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Every Contact Leaves a Trace: Forensic Analysis of Hair, Fibers, Paint, Glass, and Soil

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Abstract

Trace evidence is an essential part of forensic science as it provides associations between suspects, victims, objects and crime scenes through the transfer of minute materials. The study of hair, fibers, paint, glass, and soil can yield clues that help in reconstructing the scene of a crime and making investigative decisions, according to the principles of Locard's Exchange Principle. The main categories of trace evidence are discussed, as well as their forensic importance, in addition to how it can be collected, preserved, and analyzed, including the use of microscopy, FTIR, Raman, SEM-EDS, XRF, XRD, ICP-MS and DNA. It also examines the forensic applications, interpretation challenges associated with transfer, persistence, and contamination, as well as quality assurance practices. Finally, recent developments using chemometrics, hyperspectral imaging, laser ablation ICP-MS, artificial intelligence and machine learning are discussed, highlighting their potential to enhance the accuracy, reliability and scientific value of trace evidence in contemporary criminal investigations.

Keywords; Trace evidence; Locard's Exchange Principle; Hair and fiber analysis; Paint, glass, and soil evidence; Forensic analytical techniques.

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1 Introduction

“Trace evidence" is defined as small amounts of physical material transferred when a person, object or environment makes physical contact and then left behind for forensic analysis. These materials are typically imperceptible to the naked eye and can be hard to notice, but they can offer helpful clues about the kinds of interactions that took place, the order of events, and potential correlations between suspects, victims, and crime scenes. Examples of type evidence are hair, textile fibres, paint fragments, glass particles, soil, pollen, and other particles that can remain after physical contact. The ability to detect, characterize and compare these tiny materials has increased greatly due to advances in analytical science, and trace evidence now plays an important role in modern forensic investigations.[2]

The scientific principles underlying the examination of trace evidence were established by the French forensic pioneer Edmond Locard in the early twentieth century, and are known as Locard's Exchange Principle. The principle, often expressed as 'Every contact leaves a trace,' is that when two objects come into contact, there is an exchange of material between the two. This exchange can include hair, fibers, paint chips, glass shards, soil particles or other minute pieces that could be the silent witnesses of a crime. Therefore, trace evidence forms physical connections or associations that are objective and help investigators understand what has happened and how things are connected to the people, things, and places involved.[3]

Forensic value of Trace Evidence is related to corroborating investigative evidence, supporting the testimony of witnesses, excluding innocent people and enhancing the evidential value of other types of forensic evidence. Trace materials are often found in the course of normal human activities or in criminal contexts, and are highly useful in homicide, burglary, sexual assault, hit & run, explosion and environmental crime situations, where biological evidence is not always collected. This is because most of the trace materials display a class characteristic rather than

[2] C. Roux, B. Talbot-wright, J. Robertson, F. Crispino, and O. Ribaux, “The end of the (forensic science) world as we know it? The example of trace evidence,” Philos. Trans. B, 2015, doi: http://dx.doi.org/10.1098/rstb.2014.0260.

[2] E. Mistek, M. A. Fikiet, S. R. Khandasammy, and I. K. Lednev, “Toward Locard’s Exchange Principle: Recent Developments in Forensic Trace Evidence Analysis.,” Anal. Chem., vol. 91, no. 1, pp. 637–654, Jan. 2019, doi: 10.1021/acs.analchem.8b04704.

individual characteristics and interpretation must be based on the careful analysis of transfer, persistence, contamination and contextual information.[4]

The various types of trace evidence include hair, fibers, paint, glass, and soil, which are the most common materials found in the crime lab. Hair can be used for species origin, body area and, in some cases, nuclear and mitochondrial DNA for identification. The transfer of textile fibres from garments to surfaces, such as furniture or vehicles, allows for the creation of physical contact between people or objects. Paint fragments, especially automotive coatings, are of great importance in hit and run/collision investigations and fragments of glass can help to reconstruct breakage incidents and relative positions of suspects and victims. In the same way, the soil has the unique mineralogical, chemical and biological properties that may be linked to a geographic point, a person, a shoe, a vehicle or a tool. All of these forms of trace evidence play an important role in crime scene reconstruction and are also essential to contemporary forensic science as new developments are made in microscopy, spectroscopy, elemental analysis, and statistical interpretation.

2 Classification and Forensic Significance of Trace Evidence

Trace evidence can include a variety of microscopic materials that are transferred by physical contact and left behind on an individual, an object or the environment. These materials are usually considered class evidence, but they also have a significant forensic value in connecting suspects to victims, crime scenes to objects associated with criminal activity, and the people within the class with each other. Their significance is influenced by the nature of the material, transfer mechanism, persistence following transfer and the likelihood of coincidental occurrence. Some of the most common types of trace evidence are transferrable during normal activities and crimes and include hair, fibers, paint, glass, and soil. These trace materials, when combined with other physical evidence, may be an important tool in the reconstruction of a crime and in the interpretation of the investigative evidence.

A. Hair Evidence: Types and Evidential Value

Hair found at a crime scene can be either human or animal and can be additionally sorted by the body site where it was discovered, such as scalp or facial, pubic or limb. Forensically, colour, diameter, medullary pattern, cuticle structure and pigmentation are all features that can be used to compare the hairs, and a hair with a follicular root may be able to be used for nuclear DNA for individual comparison. Rootless hair can also provide mitochondrial DNA making hair

[4] D. Hazard, "The Relevant Physical Trace in Criminal Investigation," J. Forensic Sci. Med., pp. 208–212, 2016, doi: 10.4103/2349-5014.164662.

evidence useful in establishing a linkage, excluding a suspect, and a reconstruction of a contact between victim and perpetrator[5].

B. Fiber Evidence: Natural and Synthetic Fibers

Textile fibres are one of the most frequently found trace materials in forensic investigations. Natural fibres such as cotton, wool, silk and flax are structurally and chemically distinct from synthetic fibres such as polyester, nylon, acrylic and polypropylene. A common way to get fiber transferred is direct contact between clothing, furniture, carpets, vehicles or other fabric. Their evidential value becomes greater when there are multiple matching fibres found in the related areas that have similar physical, optical and chemical properties.[6]

C. Paint, Glass, and Soil Evidence

Paint, glass and soil are very informative types of trace evidence because they have unique physical and chemical characteristics. Paint fragments, often multi-layer automotive coatings, can be found in hit-and-run, burglary and vandalism cases and can be compared based on the structure of the layers, pigmentation, and composition by elements. Glass fragments that are transferred during break up events can be identified by their refractive index, density, elemental composition and fracture characteristics to link individuals and/or objects to a source. Soil evidence refer to the variety of minerals, organic matter, microorganisms and anthropogenic particles that occur in unique combinations and vary geographically. As a result, soil can be collected from shoes, clothing, vehicles or tools to tie people to a specific area.[7]

D. Common Sources, Transfer Mechanisms, Persistence, and Forensic Applications

The transfer, persistence and recovery of trace evidence determines their forensic value. Transfer can happen direct, secondary, or by environmental deposition, while persistence is a function of material type, length and intensity of contact, environment, and subsequent activities. Hair, fibers may remain on clothing after impact, paint and glass may stick to vehicles and tools after impact, soil may stick to footwear and tires after they have been in contact with the ground. These trace materials are commonly used in homicide, sexual assault, burglary, hit and run and

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[5] M. A. Anjum et al., "A Comprehensive Study On Hair As An Investigative Approach In Forensic Science," JHWCR, vol. 4, no. 1, pp. 1–11, 2026.

[6] A. Aljannahi et al., "Forensic Analysis of Textile Synthetic Fibers Using a FT-IR Spectroscopy Approach," Molecules, vol. 27, no. 4281, pp. 1–12, 2022, doi: https://doi.org/10.3390/molecules27134281.

[7] J. Almirall and T. Trejos, "Interpol review of paint, tape, and glass evidence 2019–2022," Forensic Sci. Int. Synerg., vol. 6, p. 100306, 2023, doi: https://doi.org/10.1016/j.fsisyn.2022.100306.

environmental investigations, in addition to providing corroboration to witness evidence, providing association to people, objects and place, and scientific reconstruction of the crime.[8]

3 Collection, Preservation, and Laboratory Examination of Trace Evidence

The forensic significance of the trace evidence is dependent on the successful detection and the appropriate collection, preservation and scientific analysis. Standardized procedures are very important throughout the investigative process because trace materials can be microscopic, fragile, and easily contaminable and lost. The use of proper crime scene procedures, proper evidence handling, and advanced laboratory techniques help ensure trace evidence maintains the integrity and value of the evidence. Modern forensic laboratories use a variety of microscopes, spectroscopes, elemental, crystallographic, and molecular analysis methods to characterize trace materials and make links between the victim, the suspect, the object, and the crime scene.[9]

A. Crime Scene Search Strategies

Systematic crime scene searches are carried out in order to locate visible and microscopic trace evidence prior to the removal of evidence. Search patterns such as grid, spiral, strip and zone are determined depending on the size and complexity of the scene. Evidence is documented in the field with photography and sketching before evidence is recovered and the use of alternative light and magnification aids in finding latent hairs, fibers, paint fragments, glass particles, and soil deposits that may not be visible under normal illumination.

B. Collection Methods for Different Trace Materials

Different collection methods are used depending on the type of trace material. Hair and fibers are usually recovered with clean forceps or adhesive tape lifts and/or specialized vacuum devices. While soil samples are collected from several locations and from several depths, using clean equipment and representative control samples, paint chips and glass fragments are collected using forceps so as to avoid breaking or contaminating them. Throughout the collection

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[8] L. Cadola, M. Charest, C. Lavallée, and F. Crispino, "The occurrence and genesis of transfer traces in forensic science: a structured knowledge database," Can. Soc. Forensic Sci. J., vol. 54, no. 2, pp. 86–100, 2021, doi: https://doi.org/10.1080/00085030.2021.1890941.

[9] T. Schwartz, D. Rothenberg, B. Clark, V. Desiderio, C. Taylor, and N. Daéid, "Trace Evidence Recognition, Collection, and Preservation," pp. 1–31, Aug. 2020, doi: 10.1002/9781119373438.ch1.

process, investigators employ personal protective equipment and disposable instruments whenever possible to minimize contamination.[10]

C. Packaging and Preservation

Trace evidence should be maintained in its physical and chemical state during transit and storage through appropriate packaging. Depending on the type of evidence, individual items are packaged in paper folds, envelopes, vials or rigid containers. To prevent microbial breakdown, moist items such as biological materials and also to prevent fragmentation, glass items and paint shards are dried before being packaged and placed in hard containers. The forensic product is labeled, documented and has an unbroken chain of custody to ensure it is admissible and reliable.

D. Laboratory Examination

Laboratory examination starts with a visual inspection and a stereomicroscopic examination and then the choice of the analytical methods depending on the type of the evidence. If possible, examinations are performed without harming the object, with the option to repeat tests if necessary to confirm. Comparative analysis is the process of using the morphological, physical, chemical, and elemental properties of items to assess the likeness of the questioned sample and the known sample.[11]

E. Common Analytical Techniques

Microscopy continues to be the most important screening tool for examining the morphology, color, surface characteristics and optical properties of hair, fibers, paint, glass and soil particles. Fourier Transform Infrared Spectroscopy (FTIR) is a method that can be used to identify organic compounds and polymer composition, especially for characterization of fibers and paints. Raman spectroscopy can give complementary molecular information with very little sample preparation, and is useful for pigments, dyes and glass analysis. A combination of Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) can be used to provide high magnification surface morphology and elemental characterization and X-ray Fluorescence (XRF) allows for rapid, non-destructive elemental analysis for glass, paint and soil. X-ray Diffraction (XRD) is used to identify crystalline minerals especially in soil and inorganic particles, while Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) is used to

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[10] S. Sandhya and E. Varsha, "Non-Destructive Methods for Trace Evidence Collection: A Review," Int. J. Res. Publ. Rev., vol. 7, no. 4, pp. 10995–11000, 2026.

[11] D. A. Stoney and P. L. Stoney, "Critical review of forensic trace evidence analysis and the need for a new approach," Forensic Sci. Int., vol. 251, pp. 159–170, 2015, doi: https://doi.org/10.1016/j.forsciint.2015.03.022.

provide high sensitivity elemental profiling and source discrimination. DNA analysis including nuclear DNA and, if applicable, mitochondrial DNA, can be used to aid in individual identification and kinship analysis with hair samples that contain whole follicles. Together these complementary techniques offer good scientific support for comparative analysis, source identification, and crime scene reconstruction.[12]

4 Applications, Challenges, and Emerging Advances in Trace Evidence Analysis

Trace evidence is increasingly a multidisciplinary aspect of forensic science which brings objective physical evidence to complement the biological, chemical and digital investigations. Trace materials are usually considered to be class evidence, which means their overall analysis can create meaningful relationships between people, objects and places. Recent technological developments in analytical instrumentation and computation have greatly enhanced the sensitivity, specificity, and reliability of trace evidence examination. It is important to note, however, that the value of the trace material is dependent on rigorous interpretation, consistent quality assurance procedures and the use of new technologies developing that will aid in the forensic decision-making process.

A. Applications of Trace Evidence Analysis

Trace evidence is essential to the process of crime scene reconstruction and may be used to establish the order of events and the type of contact between people and objects. They can provide a connection between suspects, victims, vehicles, weapons and crime scenes to corroborate witness statements or investigative hypotheses through the transfer of hair, fibers, paint, glass or soil. Hair and fiber evidence is often used in homicide and sexual assault cases to show physical contact, while paint and glass fragments in hit and run accidents, burglaries and vehicle collisions are extremely useful. Likewise, footprints, clothing or vehicle tires that have a soil residue on them can tie a suspect or object to a specific area. When considered with other forensic information, trace materials can enhance the reconstruction of a crime event, and contribute to the overall picture of a crime scene.[13]

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[12] V. Alvaro Morillas, K. Suhling, and N. Frascione, “Unlocking the potential of forensic traces: Analytical approaches to generate investigative leads Alvaro,” Sci. Justice, vol. 62, pp. 310–326, 2022, doi: https://doi.org/10.1016/j.scijus.2022.03.005.

[13] A. J. Jeffery, J. K. Pringle, and I. G. Stimpson, “applications of geoforensic trace evidence,” Feature, vol. 40, no. 4, pp. 139–145, 2024, doi: 10.1111/gto.12484.

B. Challenges in Trace Evidence Interpretation

Trace evidence analysis is useful in a crime investigation, but there are some interpretative issues. The secondary transfer might lead to the deposition of trace materials indirectly, which makes the identification of the real source of the material or the time of transfer difficult. The influence of contextual evaluation is also due to the environmental factors as well as daily routine and evidence persistence on the retention or loss of trace materials. Additionally, if proper protocols are not adhered to, contamination during crime scene processing, collection, shipping, and laboratory analysis can influence analytical results. Forensic laboratories have therefore well-established quality assurance protocols, such as analytical methods that have been validated, instrument calibration, proficiency testing, accreditation, thorough documentation and a continuous chain of custody to guarantee the accuracy, repeatability and admissibility of forensic results.[14]

C. Emerging Advances in Trace Evidence Analysis

Advances in technology are still revolutionizing trace evidence analysis, providing greater analytical sensitivity and objective data interpretation. Elemental profiling for source discrimination of glass, paint and other inorganic materials can be done with high resolution using Laser Ablation Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS). Hyperspectral imaging can be used for fast and non-destructive spectral characterization of trace materials, and chemometric techniques can combine multivariate statistical analysis to aid in complex data classification and comparison. In recent years, the field of forensic science has integrated with artificial intelligence (AI) and machine learning algorithms to help automate pattern recognition, classify trace materials, and eliminate examiner bias. These developments in technology increase the reliability, reproducibility and evidential interpretation of trace evidence, thus providing further assistance in the reconstruction of crime scenes and providing a more scientific basis for contemporary forensic investigations.[15]

5 Conclusion

Forensic science is one of the best sciences to use trace evidence as it offers objective links between people, objects, and crime scenes. Hair, fibers, paint, glass and soil all have unique

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[14] S. Luo and X. Qin, "Applications and Challenges of Forensic Science and Trace Examination Techniques inModern Criminal Investigation," Adv. Med. Eng. Interdiscip. Res., vol. 1, no. 4, pp. 1–4, 2023, doi: 10.32629/ameir.v1i4.1427.

[15] J. Almirall and T. Trejos, "Interpol review of forensic paint, tape, and glass evidence 2022-2025," Forensic Sci. Int. Synerg., vol. 13, p. 100696, 2026, doi: https://doi.org/10.1016/j.fsisyn.2026.100696.

physical and chemical properties that, when collected, preserved and studied in a scientific manner, can aid in the reconstruction of a crime. The use of sophisticated analytical methods such as microscopy, spectroscopy, elemental analysis and DNA profiling has significantly enhanced the accuracy and reliability of the characterization of trace evidence. However, because of the difficulties of secondary transfer, persistence, contamination, and classism of most trace materials, careful interpretation is essential. The use of standard operating procedures and quality assurance procedures further bolsters the credibility of forensic results. New technologies like chemometrics, hyperspectral imaging, LA-ICP-MS, artificial intelligence and machine learning are changing how trace evidence is analyzed to improve source discrimination and objective interpretation. As technology advances and interdisciplinary studies continue, there is continued potential for further development of the value of trace material, and its continued irreplaceability in contemporary forensic investigation.

6 REFERNCE

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[2] E. Mistek, M. A. Fikiet, S. R. Khandasammy, and I. K. Lednev, "Toward Locard's Exchange Principle: Recent Developments in Forensic Trace Evidence Analysis.," Anal. Chem., vol. 91, no. 1, pp. 637–654, Jan. 2019, doi: 10.1021/acs.analchem.8b04704.

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