistics Experts generally articulated the concept accurately, emphasising the need for consistent documentation and uninterrupted evidence transfer from the crime scene to the laboratory and ultimately to the courtroom. In contrast, many Investigating Officers demonstrated significant misconceptions, offering explanations such as "chain of custody means repeating marks as the bullet rotates" or describing it vaguely as relating to "stability of the evidence." Such misunderstandings highlight critical gaps in procedural knowledge, as errors in maintaining or documenting the chain of custody can result in evidence being excluded, challenged for contamination, or accorded reduced probative value.

The findings related to forensic integrity demonstrate that weaknesses in practitioners' conceptual understanding and procedural execution significantly compromise the reliability of firearm evidence. Even when the scientific foundations of ballistic examination are understood, inconsistencies in documentation, ambiguous terminology, and misconceptions surrounding processes such as identification, individualisation, and chain of custody undermine the continuity and credibility of forensic work. These findings illustrate how participants' explanations of identification, individualisation, and chain of custody vary across professional roles.

3.3. Legal Admissibility

This theme explores participants' understanding of the legal admissibility of firearm evidence, including requirements relating to chain of custody, expert testimony, and evidentiary handling. Responses revealed substantial variation across professional roles, with notable gaps among Investigating Officers and more consistent alignment among Crime Scene Experts and Ballistics Experts. Physical evidence must be directly related to the facts in dispute and possess probative value [31]. The role of proper evidence handling in ensuring admissibility is well recognised in forensic practice. References to accurate collection, preservation, and an unbroken chain of custody reflect the established understanding that evidence that has been mishandled may be excluded. In contrast, properly maintained proof is more likely to be accepted in court. The emphasis on a clear and continuous chain of custody from the crime scene to the courtroom further underscores its critical function in affirming the integrity of the evidence [31,32].

The empirical data from the responses of I/Officers demonstrated a notable lack of alignment with the reviewed literature regarding their understanding of the chain-of-custody concept. All participants provided answers that were either irrelevant or inconsistent with the consulted sources. Additionally, two participants did not respond to the question. The absence of accurate responses from I/Officers is concerning, given the critical role that the chain of custody plays in ensuring the admissibility and integrity of evidence in court proceedings. Participants' responses indicate limited conceptual engagement with the legal meaning of chain of custody among Investigating Officers.

In contrast, empirical data from all participants, including CS experts, yielded responses consistent with the consulted literature. Their understanding reflected the principle that the chain of custody entails documenting all actions taken, with evidence from the point of collection through its presentation in court. The chain of custody documentation serves to demonstrate the integrity and continuity of possession, thereby supporting the admissibility of evidence [31,32]. Most Crime Scene Experts provided descriptions consistent with documentation-based definitions of chain of custody.

The majority of participants from Ballistics experts [12] also demonstrated alignment with the literature, indicating a fair understanding of the chain of custody. However, three participants provided responses that were either vague or conceptually incorrect. For example, one participant equated chain of custody with the repetition of marks during rotation, while another described it as a lack of stability. These interpretations deviate significantly from the accepted forensic definition [31,32]. Most Ballistics Experts articulated elements of the chain of custody consistent with formal definitions, though variation was observed.

Across practitioner groups, although several participants demonstrated procedural knowledge, few explicitly articulated the importance of maintaining a chain of custody, as emphasised in the literature [31,32]. Some participants correctly identified that maintaining an unbroken chain of custody is essential to preserving the integrity of evidence. This finding is in line with the literature, which states the importance of ensuring that the evidence presented in court has not been tampered with and that its origin and handling can be reliably accounted for [31,32]. The findings reveal variation in participants' understanding of the chain of custody across samples. While CS and Ballistics experts generally demonstrate conceptual alignment with forensic standards, I/Officers exhibit a concerning lack of understanding of these standards.

The admissibility of physical evidence in court is widely understood to require proper identification and authentication, typically through oral testimony provided by investigators and forensic experts. References to expert opinion underscore the necessity that such testimony originate from a recognised field of specialised knowledge, be supported by training, study, or experience, and be grounded in verified or assumed facts. To ensure credibility, the expert must clearly demonstrate the relevance of their expertise to the specific facts of the case [15,26].

Participants were requested to articulate the prerequisites for the admissibility of firearm evidence in a court of law. Empirical data from participants in I/Officers indicated that four individuals held that proof must remain unaltered to be admissible in court. Three participants indicated that admissibility depends on the evidence collected by experts, consistent with Field's [15] assertion that expert opinion evidence is admissible when it pertains to a recognised field of specialised knowledge. However, a participant did not respond, and the remaining responses were vague and lacked conceptual clarity. Based on these findings, participants/Officers demonstrate only a partial understanding of the legal and procedural requirements for the admissibility of firearm evidence. Participants' responses reflected partial and, in some cases, incomplete understanding of the legal and procedural requirements governing admissibility.

The responses from the CS experts provided varied but generally accurate assessments of the admissibility of firearm evidence. The majority emphasised the importance of maintaining the chain of custody, which is consistent with Field [15] and Lyle [26], who underscore the necessity of documenting the handling of evidence from collection to courtroom presentation. All responses corresponded to the literature consulted, except for two participants who did not provide answers. CS experts thus possess a sound

understanding of the procedural requirements for the admissibility of firearm evidence, particularly with respect to evidentiary continuity and documentation.

The majority of participants from Ballistics highlighted the importance of expert credibility, competence, and training in ensuring the admissibility of firearm evidence. These responses align with Field [15], who states that expert witnesses must demonstrate specialised knowledge through training, study, or experience in the relevant field. This understanding reflects the participants' operational roles, which often involve providing expert testimony in firearms-related cases. Two participants did not respond, and two others provided conceptually incorrect definitions of chain of custody. Despite these outliers, the majority of Ballistics participants exhibit a comprehensive understanding of the requirements for firearm evidence to be admissible in court, likely due to their professional responsibilities in forensic analysis and in providing expert testimony.

The findings show that participants across the three samples differ in their understanding of the admissibility of firearm evidence in court. Participants from I/Officers showed limited knowledge, with some confusing the requirements for admissibility, such as believing that evidence must only be preserved or collected by experts, without recognising the broader legal standards involved. In contrast, CS expert participants demonstrated a firmer grasp of procedural requirements, especially the importance of maintaining the chain of custody. Their responses were generally consistent with the reviewed literature [15,26]. Participants from Ballistics showed the most advanced understanding. They emphasised the importance of expert credibility, competence, and specialised training, which are essential for evidence to be accepted in court. This response likely reflects their professional roles, which involve providing expert testimony. These findings highlight the need for targeted training to ensure that investigating officers, crime scene experts, and forensic practitioners understand and apply the correct legal standards when handling and presenting firearm evidence in court. This understanding and its application in both training and practice are essential for preserving the integrity of forensic investigations and ensuring that evidence remains admissible in court.

Participants' responses also revealed varying levels of understanding of the broader legal requirements governing admissibility. While Crime Scene Experts highlighted documentation and continuity, and Ballistics Experts emphasised methodological reliability and expert competence, Investigating Officers frequently offered narrow or incomplete interpretations. Many I/Os reduced admissibility to the idea that evidence must remain "unaltered," or that only experts may collect it, without recognising wider legal principles such as relevance, probative value, scientific validity, and expert qualification standards.

These variations were further reflected in participants' descriptions of expert testimony requirements. Ballistics Experts demonstrated greater awareness of the need for specialised knowledge and methodological grounding consistent with literature noting that expert opinion must arise from recognised fields and be clearly linked to the factual issues in a case. Crime Scene Experts also acknowledged the importance of documentation as a legal safeguard. However, several I/Os expressed uncertainty, vague interpretations, or no response at all, indicating limited comprehension of the legal expectations placed on expert witnesses and first responders.

In this context, inconsistent practitioner understanding represents a potential vulnerability, as weak articulation of legal standards may reduce evidentiary robustness or expose firearm evidence to successful courtroom challenges. The findings demonstrate substantial variation in participants' understanding of legal admissibility across professional groups. Crime Scene Experts and Ballistics Experts generally articulated expectations consistent with evidentiary continuity and expert qualification, while Investigating Officers frequently

offered narrow, incomplete, or inaccurate interpretations. These variations highlight differences in professional exposure to legal standards governing firearm evidence.

The findings across scientific foundations, forensic integrity, and legal admissibility reveal recurring patterns of conceptual fragmentation and inconsistent application of forensic principles among practitioners.

4. Discussions

The discussion interprets the findings through the Triadic Model of Science, Integrity, and Law, demonstrating how practitioner understanding influences the reliability and admissibility of firearm evidence. The findings reveal systemic gaps in conceptual knowledge that have direct scientific, operational, and legal implications. These insights illustrate how weaknesses in one domain of the model can undermine evidentiary reliability across the entire forensic process.

4.1. Scientific Foundation: Conceptual Gaps in Forensic Theory

The variation in practitioners' understanding of Locard's Exchange Principle reflects a significant weakness in theoretical grounding. Although many participants routinely handle firearm-related evidence, their conceptual interpretation often lacks depth and fails to reflect contemporary advances in forensic science. This disparity reinforces concerns raised in international forensic scholarship that operational familiarity does not necessarily equate to robust scientific understanding. As forensic disciplines move toward more objective, quantitative methods such as 3D topographical imaging and computational similarity scoring a well-grounded understanding of trace transfer mechanics becomes increasingly essential. Without such grounding, practitioners risk misinterpreting trace patterns, overlooking contamination, or misunderstanding the limitations of subjective comparison. These weaknesses can directly undermine the scientific reliability of ballistic interpretations and increase vulnerability during judicial scrutiny.

4.2. Forensic Integrity: Conceptual Accuracy and Procedural Consistency

The inconsistent understanding of identification, individualisation, and chain of custody observed across practitioner groups raises serious concerns regarding the integrity of forensic processes. Confusion between identification and individualisation is particularly troubling, as unclear or overstated terminology may misrepresent the scientific limitations of pattern evidence. Variability in chain of custody practices especially among Investigating Officers further introduces operational risks that may compromise otherwise valid scientific findings. Weak documentation, ambiguous transfer records, or incomplete evidentiary tracking not only diminish probative value but may also jeopardise admissibility. These findings indicate gaps in conceptual clarity that may contribute to procedural inconsistency and evidentiary vulnerability.

4.3. Legal Admissibility: Bridging Forensic and Judicial Expectations

Understanding of legal admissibility varied substantially across professional groups. While Ballistics Experts demonstrated the strongest grasp of admissibility standards, many Investigating Officers appeared unaware of essential legal criteria such as relevance, materiality, reliability, and the requirements governing expert testimony. This is especially concerning given increasing judicial scrutiny of forensic evidence internationally. Courts now expect transparent methodological justification, carefully qualified expert conclusions, and explicit acknowledgement of uncertainty. Weak practitioner understanding appears to heighten the risk of reduced evidentiary weight and increased susceptibility to legal challenge. These findings underscore the need for integrated legal scientific training to

ensure that practitioners present firearm evidence in ways that accord with contemporary judicial expectations.

4.4. The Triadic Model: Integrating Science, Integrity, and Law

To synthesise the scientific, procedural, and legal themes emerging from the findings, the study developed a conceptual framework that integrates these domains into a coherent model. Building on these findings and inductively on the empirical patterns identified across domains, the study proposes a conceptual framework titled “A Triadic Model of Forensic Investigation: Science, Integrity, and Law,” developed to articulate the interrelationship between foundational scientific principles, procedural integrity, and legal admissibility of forensic evidence. The framework is structured around three core domains: Scientific Foundation: Drawing on Locard’s Exchange Principle, this domain emphasises the theoretical underpinnings of forensic evidence transfer and detection. It provides the epistemological basis for the reliability of forensic methods and supports the legitimacy of trace evidence in investigative contexts. Forensic Integrity: This component encompasses the processes of identification and individualisation, which are central to maintaining the accuracy and credibility of forensic analysis. These processes ensure that evidence is scientifically sound and ethically managed, thereby reinforcing its probative value. Legal Admissibility: The final domain addresses the criteria for the acceptance of forensic evidence in judicial proceedings. It includes relevance, reliability, chain of custody, and expert testimony, each of which contributes to the evidentiary robustness required for courtroom presentation. Figure 1 is a Triadic Model of Forensic Investigation: Science, Integrity, and Law.

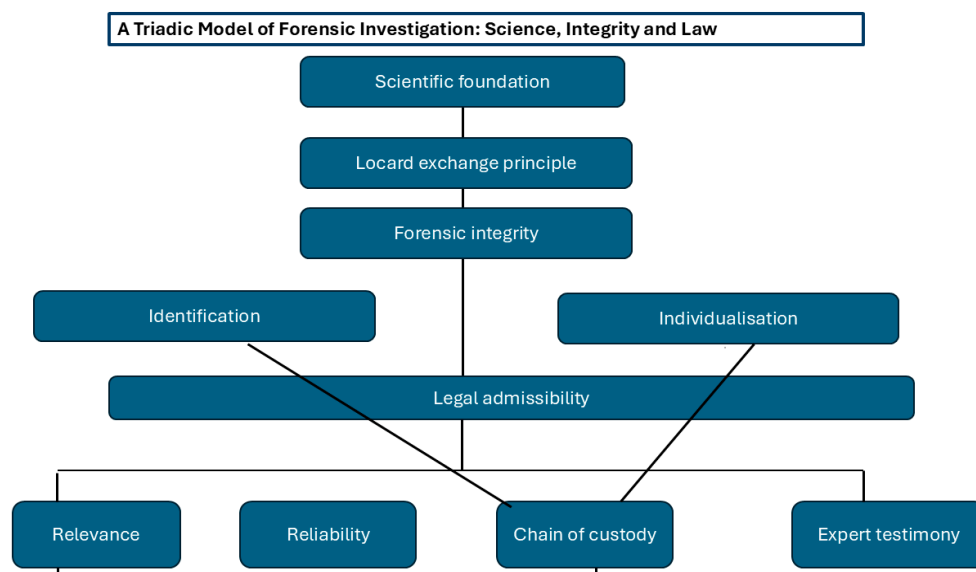


Figure 1. Triadic Model of Forensic Investigation: Science, Integrity, and Law. Source: Developed by the researcher, adapted from [6,7,9,15,23,26,31,32,46].

This model integrates the three domains into a unified structure that illustrates the continuum from evidence generation to courtroom presentation. The integration of these domains within a unified framework highlights the continuum from evidence collection to legal adjudication. It underscores the necessity of maintaining scientific rigour, procedural integrity, and legal compliance throughout the forensic investigative process. This triadic model offers a structured lens through which forensic evidence can be conceptualised, evaluated, and applied in both academic and operational contexts.

The Triadic Model provides a conceptual framework for understanding how scientific foundations, forensic integrity, and legal admissibility interact to shape the evidentiary value of firearm evidence. The model illustrates that the scientific domain establishes the epistemological basis for interpreting trace evidence; the integrity domain ensures that evidence is generated, processed, and interpreted with conceptual and procedural rigour; and the legal domain governs how that evidence is evaluated and used in judicial decision making. The findings show that gaps in any of these domains weaken the entire evidentiary chain. The Triadic Model thus offers a systematic approach for strengthening training, practice, and inter professional coordination across forensic and investigative environments.

4.5. Conceptual Contribution of the Triadic Model of Forensic Investigation

The Triadic Model of Forensic Investigation proposed in this study provides a structured and integrative framework for understanding how firearm evidence acquires evidentiary value from the moment of transfer to its evaluation in court. Rather than conceptualising forensic investigation as a sequence of discrete steps, the model positions it as a continuum in which scientific, procedural, and legal dimensions operate in constant interaction. The scientific foundation domain highlights the importance of validated knowledge and accurate understanding of evidence generation and transfer, especially as the discipline transitions toward more quantitative methods. The forensic integrity domain emphasises conceptual precision, ethical practice, and meticulous documentation as essential requirements for producing defensible forensic outcomes. The legal admissibility domain reflects the increasing judicial expectation that expert testimony be transparent, methodologically grounded, and appropriately qualified.

The model demonstrates that the evidentiary strength of firearm evidence emerges not from any single domain in isolation but from the alignment of scientific validity, procedural integrity, and legal defensibility. A weakness in any dimension such as conceptual uncertainty, poor documentation, or misaligned legal expectations can compromise the overall evidentiary value. Conversely, strong alignment across domains enhances investigative accuracy, strengthens the clarity and credibility of expert testimony, and promotes judicial confidence. In this way, the Triadic Model offers a coherent conceptual tool for identifying points of breakdown, guiding reform efforts, and fostering interdisciplinary collaboration aimed at improving the reliability and admissibility of forensic evidence in murder investigations.

5. Conclusions

This study examined the scientific foundations, forensic integrity, and legal admissibility of firearm evidence in murder investigations, with particular emphasis on practitioners' conceptual understanding and application of key forensic principles. Drawing on Locard's Exchange Principle, the study examined how identification and individualisation processes are understood and operationalised by practitioners when interpreting firearm-related evidence.

Building on this empirical foundation, the study further demonstrated substantial variation in practitioners' understanding of key forensic constructs, including Locard's Exchange Principle, identification, individualisation, and chain-of-custody procedures. While some participants aligned with established forensic literature, many provided incomplete, inconsistent, or inaccurate interpretations, highlighting meaningful gaps in theoretical grounding and operational knowledge. These disparities have implications for investigative reliability, the interpretation of trace evidence, and the consistency with which forensic testimony is prepared and delivered.

Ongoing international debates regarding the scientific validity and reliability of firearm and toolmark analysis further underscore the need for conceptual and methodological clarity. As the discipline moves toward more reproducible, quantifiable, and structured comparison methods, practitioners must possess a sound understanding of the scientific assumptions that underpin firearm examination. Procedural rigour across evidence recovery, laboratory analysis, and courtroom presentation remains a central condition for preserving evidentiary integrity. The findings indicate that weaknesses in practitioners' understanding of these principles may undermine both the scientific robustness of forensic conclusions and judicial confidence in such evidence.

The findings also reveal that legal expectations concerning expert evidence are evolving. International jurisprudence increasingly restricts categorical source-attribution claims and requires experts to articulate their conclusions with greater transparency and accuracy. As courts tighten evidentiary standards and emphasise scientific validity, methodological justification, and the appropriate communication of uncertainty, practitioners bear significant responsibility for articulating evidentiary limitations clearly. The findings indicate that not all practitioner groups possessed a comprehensive understanding of these legal requirements, suggesting misalignment between forensic practice and contemporary judicial expectations.

To synthesise the empirical patterns identified across scientific, procedural, and legal domains, the study proposes the Triadic Model of Forensic Investigation: Science, Integrity, and Law. This model illustrates the continuum from evidence generation to courtroom presentation and demonstrates how weaknesses in any one domain can compromise outcomes across the forensic process. By offering a coherent conceptual lens, the model supports more systematic evaluation of how firearm evidence is produced, interpreted, and presented, and provides a foundation for both academic reflection and operational improvement.

This study underscores the need for continued attention to professional development, conceptual standardisation, and interdisciplinary collaboration. Strengthening alignment between forensic training, scientific research, and legal requirements will help ensure more reliable investigative practices and enhance the evidentiary value of firearm evidence in court. Future research may examine the effectiveness of specialised training programmes, the integration of emerging technological tools into firearm analysis, and cross-jurisdictional comparisons to understand how scientific developments and legal frameworks shape forensic practice globally. Through such efforts, forensic and legal communities may further refine practices supporting the scientifically grounded and legally defensible use of firearm evidence.

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Informed Consent Statement: Informed consent was obtained from all subjects in the study. All participants were informed of the purpose of the research, their voluntary participation, and their right to withdraw at any time. No identifiable personal information was collected, and all responses were anonymised to ensure confidentiality. No identifiable individual data are presented in this manuscript.

Data Availability Statement: Due to the sensitivity of the qualitative data and confidentiality agreements with participants, the interview transcripts and raw data are not publicly available. Anonymised excerpts may be provided by the author upon reasonable request, subject to approval by the UNISA College of Law Research Ethics Review Committee.

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