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Fingermark as source of DNA: Systematic Review on Recovery and Factors affecting DNA Typing

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Systematic Review

Keywords: Forensic Science, DNA, Diamond Dye, Fingermark, Electrostatic Detector Apparatus, Shedder status

Posted Date: July 21st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10058223/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

Latent fingermarks have traditionally been used for fingerprint identification; however, advances in forensic genetics have transformed fingermarks into a potential source of DNA evidence. Hence, this systematic review was developed to evaluate the progress of fingermarks as source of forensic DNA between 2000 and 2025 and to synthetize evidence regarding DNA recovery, typing methodologies, factors influencing success, and emerging analytical workflows.

Methods

A PRISMA guideline was used to obtain eligible literature from Scopus, PubMed, and ScienceDirect published from 2000 onward. Screening conducted based on predefined Population-Exposure-Outcome (PEO) framework, where the Population was fingermarks as a source of DNA, the exposure comprised DNA recovery methods and Influencing Factors, and the outcomes were DNA yield, quality, and STR typing success.

Results

3,521 records, of which 78 studies met the inclusion criteria. The final set comprised 39 laboratory experiments, 3 real-case investigations and 1 mixed study. The reviewed studies demonstrated that successful DNA profiling from fingermarks depends on a complex interaction among biological, environmental, and analytical factors. Advances in visualization techniques, including fluorescence-based approaches and Diamond Dye staining, have improved targeted DNA recovery. Extraction efficiency varied according to substrate characteristics and fingerprint enhancement methods, while low-copy number amplification strategies increased profile recovery at the expenses of greater stochastic effects. Donor shedding propensity, deposition pressure, substrate type, and evidence age were identified as major determinants of profiling success. Most contemporary fingerprint enhancement techniques were compatible with downstream DNA analysis, although certain reagents adversely affected DNA recovery. Emerging technologies, including mtDNA analysis, miniSTRs, SNP, and direct-PCR workflows, demonstrated promise for improving the analysis of low-template and degraded fingermarks.

Conclusion

Successful DNA typing depends on an optimized combination of visualization, extraction chemistry, amplification method and sample condition rather than any single factor. Continued standardization of methodologies, validation under operational conditions, and integration of emerging molecular technologies are essential to maximize the evidential value of fingermark-delivered DNA in forensic investigation.

1. Introduction

Fingermarks remain one of the most valuable trace forms in forensic science, traditionally used for personal identification through ridge, pattern analysis, pore characteristics, and other morphological features. However, the recognition that fingermarks also contain shed epithelial cells [1] has expanded their relevance to include DNA analysis. This dual evidentiary potential for ridge details and genetic information [2], [3] offers a significant advantage, especially in cases where either modality alone provides limited probative value. Despite these benefits, recovering sufficient DNA from fingermarks remain challenging. Fingermarks often contains low levels of cellular material, and their composition is highly valuable, influenced by individual biological factors, deposition behavior, substrate characteristics, and environmental exposure[4]. Latent fingermarks, in particular, present additional obstacles because they must first be enhanced before sampling, introducing the risk of DNA loss or degradation during enhancement. The growing body of research on latent DNA has therefore focused on identifying visualization and collection strategies that preserve DNA integrity while maintaining the quality of ridge detail. Advances include the development of sensitive DNA-specific dyes such Diamond Dye (DD), YBR Green, and GelGreen, alongside nondestructive visualization technique like Electrostatic Detector Apparatus (ESDA). At the same time, studies increasingly examine the compatibility of fingerprint development reagents, sampling methods, and extraction method with downstream STR typing. These investigations collectively highlight that successful DNA recovery from fingermarks depends not on the single factor but on an optimized combination of visualization, substrate, extraction chemistry, and sample condition.

Given the expanding interest in harnessing fingermarks for dual forensic analysis, this review integrates findings on DNA recovery, typing performance, and the factors influencing genetic outcomes. By consolidating these insights, it aims to guide practitioners in selecting strategies that maximize evidential value from fingermark traces.

2. Materials and Methods

2.1. Registration and Search Strategy

This review relied on Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines for 2020 [5]. But it was not registered with the International Perspective Register of Systematic Reviews (PROSPERO) since it does not cover Health-related aspects. Accordingly, this systematic review addressed the following question: “How DNA is recovered from fingermarks and influencing Factors affect DNA yield, quality, and STR typing success from fingermark?”. This review question was formulated using the Population-Exposure-Outcome (PEO) framework, where the Population was fingermarks as a source of DNA, the exposure comprised DNA recovery methods and Influencing Factors, and the outcomes were DNA yield, quality, and STR typing success. To search related articles, the Boolean operators used were “AND” and “OR” along with truncation for flexibility. Systematic search was adjusted from 1st

January 2000 onward in peer-reviewed journals from three electronic databases: Scopus, PubMed, and ScienceDirect. A systematic literature search was conducted in PubMed using a combination of Medical Subject Headings (MeSH) terms and free-text keywords. The search strategy adapted for Scopus, and ScienceDirect using relevant keywords. The following key terms used were 'Fingermark', 'Latent fingerprint', 'Fingerprint residue', 'DNA recovery', 'DNA extraction', 'DNA yield', 'Touch DNA', 'Latent DNA'. Specific search strategy is presented in Supplementary material, Table S1. Title, and abstract were first screened for relevance, and clearly irrelevant records were excluded. The next phase involved a removal of duplicates using Excel software, then full texts of potentially eligible articles were assessed in detail, and reasons for exclusion at the full text stage were documented in Supplementary material, Table S2.

2.2. Eligibility Criteria

Based on PEO-based review question developed and other corresponding factors, the studies selected fitting the inclusion criteria were:

- Studies focusing on DNA analysis form fingermarks/latent fingerprints
- Studies analyzing factors affecting DNA quality/quantity from fingermarks/latent fingerprints
- Studies related to recovering DNA from fingermarks/latent fingerprints
- Studies uses naturally deposited human fingerprint
- Published in peer-reviewed Journals
- Published in English
- Original Research, case report, and technical note

Rest of the studies were excluded if:

- Not Forensic related
- Study on non-human DNA
- Focus solely on fingerprint pattern identification without DNA analysis
- Published prior to 2000
- They were not peer-reviewed
- They were not written in English
- They did not provide access to the full text
- They are outside the Scope of forensic DNA analysis.

3. Results

Searching through three electronic databases resulted in a total of 3,521 records from January 2000 onward: PubMed (n = 992), Scopus (n = 1,869), ScienceDirect (n = 660). Screening the title and abstracts of these records yielded 178 articles. After removing 55 duplicate records across the three databases, 123 articles remained. Due to limitations in accessing the full texts of some of the studies, 117 studies were available for eligibility assessment through full-text screening. Of these 39 studies, were excluded for the following reasons: Not meeting the inclusion criteria (n = 32), and review articles (n = 5). Ultimately, 78 studies were included in this systematic review as illustrated in PRISMA flow diagram (Fig. 1).

3.1. Characteristics of the studies

Table 1 provides an overview of studies investigated the recovery and typing of DNA from fingermarks, and factors associated. It was observed that all the included studies were conducted across 19 countries (these data obtained based on the first author's affiliation), such as Australia (n = 21), USA (n = 17), UK (n = 8), Italy (n = 6), Germany (n = 5), Israel (n = 3), Brazil (n = 2), Netherlands (n = 2), Spain (n = 2), Switzerland (n = 2), Thailand (n = 2), Canada (n = 1), New Zealand (n = 1), Norway (n = 1), Portugal (n = 1), Republic of Korea (n = 1), Romania (n = 1), Sweden (n = 1), and Taiwan (n = 1). A significant volume of research conducted between 2015 and 2023, but the highest publication number occurred in 2017, and 2019.

Seventy-four studies were laboratory-based experimental investigations (i.e. the author collected fingerprint from participants in laboratory conditions), while 3 studies were real caseworks (the fingerprint collected from the crime scene), and 1 study combined laboratory experiment and casework. Two kind of fingerprint samples were used: Latent fingerprint/Thumbprint, and Bloody fingerprints/fingerprint contaminated with blood. The included studies evaluated DNA recovery from a wide range of substrate surfaces (see Table 1), including both porous and non-porous materials. Commonly examined surfaces included glass, plastic, metal, paper, adhesive tapes, fabrics, and other everyday materials frequently encountered in forensic casework. Among 78 studies included, only 44 studies incorporated Fingerprint Development Reagent in their experiment and a total of 59 Fingerprint Development Reagent were investigated from 2000 to 2025 (see Supplementary material 1), but 27 investigated and observed their effect on STR profiling. The most studied Fingerprint Development Reagent (FDR) are black powder followed by ninhydrin, black magnetic powder, DFO, and Cyanoacrylate.

Various DNA extraction methods were used across the studies. Commonly applied methods included commercial extraction kit such as QIAamp DNA Mini kit, PrepFiler, EZ1 DNA Investigator kit, Wizard Genomic DNA Purification kit, DNA IQ System, and other specialized forensic extraction systems. Some studies also used traditional organic extraction methods, including phenol-chloroform extraction, or Chelex® based extraction protocols.

For DNA amplification, most studies employed Short Tandem Repeat (STR) profiling kits, particularly widely used forensic kits such as AmpFℓSTR Identifiler, SGM Plus, NGM Plus, NGM Select, and PowerPlex systems. In addition to conventional STR analysis, several studies explored alternative genetic approaches,

including miniSTR markers, Y-STR analysis, mitochondrial DNA, and Single Nucleotide Polymorphism (SNP) genotyping using Massive Parallel Sequencing (MPS) technologies.

Table 1
Characteristics of Included studies

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Szkuta et al, [6] Australia	2017	To evaluate the risk of DNA contamination and secondary transfer via fingerprint brushes and to assess the effectiveness of DNA decontamination methods (1% sodium hypochlorite and 5% Virkon) on squirrel hair and fiberglass fingerprint brushes	Laboratory experimental	DNA IQ™; Powerplex® 21 System (Promega)	-	Glass
Lee et al, [7] Republic of Korea	2019	To investigate the recovery, persistence, and transfer of touch DNA from latent fingermarks and to evaluate factors influencing DNA profile success, including surface type and handling conditions	Laboratory experimental	QIAamp DNA Micro Kit (QIAGEN); AmpFℓSTR® Identifiler® PCR Amplification kit (Applied Biosystems)	Latent fingermarks	Cigarette papers
Bathrick et al, [8] USA	2024	To evaluate the impact of single and sequential latent fingerprint visualization methods on downstream DNA recovery and STR profiling success	Laboratory experimental	EZ1® DNA Investigator Kit (Qiagen); GlobalFiler®PCR Amplification kit (Thermo Fisher)	Latent fingermarks	Black Polyethylene bags
Plaza et al, [9] USA	2015	To evaluate the ESDA as non-destructive method for collecting DNA from latent fingerprint	Laboratory experimental	EZ1® DNA Investigator Kit; AmpFℓSTR IdentifilerPlus kit	Latent fingermarks	Papers (different types)
Romano et al, [10] Italy	2019	To develop a standardized workflow that can generate forensic-useful STR profile from latent fingerprints that were enhanced with dactyloscopic powders and archived for 14 years.	Real casework	EZ1® DNA Investigator Kit; GlobalFiler®PCR Amplification kit	Latent fingermarks	Car glass
al Oleiwi et al, [11] UK	2017	To assess whether the infrared-fluorescent fingerprint powder *fp*Natural 1™ impacts the quantity or quality of touch-DNA recovery from fingermarks.	Laboratory experimental	EZN®Forensic DNA kit; PowerPlex ESI 16 Fast System	Latent fingermarks	Glass slide
Shulte et al, [12] USA	2021	To develop a simple forensic workflow that simultaneously extracts DNA and Protein from individual latent fingerprint samples	Laboratory experimental	Investigator DNA extraction kit; GlobalFiler®PCR Amplification kit	Latent fingermarks	Glass slide
Cornwell et al, [13] Australia	2020	To evaluate the efficiency of DNA extraction from samples coated with 3 brands of fingerprint powders	Laboratory experimental	Chelex, IQ™ System, PrepFiler Express; PowerPlex 21 multiplex system	-	-
Templeton et al, [14] Australia	2017	To investigate how four commonly used dactyloscopic fingerprint powders affect subsequent DNA profiling when direct-PCR approach is applied	Laboratory experimental	No DNA extraction; AmpFℓSTR®NGM SElect™ kit	Latent fingermarks	Plastic slide
Gausterer et al, [15] Austria	2023	To investigate the impact of solvent-based adhesive removal procedures on some critical steps of forensic DNA analysis, focusing of DNA recovery, transfer and amplification by PCR	Laboratory experimental	QIAamp DNA mini Kit; NGM Detect™ kit	Latent fingermarks	Postage stamp, piece of envelope
Sewell et al, [16] UK	2008	To investigate the various factors affecting DNA profiling from DNA recovered from fingerprint deposited on paper before and after fingerprint enhancement	Laboratory experimental	QIAamp DNA mini Kit, DNeasy Plant Mini Kit; AmpFℓSTR®SGM Plus™ kit	Latent fingermarks	Papers (different types)
Zieger at al, [17] Switzerland	2019	To determine how much DNA from a fingerprint transfers to a gelatin filter and to develop a direct proteolytic digestion protocol for extracting that DNA	Laboratory experimental	Organic extraction (Phenol:chloroform: isoamyl alcohol); AmpFℓSTR®NGM SElect™ kit	Latent Thumbprint	Glass
de Oliveira Francisco et al, [18]	2020	To verify and compare the efficiency of two different extraction kits for touch DNA	Laboratory experimental	DNA IQ™ System, Casework Direct Kit (both Promega	Latent fingermarks	Computer keyboard, Knife handle,

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Brazil		samples obtained from fingerprints		and Corporation); PowePlex®Fusion System		exterior and interior door handles, steeling wheels of a car
Harush-Brosh et al, [19] Israel	2021	To determine whether chemical enhancement of blood-contaminated fingermarks can reveal "Touch DNA" of the suspect by comparing the effect of Ninhydrin and Amido Black on DNA recovery	Laboratory experimental	PrepFiler™ BTA kit; PowerPlex® ESI 16 Fast STR Sustem	Blood-contaminated fingerprint	Painted plaster wall coated with acrylic matt
Balogh et al, [20] Germany	2003	To determine whether DNA can be reliable extracted from latent fingerprints on ordinary paper and profiled by STR genotyping and mtDNA sequencing, after optimization of extraction and low-copy-number PCR combinations	Laboratory experimental	InViSorb™ forensic kit; AmpFℓSTR Profiler Plus™ kit	Latent fingermarks	Office printer paper
Steadman et al, [21] USA	2015	To evaluate methods for removing, extracting, and obtaining STR-type from latent-fingerprint lifts that were archived between tape and matte acetate cards from a 1977 burglary-murder case	Real post-conviction casework	Organic extraction (Phenol:chloroform: isoamyl alcohol); AmpliTaq Gold® DNA polymerase	Latent fingermarks	Matte acetate cards
Thomasma et al, [22] USA	2013	To determine whether swabbing solutions containing detergents increase DNA yields from touch-sample fingerprints compared with water-moistened swabs	Laboratory experimental	Organic extraction (Phenol-chloroform and purification on silica spin column; MiniFiler™ kit	Latent fingerprint	Glass slide
Tozzo et al, [23] Italy	2014	To determine whether eight commonly used dactyloscopic powders interfere with short-tandem-repeats (STR) profiling of bloodstains and latent fingerprints, and to compare the effect of different powders and substrates on DNA recovery	Laboratory experimental	ChargeSwitch Forensic DNA Purification kit, QIAamp DNA Micro kit; AmpFℓSTR IdentifilerPlus kit	Latent fingerprint	Glass, paper, plexiglass, ceramic, metal plate
Hughes et al, [24] Australia	2022	To optimize the preparation, application, and visualization of Diamond™ Nucleic Acid Dye for improved detection and localization of latent DNA on non-porous substrate, with a view to improving targeted DNA sampling in forensic practice	Laboratory experimental	Not Applicable	Latent fingerprint	Aluminium foil, Borosilicate glass, Polypropylene, Acrylic, PVC composite material, Crystalline silicon
Fox et al, [25] New Zealand	2014	To investigate the recovery and profiling success of DNA from latent fingermarks and to evaluate factors influencing DNA yield and STR profiling quality when fingermarks are deposited on different surfaces under controlled conditions	Laboratory experimental	QIAamp DNA Investigator Kit (QIAGEN); AmpFℓSTR IdentifilerPlus kit	Latent fingermarks	Glass, Plastic
Khuu et al, [26] Australia	2020	To evaluate the impact of fingermark detection techniques on the recovery and quality of DNA profiles obtained from latent fingermarks, and to assess whether common enhancement processes compromises downstream STR profiling	Laboratory experimental	QIAamp DNA Investigator Kit; GlobalFiler™	Latent fingermarks	Glass, Plastic Surfaces

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Solomon et al, [27] USA	2018	The study sought to "comparatively analyze a variety of collection and analytical methods in an effort to seek an optimized workflow" for obtaining DNA profiles from archived latent fingerprints "sandwiched" between adhesive and paper.	Laboratory experiment	QIAamp DNA Investigator Kit, Phenol-chloroform organic extraction, Invisorb Spin Forensic Kit, prepGEM™ Tissue Kit; AmpFℓSTR IdentifilerPlus kit	Latent fingerprints	glossy paper
Goray et al, [28] Australia	2024	The study aimed to test different data analysis aspects of the Diamond™ Nucleic Acid Dye (DD) method, specifically: Testing counting variability within and between individuals when manually counting DD-stained cells, Testing the "sampling effect" by comparing cell counts from a portion of a deposit to the total number of cells in the entire deposit., Evaluating the accuracy of different shedder status classification methods (Threshold and Cluster analysis).	Laboratory experiment	Not applied	Latent thumbprints and fingerprints	Glass slides and glass plates
Yu et al, [29] USA	2007	The study aimed to determine the effect of 1,2-indanedione treatment on PCR-STR DNA typing of fingerprints deposited on thermal and carbonless paper substrates.	Laboratory experiment	Chelex, QIAamp; AmpFℓSTR IdentifilerPlus kit	Latent fingerprints	Thermal paper, carbonless paper
Shalhoub et al, [30] UK	2008	To investigate the recovery of latent fingermarks using Isomark™ (a silicone-based casting material) and to ascertain whether it is possible to obtain reliable DNA profiles from those casts	Laboratory experiment	QIAamp DNA Mini Kit; AmpFℓSTR SGM Plus Kit	Latent fingerprints	Aluminium cans, plastic water bottles, £2 coins, and 60 W glass light bulbs, Waxy paper cups and hard plastic mobile phone cases
Van Helmond et al, [31] Netherlands	2018	The study aimed to detail the use of cross-linkable solutions of dextran-methacrylate to form hydrogels capable of collecting amino acids from surfaces followed by extraction and quantification, while also investigating the use of hydrogels to collect DNA from fingerprints	Laboratory experiment	Extraction and Amplification not explicitly named	Latent fingerprints	Glass slide
Färber et al, [32] Germany	2010	The objectives included the verification of results to visualize latent fingerprints on human skin with common adhesive agents, determining suitable instruments, proving the possibility of recovering "offender's" DNA from fingerprints placed on skin, exploring the best extraction method for DNA typing with regard to inhibition problems caused by adhesive powders, and developing a standardized method.	Laboratory experiment	Organic Extraction (phenol/chloroform/isoamyl alcohol), NucleoSpin® Tissue XS kit (Macherey-Nagel); Amplification not explicitly named	Latent fingerprints	Human skin (corpses)
Loarce et al, [33] Spain	2023	The study aimed to establish a specific protocol for extracting latent fingerprint DNA that accounts for the characteristics of keratinocytes to assess the quality of the isolated DNA and determine the minimum amount of DNA required to obtain a complete genetic profile of nuclear STR markers and mtDNA hypervariable regions	Laboratory experiment	NZY Tissue gDNA Isolation kit, PrepFiler™ Forensic DNA Extraction Kit, and Gentra Puregene Buccal Cell Core Kit; AmpFℓSTR Identifiler Plus PCR Amplification Kit, BigDye Terminator v3.1 kit	Latent fingerprints	Glass slide

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Di Nunzio et al, [34] Spain	2025	The study's aim was to investigate and optimize DNA collection and extraction methods to determine the Minimum ridge Surface Requirement (MSR), the smallest surface area of a latent fingermark needed to extract suitable human STR genotypes	Laboratory experiment	QIAamp DNA Blood & Tissue kit; AmpFℓSTR Identifiler Plus PCR Amplification Kit	Latent fingermarks	Glass surface
Kwok et al, [35] UK	2023	To compare the use of gelatin lifters with more readily available masking tape in their ability to recover cellular material from latent fingermarks.	Laboratory experiment	Not applied	Latent fingermarks	Glass surface
Bathrick et al, [36] USA	2021	To evaluate the effect of various sequential latent fingerprint processing techniques on the quantity and quality of DNA recovered from fingerprints on paper.	Laboratory experiment	Qiagen® EZ1® DNA Investigator Kit; GlobalFiler PCR Amplification Kit	Latent fingerprints	copy paper
Johannessen et al, [37] Norway	2021	To compare two methods to determine shedder status: the handheld tube (HH) method and a fluorescent cell count (CC) method, and to assess the association between the number of detected cells in a fingerprint and the strength of the DNA result.	Laboratory experiment	No extraction; PowerPlex® Fusion 6C System	Latent fingerprints	Microscopic slide, plastic centrifuge tubes
Young et al, [38] Australia	2020	To examine the spray pattern of 15 different commercial spray devices and test the feasibility of a spray system to apply Diamond Nucleic Acid Dye (DD) to large surfaces to detect cellular material (touch DNA) on casework items.	Laboratory experiment	No extraction; AmpFℓSTR Identifiler Plus Kit	Latent fingerprints	Glass slides, plastic sheets, and brown packing tape, Ziplock bags, a rubber-handled knife, aluminum, credit cards, hammer heads, cotton, polyester, rope, paper wine labels, and wooden surfaces
Nontiapirom et al, [39] Thailand	2019	To assess fingerprint brush contamination and the effectiveness of a simple brush cleaning procedure (using 10% sodium hypochlorite) in preventing DNA transfer during the dusting of latent fingerprints.	Laboratory experiment	Wizard SV Genomic DNA Purification kit; AmpFℓSTR Identifiler Plus Kit	Latent fingerprint	Glass plates
Kanokwongnuwut, Kirkbride & Linacre, [40] Australia	2019	To report a simple method for visualising and screening latent DNA on tapes using a Diamond™ dye (DD) staining process followed by visualisation using a portable fluorescence microscope, and to assess the efficiency of these tapes in recovering cellular material without inhibiting PCR.	Laboratory experiment	No extraction; AmpFℓSTR Identifiler Plus Kit	Latent fingermarks	Glass slides
Subhani et al, [41] UK	2018	To evaluate the compatibility of the most common enhancement methods and lifting techniques with DNA profiling, with an emphasis on modern lifting techniques (gelatin lifters and Isomark™) and historical fingerprint lifts.	Laboratory experiment	QIAamp DNA Investigator Kit; PowerPlex ESI 17 pro system	Latent fingerprint	Glass slide
Kanokwongnuwut et al, [42] Australia	2018	To develop a simple, fast, DNA-staining and fluorescence microscopy-based screening method for swabs to indicate if	Laboratory experiment	QIAamp DNA Investigator Kit; AmpFℓSTR® NGM SElect™ PCR Amplification Kit	Latent fingermarks	Glass slides

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
		there is any DNA from which to generate a profile, thereby reducing the wastage of resources on swabs devoid of biological material.				
Kanokwongnuwut et al, [43] Australia	2018	To demonstrate the effective use of Diamond Dye to bind to DNA and allow visualization of deposited cellular material using a mini-fluorescence microscope on a range of items typical of those submitted as part of a forensic investigation.	Laboratory experiment	No extraction; AmpFℓSTR® NGM SElect™	Latent fingermarks	Glass slides, Credit cards (plastic & metallic chip), Mobile phones (screen & home button), SIM cards, Zip-lock plastic bags, Nickel cartridge cases, Aluminium cartridge case
Martin et al, [44] Australia	2018	To report on successful STR DNA profiling from a range of touched items using direct PCR, with no increase in cycle number.	Laboratory experiment	DNA IQ™; AmpFℓSTR® Identifiler, GlobalFiler® kit	Latent fingermarks	Unfired aluminium cartridge case, insulated wire, circuit board, zip-lock pad, Glass slide, mobile phone, simcard, fuse
Alem et al, [45] Brazil	2017	To evaluate the feasibility and efficiency of recovering STR DNA profiles from latent fingerprints after enhancement with black and magnetic powders, commonly used in forensic practice, particularly when fingerprint identification fails	Laboratory experiment	Lysis-based extraction (SDS+Protease K, Micron®100); PowerPlex® CS7 Kit	Latent fingerprints	Glass slides
Tobias et al, [46] UK	2017	To investigate whether pressure can affect the amount and quality of DNA directly deposited by touch.	Laboratory experiment	QIAamp® DNA Investigator Kit; AmpFℓSTR® NGM SElect™	Latent fingermarks	Polycarbonate boards
Sinelnikov et al, [47] USA	2017	To determine the feasibility of obtaining a genetic profile after fingerprint enhancement with black and magnetic powders commonly used by forensic experts on glass surfaces.	Laboratory experiment	Lysis-based extraction (SDS+Protease K, Xs DNA purification); Identifiler kit, PowerPlex 16	Latent fingerprints	Non-porous surfaces (not specified)
Goecker et al, [48] USA	2016	To compare the efficacy of two DNA quantification kits, Quantifiler® Trio and InnoQuant™, for measuring the extent of DNA degradation in forensic samples, specifically developed and aged fingerprints.	Laboratory experiment	QIAamp® DNA Investigator Kit; AmpFℓSTR® STR amplification kit	Latent fingermarks	Glass
Lim et al, [49] UK	2016	o investigate the success of DNA recovery from the surface of cable sheaths and to evaluate the impact of common fingermark enhancement techniques (cyanoacrylate fuming and wet powder suspensions) on subsequent DNA profiling.	Laboratory experiment	QIAamp DNA Investigator Kit; PowerPlex® ESI 17 Pro System	Latent fingermarks	Black cable sheaths
Pamela et al, [50] Italy	2015	To investigate the effect of fingerprint enhancement powder methods on subsequent STR profiling from bloodstains and latent fingerprints.	Laboratory experiment	Charge Switch® Forensic DNA Purification kit, QIAamp® DNA Micro kit; AmpFℓSTR® STR amplification kit	Latent fingermarks	Glass, paper, Plexiglass, ceramic, metal
et al, [51] USA	2015	The study focuses on whether it is possible to obtain complete and concordant short tandem repeat (STR) DNA profiles from fingerprints wetted with body fluids such as blood and saliva after they have been developed with the columnar-thin-film	Laboratory experiment	EZ1 DNA Investigator Kit, Qiagen BioRobot EZ1 Advanced workstation; AmpFℓSTR Identifiler Plus Amplification Kit	Latent and Bloody fingerprint	1 in × 1 in brass

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
		(CTF) technique. It also explores whether the CTF technique results in partial or no STR profiles and if the method introduces inhibition that may interfere with the DNA analysis process.				
Templeton et al, [52] Australia	2014	The authors state that the study reports a "direct DNA profiling method" designed to generate "interpretable profiles from single fingermarks" by "omitting the extraction process". This approach aims to maximize the retrieval of DNA from "touch" DNA samples and improve success rates compared to standard methodologies	Laboratory experiment	No extraction; AmpFℓSTR® NGM SElect™	Latent fingermarks	Plastic Slide
Templeton et al, [53] Australia	2015	To determine the value of an optimized swabbing technique and direct PCR for amplifying 'touch' DNA from fingermarks in a mock case study	Laboratory experiment	No extraction; AmpFℓSTR® NGMSElect™ kit	Latent fingermarks	Glass, wood, masking tape, brass cartridge cases, aluminium cartridge cases, nickel cartridge cases
Ostojic et al, [54] USA	2014	To find the best procedure for handling fingerprint samples in order to obtain STR profiles of a quality to compare them to databases, such as CODIS	Laboratory experiment	HighSens, Titron-one-tube, prepGEM® Tissue extraction kit; AmpFℓSTR Identifiler Plus Kit	Latent fingermarks	Glass slide
Thamnurak et al, [55] Thailand	2011	To 2 extraction methods for DNA recovery from fluorescent powder dusted latent fingerprints on 3 different surface types and demonstrated the optimal conditions for DNA profiling	Laboratory experiment	QIAamp® DNA Mini Kit, Chelex® 100 extraction method; AmpFℓSTR® Identifiler® PCR Amplification Kit	Latent fingerprint	Glass plates, Glossy magazine papers, Plastic sheets
Bhoelai et al, [56] Netherlands	2011	To study the effects of fingerprint enhancement methods on subsequent DNA profiling	Laboratory experiment	QIAamp; AmpFℓSTR® SGM plus kit	Latent fingerprints	Chlorine-free paper, Plastic sheets
Dominick et al, [57] UK	2009	To investigate whether there is a relationship between the ability to donate fingerprints and the ability to shed DNA	Laboratory experiment	QIAamp DNA Mini Kit; AmpFℓSTR® SGM plus kit	Latent fingerprints	Glass slide
Schulz et al, [58] Germany	2004	To describe the possibility of using ninhydrin-dyed fingerprints as a DNA source for STR typing.	Real case work	Chelex®; no commercial amplification kit used (amplification employed custom singleplex PCR with labeled primers).	Latent fingerprints	Wallpaper
Raymond et al, [59] Australia	2004	To examine the effect of common fingerprint detection techniques on the ability to obtain DNA profiles from fingerprints deposited on different surfaces.	Laboratory experiment	No extraction method stated; AmpFlSTR® Profiler Plus™ kit	Latent fingerprints	Glass, Plastic, Metal, Paper
Bunescu et al, [60] Romania	2025	To develop an alternative methodology for latent fingerprint visualization, adapted for forensic use.	Laboratory experiment	MasterPure™ Complete DNA; AmpFℓSTR® Identifiler® Plus PCR Amplification Kit	Latent fingerprints	Wood, knife (metal)
Hefetz et al, [61] Israel	2015	To examine the direct effect of deposition pressure on the size and quality of latent fingermarks and on the success rate of STR profiling from those marks	Laboratory experiment	AutoMate Express™ Forensic DNA Extraction System combined with PrepFiler Express chemistry; PowerPlex® ESI 16 Fast Systems	Latent fingermarks	Glass slide, White office paper, Plastic bag
Risoluti et al, [62] Italy	2019	To provide a comprehensive study of Lumicyano's capabilities in fingermark detection, compare its performance with conventional cyanoacrylate + Basic Yellow 40, assess the possibility of	Laboratory experiment	EZ1 DNA Investigator; AmpFℓSTR® NGM SElect™ PCR Amplification Kit	Latent fingerprints	Plastic Bottle, Plastic Sheets

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
		subsequent DNA analysis, and clarify the chemical interaction by NMR analysis				
Gino&Omedei, [63] Italy	2011	To determine whether chemicals used for latent-fingerprint enhancement interfere with DNA extraction and amplification from biological samples on scenes	Laboratory experiment	Nucleomag 96 Blood kit; PowerPlex ESX 17 System	Latent fingerprints	Glass, plastic, aluminium, plastic-coated paper, pantyhose, and paper (white, coloured, recycled)
Schulz et al, [64] Germany	2002	To assess the potential use of latent fingerprints as a DNA source for STR typing	Laboratory experiment	InViSorb™; Amplification kits not specifically stated	Latent fingerprints	Glass plates
Harush-Brosh et al, [65] Israel	2020	To examine the scope and limitations of a non-destructive, eco-friendly workflow for latent fingermark collection and subsequent touch-DNA recovery and STR profiling in relation to substrate type, time since deposition and donor gender	Laboratory experiment	AutoMate BTA™ Forensic DNA Extraction System combined with PrepFiler BTA chemistry; PowerPlex® 16	Latent fingermarks	Coated metal car-tin, window glass, painted dry whitewash wall
Ruprecht et al, [3] Switzerland	2022	To determine whether fingerprint processing can be performed before DNA sampling and to identify any fingerprint-processing chemicals that are incompatible with preserving DNA	Laboratory experiment	Forensic DNA Extraction Kit, PrepFiler Express BTA™ Forensic DNA Extraction Kit; AmpF‼STR® NGMSElect™ kit	Latent fingerprints	Adhesive stamp, Envelope
Kanokwongnuwut et al, [66] Australia	2019	To examined the interactions between staining a fingermark to detect DNA and then generate a DNA profile in combination with several standard latent fingermark enhancement methods	Laboratory experiment	No extraction on fingerprint samples, Identifiler® Plus amplification kit	Latent fingermarks	Glass slides, credit cards, soft-drink cans, Australian bank notes and glossy cardboard
Linacre et al, [67] Australia	2022	To illustrate how Diamond™ Nucleic-Acid dye (DD) can be used to rapidly, non-destructively visualize touch-deposited corneocytes and latent DNA on a range of substrates	Laboratory experiment	No extraction; Identifiler Plus kit	Latent thumbprints	Glass slide
Haines et al, [68] Australia	2013	To determine whether dyes such as SYBR Green I can detect DNA within fingermarks	Laboratory experiment	Not applied	Latent fingerprints and Thumbprints	Parafilm, plastic slides, and glass slides
Champion et al, [69] Australia	2019	To visually monitor and record DNA transfer from one substrate to another using the fluorescent reagent Diamond™ Dye (DD)	Laboratory experiment	Not applied	Latent fingermarks	Aluminium, cotton, polyester, plastic
Champion et al, [70] Australia	2021	To explore the use of two Diamond™ Dye (DD) solutions on eight commonly encountered substrates with varying absorbency in order to determine the most suitable diluent for visualizing touch DNA and to aid forensic examiners in selecting an appropriate solution	Laboratory experiment	Not applied	Latent fingermarks	glass slide, plastic-based Australian bank note, human tooth, black cotton fabric, T-shirt fabric (Anko), wooden matchstick, Thai paper bank note, cigarette filter paper, treated paper postage stamp

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Lagao et al, [71] Portugal	2008	To compare the application of autosomic STR, Y-STR and miniSTR markers on fingerprint genetic analysis, increasing the number of PCR cycles as a strategy to accomplish more sensitivity	Laboratory experiment	Phenol:chloroform:isoamyl alcohol (concentrated with Microcon1 spin columns); AmpFℓSTR Identifiler kit	Latent thumbprints	Glass slide
Norlin et al, [72] Sweden	2012	To perform a systematic study of the effect that different fingerprint visualization techniques have on DNA content in fingerprints deposited on various surfaces	Laboratory experiment	Wizard Genomic DNA Purification Kit; BigDye Terminator Kit version 3.1 (for mtDNA)	Latent fingerprints	White paper envelopes, brown paper envelopes, adhesive side of tape, laboratory bench (laminate), wood, plastic bags, and bench-lifted lifts
Tiedge et al, [73] USA	2021	To (a) ascertain human-identity capabilities of DNA obtained from latent fingerprints that have been environmentally insulted and then visualized with a columnar thin-film (CTF), and (b) determine whether the CTF process and materials are detrimental to single-nucleotide-polymorphism (SNP) analysis	Laboratory experiment	EZ1 DNA Investigator Kit; Precision ID Identity Panel and Precision ID Library Kit	Latent fingerprints	Black garbage-bag plastic, brass, cherry wood, glass, and clear-plastic sandwich bags
Alessandrini et al, [74] Italy	2002	To investigate the amount of DNA recovered from various substrates and the influence on it of individual and exogenous factors, as well as the suitability of DNA recovered from fingerprints for personal identification by DNA microsatellites	Laboratory experiment	phenol-chloroform (concentration with Microcon-30® device), AmpFℓSTR Profiler Plus™ kit	Latent fingerprints	Glass, wood (hard-wood cortex), and metal (alloy)
Tsai et al, [75] Taiwan	2015	To evaluate the effects of fingerprint enhancement methods on fingerprints deposited on porous surfaces	Laboratory experiment	DNA Extractor FM kit; AmpFℓSTR Identifiler kit	Latent fingerprints	Bond paper
Proff et al, [76] Germany	2006	To determine whether latent-fingerprint brushes can act as a source of DNA contamination and to assess the risk of secondary DNA transfer via such brushes	Both Real casework and Laboratory experiment	Phenol:chloroform:isoamyl alcohol (concentrated with Microcon); AmpFlSTR SEfilerk	Latent fingerprints	A 12 × 12 cm acetate sheet coated with a thin paraffin-oil film and dusted with carbon-black powder
Ostojic et al, [77] USA	2017	To examine touched items (e.g. fingerprints) for their ability to produce informative DNA profiles within forensic casework.	Laboratory experiment	prepGEM®Tissue Extraction kit; AmpFℓSTR Identifiler kit	Latent fingerprints	Glass slides, plastic sheet protectors, office paper, US Quarter dollar
Menchhoff et al, [78] USA	2020	To test a previously developed optimized workflow on aged archived latent fingerprint (ALFP) lift cards and determine whether it yields improved short-tandem-repeat (STR) profiles	Laboratory experiment	QIAamp DNA Investigator Kit; AmpFℓSTR Identifiler plus kit	Latent fingerprints	Glass, Glossy paper
Bolivar et al, [79] USA	2015	To determine the extent of cross-contamination of DNA resulting from secondary transfer due to fingerprint brushes used on multiple items of evidence.	Laboratory experiment	Tris-EDTA-NaCl-SDS buffer with Proteinase K (followed by purification on a Qiagen BioRobot EZ1 instrument); AmpFℓSTR Identifiler	Latent fingerprints	Laboratory transparencies
Kanokwongnuwut et al, [80]	2021	To determine how many visualized cells (buccal cells for	Laboratory experiment	DNA IQ™ System; AmpFℓSTR Identifiler plus	Thumb-prints	Glass slides

Author, country	Year	Aim of the study	Study type	DNA Recovery kit; Amplification kit	Type of fingermark/Fingerprint	Substrate surface
Australia		saliva and corneocytes for touch) are required to generate an informative STR DNA profile for each of four collection/processing workflows		kit		
Tiedge et al, [81] USA	2020	To explore whether massively parallel sequencing (MPS) can be used to sequence SNPs from partial bloody fingerprints enhanced with columnar thin films (CTFs) on five forensic substrates	Laboratory experiment	EZ1 DNA Investigator Kit	Partial bloody fingerprints	Cherry wood, brass, black garbage bag, microscopic glass slide, and clear plastic sandwich bag
Frégeau et al, [82] Canada	2000	To determine the effect of seven blood-enhancement reagents on the subsequent Profiler Plus™ fluorescent STR DNA analysis of fresh or aged bloody fingerprints deposited on various porous and non-porous surfaces	Laboratory experiment	phenol-chloroform/isoamyl alcohol; AmpFℓSTR Identifiler plus kit	Bloody fingerprints	Linoleum, glass, metal, wood (pine, painted white), clothing, paper

4. DNA Recovery from Fingermarks

4.1. Findings on Visualization-based approaches for targeting DNA Recovery

Several studies have explored visualization techniques as a strategy to locate cellular material prior to DNA recovery, thereby minimizing unnecessary sampling and preserving evidential integrity. Plaza et al. [9] attempted an effective way of collecting DNA from fingermarks deposited on paper and at the same time preserving the physical integrity of the evidential item. The technique begins with visualization of the latent fingermarks using Electrostatic Detector Apparatus (ESDA), which reveals fingerprint impressions on Mylan film. The fingermark on Mylan film surface is then encircled with marker. The bottom of Mylar (where the cellular materials likely present) is swabbed using either a dry swab or wet swab. However, study recommends dry swabbing, as it yielded a higher quantity of DNA and support preservation of the physical integrity of the paper evidence.

Other visualization methods identified in the various studies primarily involve chemical agents such as SYBR Green, GelGreen, and Diamond dye. A study by Haines et al. [68] investigated two of these intercalating dyes, SYBR Green and GelGreen, for their ability to visualize DNA in fingermarks. Although they serve different techniques, both dyes bind to DNA. SYBR Green typically binds to double-stranded DNA (dsDNA) and emits strong fluorescence, enabling quantification via real-time PCR. GelGreen, on the other hand, is commonly used in gel electrophoresis and is considered as safer alternative to Ethidium Bromide. The study observed that fluorescence was emitted when the fingermarks present on the substrates used in the study such as Plastic slide, glass slide, and parafirm®. However, the intensity of fluorescence varied depending on the substrate and the dye used. SYBR Green produced high fluorescence levels than GelGreen, especially on plastic slides. Conversely, glass slides showed greater fluorescence with GelGreen treatment. Haines et al [68], also noted that SYBR Green can bind to bacterial DNA, which indicate lack of specificity.

Kanokwongnuwut et al. [42] reported the effectiveness of Diamond Dye(DD) to visualize cellular materials from fingermark. The experiment involved staining the substrates (mentioned in Table 1) having fingermark deposits with 20-fold of the stock solution of DD. Dino-Lite Fluorescence digital microscope equiped with 510nm and blue LED excitation light source of 480nm used to visualize cellular materials and allowing cell counting in a frame ($1mm^2$). The amount of cellular materials correlated the human STR profile. Linacre et al [67] conducted similar experiment but additionally attempted to visualize cells on adhesive tape employed to lift thumbprint. Both study [42, 67] praised Diamond dye (DD) for its simplicity and speed, and sensitivity in detecting latent DNA. Kanokwongnuwut, Kirkbride & Linacre [40] reported method for visualizing latent DNA on tape using DD. The study tested 10 types of tape for their auto-fluorescence, properties when stained with three different DD solution (sterile water, 75% ethanol, 0.01% Triton-x), and PCR inhibition through a direct STR amplification. each tape containing fingermark was stained with 5microliter of 20x DD. Three types of tape: Brown tape (Packmate™), Clear tape (Sellotape), DNA-free tape (Lovell) did not inhibit direct STR typing and staining tapes with 20x DD diluted with 0.01% Triton-X was recommended.

Champion et al [69] also investigated application of DD which allow determination of DNA transfer from primary substrate having fingermark to secondary substrate when friction pressure applied. Goray et al [28] studied application of DD stain in different cell counting approach and determination of individual deposit variability. Kanokwongnuwut et al [80] used DD to determine the number of corneocytes needed to obtain full STR profile. The study identified that ≥ 800 corneocytes collected by swab or ≥ 4000 corneocytes collected by tapelifters produce the same number of STR alleles from touch sample.

Other studies have explored the preparation and application of Diamond Dye to enhance latent DNA detection. Champion et al [70] explored two DD diluents. This study recommended diluting Diamond Dye with 75% EtOH (which act as carrier and fixative) for non-absorbent/non-porous substrates while dilution with water was suitable for absorbent/porous substrates. Hughes et al [24], investigated how different application methods of Diamond Dye (diluted in 75% EtOH) affect visualization on non-porous surfaces, including polypropylene, acrylic aluminum, PVC, glass, and crystalline silicon. Two application methods, micropipette and spray application were compared, the micropipette method caused crystal formation at the center of the dried substrate, increasing background fluorescence under the microscope. In contrast, spray application prevented crystal formation, improved visualization, and allowed faster drying.

Young et al [38] explored the impact of spray Devices on the latent DNA detection. It was found that continuous-spray systems outperformed single-spray systems by enabling macroscale detection of cellular material. However, over-application using continuous-spray devices led to allelic dropout, a drawback not as prevalent with single-spray systems.

4.2. Findings on Recovery strategies following Fingerprint Development

Following visualization, several recovery strategies have been proposed to maximize DNA yield. Kanokwongnuwut et al [66] attempted DD visualization of fingermarks enhanced with black powder, red magnetic powder, and black magnetic powder, aluminum powder, white powder, and Cyanoacrylate (CA) with intention of examining the interaction between DD and enhancement reagent treated fingerprint. The sample were prepared in two ways: (1) Fingerprint enhancement followed by DD staining, (2) DD staining followed by fingerprint enhancement. In this experiment, the study observed that aluminum powder and white powder are effective in visualization of DNA, while magnetic powder, black powder, and red magnetic powder enhancement limit cellular material visualization. The experiment also noticed a fluorescent particles resembling cells stained with DD in fingermarks pre-treated and post-treated with CA. Kanokwongnuwut et al [43] used DD staining to develop a simple protocol to visualize buccal DNA and touch (fingermark) DNA on a different swab using Dino-Lite digital fluorescence microscope. From 8 types of swabs studied, black cotton swab, ultrafine dental applicator, and cylindrical dental applicator were found to be much more effective for collection of DNA, but the average RFU peak height from black cotton swab (~ 18,000) found similar to the RFU of the positive 1ng DNA control (~ 19,000), which make black cotton swab outperform all other swabs. It was also determined that cellular material on a swab stored for four weeks could be visualized and there is no any effect of DD staining on DNA typing observed. Zieger et al [17] looked back to the forensic practices routine, where fingerprints enhanced using powders and lifted with tapes. Then explored protocol for extracting DNA from such kind of sample. The first protocol involved swabbing the adhesive side of tape and second method were direct extraction of DNA from gelatin fingerprint lifters (BVDA® gel-lifters) through proteolytic digestion of the gelatin matrix containing latent DNA. The results of their experiment indicated that higher percentage of the total DNA from a fingerprint on gelatin lifters obtained when using direct extraction compared to swabbing the lifters. Thomasma et al [22] concerned about how the swabbing solution could influence the recovery of touch DNA (fingerprint were among studied). The target solutions were Triton X-100 (Promega), Tween 20 (promega), SDS (Fisher Scientist), Digestion buffer (Fisher scientist), Formular 409® (The Clorox company), and Simple Green® (Sunshine Markers Inc.). Fingerprint deposited on a slide daily over 6 days swabbed thoroughly using each solution, and entire cotton tips were taken to DNA extraction (mentioned in Table 1), Quantification, and STR analysis. All of the detergent-based swabbing solution produced average DNA quantities, but Triton X-100, and digestion buffer resulted in higher DNA yield. The study also concluded that using detergent in swabbing solution can significantly increase DNA yields from fingermarks compared with wetting swabs with water only. It was also observed that 2% SDS concentration compare to other compare SDS concentrations (0.1%, 0.5%, 1%, and 5%). Kwok et al. [35] compared gelatin lifters and masking tape on natural and sebaceous fingermarks aged for interval ranging from fresh to four weeks and treated with DD to visualize cellular deposits. Recovery efficiency was quantified using Image J software to estimate the potential for downstream DNA profiling. Results indicated that gelatin lifters constituently outperform masking tape, recovering a significant higher mean number of DNA-containing particles across all time frames. This superior performance was attributed to the pliable nature of the gelatin surface, which facilitate more effective uptake of fingermark residues compared to porous structure of masking tape. Steadman et al [21] conducted a study which was driven by a court order to examine methods of extracting, and STR typing of DNA entrapped between latent fingerprint lifting tape and matte acetate. First method of recovery involved swabbing and scraping (using razor) the fingerprint deposited on adhesive side of tape (Ramco®) without contact with acetate card; second, swabbing and scraping unprocessed fingerprint samples entrapped between tape and acetate card; third, swabbing and scraping processed fingerprint samples entrapped between tape and acetate card. The results of this analysis recovered 636 pg/μL autosomal DNA from swabbing one thumbprint unprocessed, while scrapping did not yield any detectable DNA to unprocessed and minimal to process fingerprint. Such related findings made the study concluding that swabbing is more effective than scraping. Shalhoub et al [30] showed the method of recovering DNA from silicone-based casting material (Isomark™) containing enhanced fingermark. DNA was recovered by slicing the casting material with sterile scalpel and the pieces were placed in the bijou bottle to undergo extraction with QIAamp®DNA Mini Kit. Van Helmond [31] generated a method of recovering DNA from fingermarks on glass using dextran methacrylate which irradiated to form a hydrogel. The study started the process by depositing a solution of 20μl dextran methacrylate over the fingerprint on glass and covered with cover slip, then irradiated for 30 second with 405nm laser pen which allow generation of hydrogel. Upon removal of cover slip, the hydrogel also detaches together with fingerprint components, which then taken to extraction process.

5. DNA Typing and Analysis from fingermarks

5.1. Findings on DNA Extraction methods and their impact on DNA profiling success

This review summarized the extraction methods described in the included studies as presented in Table 1 to provide practical insight into various techniques applied to latent DNA recovery. Across the reviewed studies, extraction efficiency varied considerably depending on extraction chemistry, fingerprint enhancement method, and substrate characteristics. In the study by Sewell et al [16] investigating various factors affecting DNA profiling from fingermarks, compared two extraction methods: DNeasy® plant mini kit and QIAamp DNA mini kit for their efficiency in recovering DNA from fingermarks pre-treated with Ninhydrin, DFO, and sequential treatment of DFO and Ninhydrin. Study observed a significant increase in DNA recovery by using DNeasy® plant mini kit compared to QIAamp DNA mini kit across all study conditions: paper substrates and fingerprint enhancement. The most prominent increase in DNA yield using DNeasy® extraction method was from fingerprint deposited on Whatman® paper with the average DNA yield of 2.28ng/μl, where using QIAamp on the same substrate yielded 0.87ng/ μl. Cornwell et al [13] evaluated the performance of Chelex, DNA IQ™, and PrepFiler™ in extracting DNA from fingermarks developed with 23 different powders from three brands (Lightning, Sirchie, and SupraNano). These powders were further categorized as non-magnetic, magnetic, or aqueous. DNA yields varied according to both the powder type and the extraction method. Using the Quantifiler™ Trio kit, PrepFiler™ proved most effective for fingermarks enhanced with all Lightning powder, generating sufficient DNA to amplify 17 of the 21 PowerPlex® 21 loci. Chelex, which performed poorly with other brands, was effective only for the samples treated with Small Particle Reagent (SPR). DNA IQ™ was the most suitable for extracting sufficient DNA (20 of loci amplified) from fingermarks developed with non-magnetic Sirchie and SupraNano powders. Thamnurak et al [55] also compared Chelex with QIAamp® DNA Mini kit on extracting DNA from fingerprint dusted with fluorescent powders (red, green, yellow). The QIAamp® DNA Mini kit

recovered 260–713 ng of DNA with acceptable purity of 1.2–1.6, while Chelex yielded higher total absorbance (1300–3500 ng) but poor purity (07-1.4) and color interference from the powders; consequently, QIAamp extracts produced partial or full STR profiles, while Chelex extracts rarely did. Increasing PCR cycles from 28–34 (low-copy-number typing) improved locus recovery, especially for the QIAamp-derived samples, allowing at least one full profile from yellow-powdered fingerprint. de Oliveira Francisco et al [18] compared two extraction kits: DNA IQ™ system and Casework Direct kit for their effectiveness to extract DNA from fingerprints. 51 (98.1%) of 52 extracted by Casework Direct kit gave full STR profile, where only 61.5% extracts by DNA IQ were able to give full STR, which made Casework Direct kit more efficient. Ostojic et al [54] compare three extraction methods: Zygem, HighSens and One-tube method. DNA yields differed markedly among these three extraction protocol. The HighSens method produced the highest mean concentration (32.2 pg/µl), followed by Zygem (11.8 pg/µl) and the one-tube protocol (9.9 pg/µl). For STR amplification, using the identifiler® Plus kit (32cycles) significantly increased the proportion of profiles achieving ≥ 70% completeness for one-tube extracts ($p = 7.23 \times 10^{-6}$), whereas this benefit was not observed for the other extract methods. Logistic regression showed that, among the samples with ≥ 2 pg/µl DNA, Zygem increased the odds of obtaining a ≥ 70% profile by 67% (non-significant) and HighSens decreased by 65% ($p = 0.005$).

5.2. Findings on DNA quantification methods and Assessment of Sample quality

Comparative evaluations of quantification kits demonstrated differences in their ability to detect DNA degradation. Although both Quantifiler®Trio and InnoQuant™ kits successfully identified degradation pattern in developed and undeveloped fingermarks, InnoQuant™ consistently reported higher degradation ratios. This difference is likely attributable to variations in targeted amplicon design and degradation assessment strategies rather than true differences in the sample quality. An important finding emerging from degradation study is that environment exposure appears to exert a greater influence on DNA integrity than many commonly used fingerprint development techniques. Significant degradation was observed following ultraviolet (UV) exposure and prolonged storage, whereas fingermarks treated with cyanoacrylate, black powder, or columnar thin-film techniques generally remained suitable for downstream DNA analysis [48].

5.3. Findings on Amplification methods for Low-Template Fingermark DNA

Low quantity of DNA typically recovered from fingermarks has driven the development of specialized amplification approaches aimed at minimizing profile recovery. Across the reviewed studies, both amplification chemistry and PCR cycle number were shown to substantially influence profiling outcomes. Comparison of commercial STR amplification kits performance on touch DNA in the study conducted by Martin et al [44] observed that fingerprint on glass slide amplified using Identifiler® Plus generated 86% informative STR Profile, and the study witnessed that Identifiler® Plus out-perform GlobalFiler® in terms of percentage of alleles amplified using the direct PCR approach. Balogh et al. [20] evaluated how the number of PCR cycles affected the low-copy-number STR typing from latent fingerprints. Amplifications were performed with 28, 32, and 38 cycles, and the 38-cycle protocol produced the highest success rate while not increasing artefact or stutter peaks. Raising the cycle number to 38 enhanced sensitivity and enabled comparable to low-cycle reactions. For mtDNA HV-1 sequencing, reliable results were achieved with only 32 cycles, reflecting the greater copy number mitochondrial templates. Bolivar et al. [79] also observed that increasing the PCR cycle number from the standard 28 cycle to 31 cycles markedly improved the detection of secondary-transfer DNA from fingerprint brushes. Under the 28-cycle standard protocol, contaminant donor alleles were observed above the analytical threshold in only 4 of 9 samples (44%) and none reached the stochastic threshold, whereas the 31-cycle low-copy-number (LCN) protocol yielded contaminant alleles in 24 of 27 samples (89%). Sewell et al. [16] observed the same findings by comparing standard 28-cycle STR amplification with low-copy-number 34-cycle PCR for DNA recovered from paper fingerprints. Using 28-cycles the average allele recovered was just over 12 (55% of the 22 loci), while extending to 34 cycle increased the average to just over 17 alleles (79%) and produced partial profiles even for samples that failed with shorter protocol especially on office-paper substrates.

5.4. Findings on Selection of Genetic Markers for Fingermark DNA Analysis

Lagoa et al. [71] assessed the sensitivity and suitability of autosomal STRs, miniSTRs, and Y-STRs for typing DNA from fingerprints. MiniSTRs provided the best balance of sensitivity and allele recovery; however, their interpretation requires caution because spurious alleles may appear alongside true alleles. In experiment conducted by Gino et al. [63] to determine the effect of fingerprint enhancements such as black powder, white powder DFO, and Cyanoacrylate on DNA from latent fingerprint. After RT-PCT, observed absence of DNA and even STR profile from treated fingerprints after being aged in four series: one day, seven days, thirty days, and sixty days. However, sequencing of HV1 region of mtDNA generated a complete profile. Norlin et al [72] observed mtDNA outperforming nDNA on fingerprint sample treated with black powder, where the prints enhanced sampled using tape lifter contained 8 nDNA and 1135 mtDNA copies. The sample consisting a little as 176 mtDNA copies found successfully generating a high-quality mtDNA sequences. Different results observed on fingerprint samples treated with Physical Developer and Silver Nitrate, where both nDNA and mtDNA detrimentally affected by these types of fingerprint enhancement reagent. Tiedge et al [81] also observed that the genetic information from partial bloody fingerprint that could not be obtained using STR was generated with SNPs (Single Nucleotide Polymorphisms). The capability of SNP was represented in the study by Tiedge et al [73], where 802 of 805 environmentally insulted latent fingerprint yielded SNP profile.

6. Factors affecting DNA Typing from Fingermarks

The success of DNA typing from fingermarks is influenced by multiple biological, environmental, and procedural factors. The reviewed studies collectively demonstrate that DNA recovery and profiling outcomes are now determine by a single variable but rather by the interaction among donor characteristics, deposition conditions, substrate properties, sample age, and fingerprint development procedures. Understanding these factors is essential for interpreting profile success rates and optimizing forensic workflows.

6.1. Findings on Shedder Status, Deposition pressure and Donor Variability

Alessandrini et al [74] found that an individual's shedder status is the primary determinant of DNA yield from fingerprints, with stripped-nucleus counts strongly correlating with recovered DNA (spearman r = 0.80). Good shedders consistently produced higher quantities and more complete profiles. Hand-washing markedly lowered DNA recovery and the success of downstream typing; washed-hand prints yielded substantially less DNA (often below 40pg detection threshold) and showed a drastic reduction in amplification success compared with unwashed prints. Tobias et al [46] placed a polycarbonate board over and individual finger to investigate whether pressure can affect the amount of DNA quality directly deposited by touch. The experiment showed that pressure not only increased the total amount of touch-DNA recovered but also amplified differences between individuals, indicating that shedder status can be affected by the force applied during deposition of fingerprint. At the lowest pressure (4kPa) the two volunteers deposited comparable DNA quantities, whereas at medium (21kPa) and high (37kPa) pressures one volunteer yielded significantly more DNA (U = 3.5, p = 0.033 and U = 0.0, p = 0.004). This pattern suggests that higher pressures can accentuate or obscure an individual's inherent shedding propensity, making the detection of shedder status pressure-dependent. Hefez et al [61] also focused on how deposition pressure (0.1–10kg) alter fingerprint dimensions, and touch-DNA recovery where the study showed that increasing the deposition pressure caused a progressive enlargement of fingermarks on glass, polyethylene and paper, with both length and width rising as pressure increased. DNA recovery followed a similar trend: the amount of DNA extracted grew linearly with deposition pressure, reaching the highest average concentration on glass (0.049ng/µl) and yielding significantly more DNA at 10kg than at the lower pressures across all substrates. Consequently, the number of amplified STR loci increased markedly, with 75% of loci recovered at 10kg on glass versus 18–27% at lower pressures, and strong correlations between deposition pressure and loci count on polyethylene (R = 0.98) and paper (R = 0.96). The proportion of forensically useful DNA profiles (≥ 8 full loci) peaked at 10kg, achieving 22.5% on glass, 21.2% on polyethylene, and 16.3% on paper. The study conclude that deposition pressure significantly increases fingermark size, and touch DNA success; moderate pressure (up to 3kg) enhances fingerprint quality, while higher pressure (up to 10kg) maximizes DNA recovery. Dominick et al [57] aimed to determine whether the amount of ridge detail in donor's fingerprint predicts the quantity of DNA shed from same individual. Results showed no correlation between fingerprint scores and the percentage of DNA profiles recovered; donors with high-detail prints did not necessarily yield full DNA profiles.

6.2. Findings on Influence of substrate characteristics

The substrate surface impact the deposition of touch deposits due to roughness and physicochemical interactions, including hydrophobicity [83]. This impact on DNA recovery from fingerprint was investigated in the study by Pamela et al [50] which found that smoother substrates, particularly glass and metal plates, yielded the highest numbers of complete DNA profile for fingerprint samples, likely because less powder adheres to these surfaces and facilitates DNA recovery. In contrast, more porous or textured materials (paper, plexiglass, ceramics) produced fewer full profiles, indicating that substrate texture influences efficiency of DNA extraction after dactyloscopic powder enhancement. Templeton et al [53] also observed t non-porous surfaces retain more recoverable touch DNA than porous substrates. Glass surfaces produced the highest recovery with 87% of samples giving interpretable profiles, while wooden handles and aluminium cases gave lower rates 53% each. Nickel cartridge cased achieved a 60% success rate but brass cartridge cases failed entirely, providing no usable DNA. Ostojic et al. [77] findings also showed that across 32 fingerprints per substrate (128 total), over half of the glass-slide samples produced ≥ 70% complete profiles, making glass the most favorable surface. Plastic yielded usable profiles in roughly a quarter of the cases, while paper generated noticeably fewer high-quality profiles. In contrast, almost no informative STR profiles were recovered from the US Quarter-dollar metal surface, likely because Cu and Ni ions promote DNA degradation and binding. Sewell at al [16] investigated the various factors affecting DNA recovery from fingerprint deposited on paper. In this study, compatibility of paper substrates with extraction method was evaluated, the DNeasy kit observed recovering up to 2.28ng/µl from filter paper, while QIAamp method recovering 0.872.28ng/µl from the same substrate. Study also find that unbleached filter paper, glossy magazine paper, and newspaper yielding the highest DNA quantities, while common office paper and white card producing negligible DNA and consequently generated poor or no STR profile.

6.3. Findings on Effect of Archival age and Storage Duration

Menchhoff et al. [78] study showed that archival age markedly reduces the likelihood of obtaining detectable DNA, yet when DNA is recovered the quality of STR profile remains comparable to fresh samples. Compared with fresh fingerprint on lift cards processed within four weeks, two-years-old cards were 26% less likely to yield detectable DNA, but the profiles that did generate DNA contained about 53% of the expected alleles with average peak heights above 900 RFU, indicating no loss of profile quality due to storage time. Extending the analysis to super-aged archived fingerprint samples on lift cards (5–28 years) revealed detectable DNA in 50% of specimen; however, the number of alleles recovered declined linearly with age (R^2= 0.757), with 40% of 5-year, 20% of 7-year, 12.5% of 10-year, and 14.3% of 28-year fingerprint samples showing alleles. Importantly, the optimized workflow enabled interpretable STR peaks from cards as old as 28 years, supporting its issue for highly compromised, long-term archived fingerprint evidence. Romano et al [10] supported that when fingerprints are properly archived, extended storage time does not preclude obtaining informative DNA profiles, after obtaining DNA yield suitable for forensic STR profiling from 14-year-old fingerprint retrieved from crime scene.

6.4 Findings on Impact of Fingerprint development procedures

a. Contamination risks associated with Fingerprint brushes

Fingerprint brush found introducing or transferring DNA, and three studies have quantified this risk and evaluated decontamination protocols. Proff et al. [76] screened 51 used latent-print brushes and detectable DNA in 86% of them, mainly mixtures, with five brushes yielding full single-person profiles suggestive of blood or saliva contamination; a secondary-transfer experiment with 16 brushes (including two artificially contaminated brushes) showed that DNA could be recovered from brushed areas, but full profiles were obtained only from the contaminated brushes and one previously used brush, indicating a limited but real contamination risk. Szkuta et al. [6] evaluated DNA contamination and decontamination of latent-print brushes by first confirming that new unused squirrel-hair brushes already carried ≤ 1 of human DNA (17–94 alleles), whereas new unused fiberglass brushes were DNA-free. Primary glass surfaces were deliberately contaminated with either dried saliva (1ml, air-dried 8 hours) or touch DNA, then dusted with new or previously used squirrel-hair or fiberglass brushes using opti-black powder. Brushes were subsequently used to dust secondary surfaces bearing a single print, and DNA was extracted from cut

bristles or swabs (DNA IQ™), quantified, amplified (0.5ng template) and profiled on 3500Xl Genetic analyzer. Cleaning protocols involved submerging brushes for 1–2 min in either 1% sodium hypochlorite or 5% Virkon, with agitation and a sequential water rinses. Results showed that dusting dried-saliva deposits transferred 95% of the donor's DNA to brush bristles and 46% to the secondary surface; after cleaning, saliva DNA on secondary surfaces fell to 1–3%. Touch-DNA transfer was minimal (< 1% of total DNA) and not significantly altered by cleaning. Fiberglass brushes transferred 10% saliva DNA but became tangled and unused after virkon cleaning. Both cleaning agents removed > 95% of contaminating DNA from squirrel-hair brushes while preserving bristle integrity for at least 20 wash/rinse/dry cycles (30 second submersion); longer submersion caused bristle loss, especially with hypochlorite. The study concluded that fingerprint brushes can act as vector for DNA, particularly when handling high-DNA fluids like saliva, and recommend routing cleaning (or replacement) of squirrel-hair brushes, disposal of fiberglass brushes after use, use of fresh powder aliquots and monitoring of cleaning efficacy. Nontiapirom et al. [39] evaluated fingerprint-dusting brushes introduce secondary DNA into latent-fingerprint profiles. Ten new camel-hair brushes were first contaminated with either 10µL fresh saliva or a dried saliva stain on sterile glass, then used to dust four latent prints on glass; hairs (10 per brush) and the dusted prints were collected by double-swab for DNA analysis. DNA was extracted, quantified on NanoDrop™, and amplified using the AmpF/STR Identifiler kit (34 cycle) before fragment analysis on an ABI 310, consensus profiles were generated from three replicates. Fresh-saliva contaminated brushes yielded highly mixed profiles on the print swabs (145 total alleles: 70 from the saliva donor, 23 from the fingerprint donor, 52 shared) and on brush hairs (75 alleles: 42 saliva, 33 shared), whereas saliva stain contamination produced fewer donor alleles (102 total: 23 saliva, 45 fingerprint, 36 shared) and only three alleles on brush hairs (1 saliva, 2 shared). No fingerprint-donor alleles were detected on brush-hairs, indicating that fresh biological fluids persist on brush hairs and dominated secondary transfer. A simple decontamination protocol was to rinse under tap water, 15 second spin in diluted dish-washing liquid, rinse again, brief sterile-water soak, blot and blow-dry-removed reproducible DNA profile from cleaned brushes.

b. Effect of Fingerprint Enhancement Reagents on DNA Typing

The compatibility of fingerprint development techniques with DNA analysis remains a major concern in forensic practices because enhancement procedures are frequently performed DNA recovery. The reviewed evidence indicates that most contemporary fingerprint enhancement methods are compatible with downstream DNA typing, although important exception exist.

Across numerous studies, commonly used enhancement techniques including black powders, magnetic powders, cyanoacrylate, infrared fluorescent powders, and several fluorescent formulation powders, showed no inhibitory effect on STR profiling. However, certain reagents consistently demonstrated adverse effects on DNA recovery or amplification. Physical developer and silver nitrate were repeatedly associated with reduced DNA typing success, while the effect of ninhydrin appeared dependent on substrate type and processing conditions. Some studies reported inhibition on porous substrate [5],[15], whereas others observed minimal impact on non-porous surfaces (see Supplementary material 3), indicating that reagent-substrate interactions may influence outcomes.

7. Findings on proposed Workflows for DNA profiling from fingermarks

Several studies have proposed experimentally validated workflows to improve DNA recovery and profiling success from fingermarks under different forensic scenarios. Although, these protocols vary in processing strategy, and analytical objectives, they generally aim to address one or more of the following challenges: (i) simultaneous fingerprint and DNA extraction, (ii) recovery of DNA from archived or processed fingermarks, (iii) reduction of PCR inhibition, (iv) maximization of profiling success from low-template samples.

Ruprecht et al. [3] established a novel approach enable simultaneous fingerprint visualization and DNA profiling from same self-adhesive postage stamp while minimizing contamination and PCR inhibition. The process begins with (1) stamp removal by applying a drop of a mixture of 50% (v/v) cyclohexane and 50% (v/v) propanol solution to the corner of the stamp, allowed the solvent to soak into the paper, then gently pull the stamp off with the tweezers while adding more solvent until fully detached. Place the moved stamp adhesive-side up on clean silicon-coated paper. (2) next step involves fingerprint development on the stamp, where the adhesive side of the detached stamp dusted with black powder suspension for 20-30s, rinsed with distilled water, photographed to document the print. (3) Fingerprint development on the envelope by immersing the envelope in the indanedione solution (1g, 1–2 indanedione in 90 ml ethyl acetate, 10 ml acetic acid, 900 ml petroleum ether, 10 ml zinc stock), soak twice, dry briefly, then placed between two sheet of baking paper and pressed at 165^{o}C for 10s, the developed fingerprints were marked and photographed using an OG56 barrier filer under 500-530nm light. The fingerprint was processed in Photoshop in order to visualize the area of the transferred fingerprint on the envelope. (4) Direct-fragment DNA sampling by identifying the contact area on the envelope (where the fingerprint was transferred) and cut the corresponding region from the adhesive side on the stamp. Extract this fragment for DNA analysis (direct fragment approach). (5) DNA extraction using the Forensic DNA Extraction kit (Thermo Fisher) for surface swabs and the PrepFiler Express BTA™ Forensic DNA Extraction kit (Thermo Fisher) for stamp fragments and adhesive swabs, following the manufacturer's protocol with lysis buffer, DTT and Proteinase K, homogenization, and column purification. (6) DNA quantification using Applied Biosystems 7500 Real-Time PCR System with the PowerQuant® System assay (Promega). (7) PCR amplification of 0.3ng of extracted DNA in duplicate using AmpF/STR® NGMSelect™ (31 cycles) and PowerPlex® ESI 17 Pro Kits in 25µl reactions, then run capillary electrophoresis on an ABI 3500Xl Genetic Analyzer.

Schulte et al. [12] described a simple workflow that enables parallel DNA genotyping and proteomic analysis from the same latent fingerprint. This review presented the process related to DNA typing from latent fingerprint deposited on glass surface. The process here starts by covering surface holding fingerprint with 100µL of 0.1% (w/v) RapiGest SF surfactant in 50 Mm ammonium bicarbonate, left 5min at room temperature, then the slide is lifted and the liquid is transferred to a 50 Ml conical tube; the slide is scraped for 30s to recover residual material. The tube is centrifuged (1000 x g, 3 min) to remove the slide and debris/ the collected liquid (65–85 µL) is then subjected to high-speed centrifugation (20000 x g, 10 min) to pellet cellular material, the supernatant is carefully removed without disturbing the pellet. The adjustable volume of supernatant is taken for DNA analysis (the study used 40 µL which is 60% of the total supernatant). DNA-rich supernatant was processed with Qiagen Investigator DNA kit: 15–65 µL + 300 µL ATL buffer + 20 µL proteinase K, followed by standard spin-column protocol and double elution of 40 µL each (final volume 80 µL). Elute DNA was concentrated to 20 µL using a DNA Fast-Flow column and stored at -20^{o}C until analysis. DNA was quantified with Qiagen Investigator Quantiplex Pro assay. Then ≤ 0.5ng of DNA was amplified using Applied

BioSystem GlobalFiler™ 29-cycle chemistry on a Veriti™ thermal cycler. Amplified STR fragments were separated using ABI 3500Xl Genetic analyzer (24s injection) and interpreted with GeneMapper v1.5 (analysis threshold 125 RFU; stochastic threshold 525 RFU).

Solomon et al. [27] described an optimized DNA workflow for archived fingerprints (this type of sample, fingerprint materials are normally sandwiched between tape lifter and substrate). The used fingerprint was developed from paper using magnetic powder, adhesive tape placed over the fingerprint, and stored at room temperature for about 4 weeks. The analysis begins with peeling the adhesive tape from the paper, outline the fingerprint on both sides and excise 3mm pieces from each substrate with sterile forceps or scissors. For extraction steps, the cuttings are placed in a separate 1.5 ml tubes, combine the adhesive and paper lysates on a QIAamp DNA Investigator spin column (Qiagen) and follow the manufacturer's "paper & other similar materials" protocol; elute in 50 µL (adhesive) and 60 µL (paper). This kit gave the highest detection rate (29/30 samples). Quantify DNA with the Investigator Quantiplex kit on an ABI 7500; if the concentration exceeds 0.2ng/µL, dilute to this level, if lower, proceed to concertation. Use Centri-Sep™ gel-spin columns (Thermo Fisher) to concentrate extracts to 0.2 ng/ µL (or the entire extract if < 1 ng). This method yielded STR profiles for 9/10 samples, outperforming Micron Y-100 and NucleoSpin. Perform STR amplification using AmpF/STR Identifiler Plus with 1ng template (or the full concentration when <1ng) in half-reaction volumes; extend the final adenylation step to 45 min. Run amplicons on an ABI 3130 Genetic Analyzer, inject 15s for experimental samples, and analyze with GenMapper v4.1 using 50 RFU analytical threshold. Omit any post-PCR purification, as it adds little benefit and increases drop-in artefacts.

Sinelnikov et al. [47] demonstrated a workflow which also allow dual fingerprint and DNA analysis. The workflow begins by enhancing fingerprint with DNA-free black powder and lifting them onto the adhesive hinge cards, which are then imaged for ridge details while the residual (Ghost) materials are collected with a sterile cotton swab moistened in 10 µL buffer (10 Mm Tris-HCl, 0.1 Mm EDTA, 0.2%SDS). Both the lifted card and the swab are placed in a sealed lysis chamber where a proteolytic digestion (10 Mm Tris-Hcl, 0.1 Mm EDTA, 0.2%SDS, 100µg Ml Proteinase K, 56^{o}C, 1h) is performed directly on the adhesive layer and on the swab-derived material. The combined lysate is passed through an Xs spin column that retains proteins, detergents, DTT and fingerprint powders while allowing DNA to flow through, yielding a purified eluate with 93% recovery. Purified DNA is amplified with Identifiler (29 cycle) or PowerPlex 16 (32 cycle) according to manufacturer protocols, and the PCR products is cleaned and concentrated using the AmpliconRX™ post-PCR kit, which removes salts, primers and nucleotides and increases capillary electrophoresis signal 5–20 folds. The final amplicons are injected onto an ABI 3100 capillary electrophoresis instrument for STR profiling, delivering on average 80–92% of expected alleles from single lifted fingerprints.

Loacre et al. [33] designed an optimized DNA-extraction protocol that overcome PCR inhibition caused by keratin present in stratum-corneum cells by incorporating keratinase, glycogen-assisted precipitation and controlled ethanol washing to yield higher DNA concentrations and more complete genetic profiles fingerprints. The protocol starts with swabbing the print using 4N6FLOQ swab pre-moistened in 2% SDS to detach cells. The swab is then processed with the Gentra Puregene Buccal Cell Core kit (Qiagen). Keratinase (1U) is added to the lysis buffer and the mixture is incubated at 50^{o}C for 30 min, which significantly improves DNA yield by degrading the keratin mesh that inhibit PCR. Optimally, proteinase K (20µg) can be added for an additional 15 min at 55^{o}C when further protein digestion is desired. During precipitation, glycogen is included to enhance recovery of the low-quantity DNA fragments typical of the fingerprint samples. After precipitation, the pellet is washed with 70% ethanol to remove residual salts and PCR inhibitors, although this step may be omitted if precise quantification is not required. The DNA is finally re-suspended in sterile water, quantified with Quantifiler™ Human DNA kit, and used for STR or mtDNA amplification.

Templeton et al. [52] presented a rapid direct-PCR workflow that generates DNA profiles straight from swabbed fingermarks without a separate extraction step. Researchers moistened sterile FLOQswabs with 0.1% Triton-X, swabbed each mark, and placed the fibers directly into commercial STR kits (Profiler Plus and NGM SElect) at the standard cycle number. From 170 fingermarks deposited 15 min after hand-washing, 122 (71%) yielded interpretable profiles containing ≥ 12 alleles, the threshold for uploading to the Australian DNA database; success rates ranged from 66% to 74% depending on the kit. Only four samples (< 2%) produced no DNA. In contrast, the conventional extraction-based method succeeded on merely 5–6% of similar samples. method was validated on real case, producing a profile with 31 dominant alleles from a drug-seizure tape. Because this method eliminates extraction, avoids extra PCR cycles, and reduces reagent costs.

Discussion

Recent visualization strategies have significantly improved the ability to target biologically rich regions prior to collection. Techniques such as Diamond Dye staining, and other fluorescence-based visualization approaches enable investigators to identify cellular material while minimizing destructive sampling [40], [42],[67]. Nevertheless, the relationship between visible cellular material and DNA profiling success remains imperfect. Some studies indicated that high cell counts do not always correspond to complete STR profiles, likely because cell-free DNA contribution substantially to touch DNA deposits [80].

Swabbing remains the most widely used approach and consistently outperforming scraping methods in study directly comparing collection techniques [21]. Though swabbing technique outperform the other collection methods, the type of swabbing [43], detergent-containing wetting reagent particularly Triton X-100 and digestion buffer [22] also improve recovery efficiency. Alternative recovery methods, including direct extraction from gelatin lifters [17], silicon-based casting materials [30], and hydrogel-assisted lifting systems [31], have also demonstrated promising results, particularly when conventional swabbing in impractical.

The review demonstrates that extraction methodology substantially influences DNA recovery from fingermarks. While numerous extraction systems have been evaluated, no single approach consistently outperformed all others under every condition. Instead, extraction efficiency appears dependent on multiple factors including substrate type [16], fingerprint enhancement treatment [13],[55]. Studies consistently showed that increasing PCR-cycle numbers improved allele recovery from low-template samples and enhanced profile success [20],[79]. However, Sewel et al [16] observed that, although the extra cycles markedly improved overall profiling success, they also introduce a higher incidence of PCR artefacts such as allelic drop-outs, heterozygote imbalance and contamination peaks, demonstrating that LCN amplification raises the percent profile obtained but compromises profile quality.

Shedder status emerged as one of the most influential determinants of DNA recovery, with good shedders consistently generating higher DNA yield and more complete profiles [74]. However, the shedding propensity is not entirely fixed and may be influenced by behavioral factors such as handwashing [74], and deposition pressure [61],[46].

The observations indicated that both physical and chemical properties of substrates contribute to DNA persistence and recoverability where across the studies reviewed, non-porous surfaces, consistently produced superior DNA recovery compared with porous materials [50][53][61], particularly, glass substrate which surpassed even other porous surfaces [68][77].

Limitation of the literature

Several limitations within the existing body of research complicate interpretation of the findings presented in this review. First, substantial methodological heterogeneity exists among studies, including differences in substrates, fingerprint development techniques, extraction methods, amplification protocols, and prevents quantitative synthesis. Second, many investigations relied on controlled laboratory experiments involving cooperative donors, standardized deposition procedures, and ideal environmental conditions. Such settings may not accurately reflect the complexity of real forensic casework, where samples are often degraded, contaminated, mixed, or environmentally exposed. Third, inconsistency in reporting DNA yield, profile completeness, and analytical thresholds further hinders comparison across studies. The absence of standardized performance metrics remains a major obstacle to establishing evidence-based best practices.

Future Research Directions

Future research should focus on standardization and validation. Large-scare comparative studies using standardized methodologies are needed to evaluate cellular materials visualization and counting, extraction methods, enhancement procedures, and amplification strategies under comparable conditions. Greater emphasis should also be placed on realistic casework simulations involving environmental degradation, mixed DNA samples, and long-term storage. A wide range of reviewed studies used PCR methods which is limited to some of enhanced fingerprint samples, therefore, attempting Next-Generation Sequencing to these types of samples, would improve the evidential value of fingermark samples.

Conclusion

This review demonstrates that fingermarks are not only critical for ridge-based identification but also a source of genetic materials for DNA typing across diverse studies, DNA recovered from fingermarks (whether latent or enhanced) has proven capable of supporting STR profiling and, when necessary, alternative markers such as miniSTRs, and SNPs. However, the efficiency of DNA recovery is highly dependent on multiple interacting factors, including the fingerprint enhancement method applied, nature of the substrate, and biological variables such as shedder status and deposition pressure. The literature consistently indicates that latent DNA retrieval remains technically demanding due to low cell numbers, environmental degradation, and potential loss or inhibition introduced during fingerprint development. Nevertheless, methodological advancements continue to improve outcomes. Visualization techniques such as Diamond Dye (DD) and SYBR Green have shown substantial promise for detecting cellular materials without compromising downstream STR typing, with DD standing out for its simplicity, safety, and sensitivity. ESDA offers a non-destructive alternative for paper substrates. Fingerprint development reagents and sequential enhancement processes can variably affect DNA integrity, although several widely used reagents including ninhydrin, cyanoacrylate, and various powders have been shown to be largely compatible with DNA analysis when properly applied. The persistent issue of contamination from fingerprint brushes underscores the need for rigorous laboratory practices, such as the routine use of DNA-free fingerprint brushes. Overall, this review highlights the substantial progress made in integrating fingerprint and DNA evidence, enabling dual-use of a single trace and minimizing evidential loss. While variability in DNA yield and quality remains an inherent challenge, continued refinement of visualization techniques, extraction strategies, and contamination controls will further enhance the reliability of DNA typing from fingermarks. The convergence of these advancements ultimately strengthens the forensic value of fingermark evidence, particularly in cases where traditional fingerprint analysis may be inconclusive.

Abbreviations

DNA: Deoxyribonucleic Acid

FDT: Fingerprint Development technique

DD: Diamond Dye

SYBR Green: Symmetrical Yanine Blue Green

STR: Short Tandem Repeat

ESDA: Electrostatic Detector Apparatus

LCN: Low-Copy Number

NGS: Next Generation Sequencing

PCR: Polymerase Chain Reaction

VMD: Vacuum Metal Deposition

ORO: Oil Red O

EDTA: Ethylenediaminetetraacetic Acid

Declarations

Ethics approval and consent to participate

Not Applicable

Consent for Publication

Not Applicable

Funding

No funding received

Author Contribution

CN: Conceptualization, Methodology, Data curation and interpretation, Original draft preparation, Corresponding author. CU: Conceptualization, Review and editing. EL: Review and editing, Writing final manuscript.

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Figures

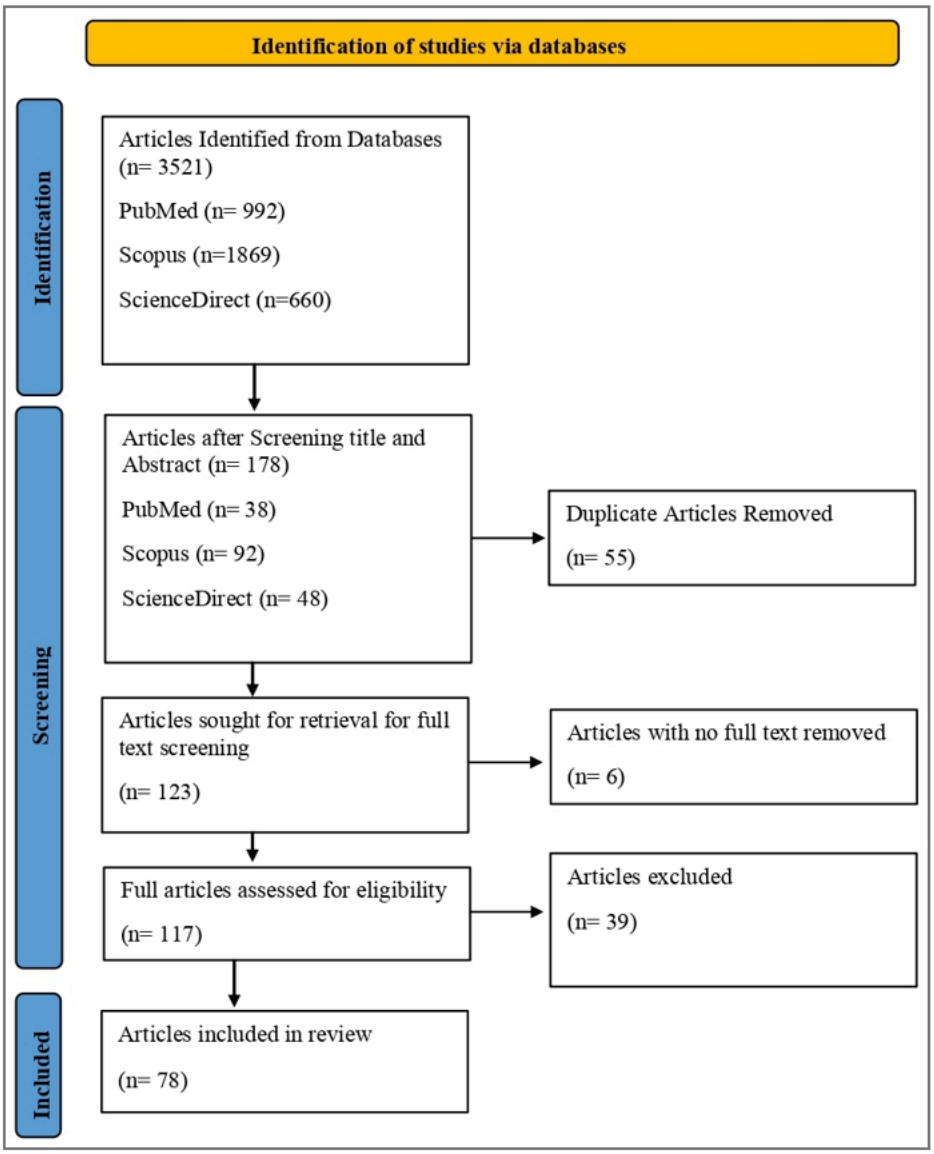


Figure 1

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