

Fingernail samples as DNA reservoirs: Implications for forensic interpretation

Salem K. Alketbi^{1, 2, 3, *}

¹ *The Biology and DNA Section, General Department of Forensic Science and Criminology, Dubai Police General Headquarters, Dubai, United Arab Emirates.*

² *International Center for Forensic Sciences (ICFS), Dubai Police General Headquarters, Dubai, United Arab Emirates.*

³ *School of Law and Policing, University of Lancashire, Preston, UK.*

World Journal of Advanced Research and Reviews, 2026, 30(01), 1154-1185

Publication history: Received on 01 March 2026; revised on 08 April 2026; accepted on 10 April 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.30.1.0913>

Abstract

DNA recovered from beneath fingernails is frequently presented in violent crime investigations as potentially probative evidence of physical struggle. However, the biological and interpretive complexity of the subungual environment has not been comprehensively synthesized within a structured activity-level framework. This review reconceptualizes fingernails as semi-protected, time-integrated DNA reservoirs characterized by high background prevalence, mixture complexity, and transfer variability. Drawing upon anatomical, experimental, casework, and probabilistic interpretation literature, this review examines the mechanisms by which DNA accumulates beneath fingernails, including primary, secondary, and tertiary transfer, as well as routine social contact and environmental exposure.

Evidence from prevalence and persistence studies demonstrates that foreign DNA beneath fingernails is common in non-criminal contexts and that mixed profiles represent expected rather than exceptional findings. Dominant contributors may be influenced by stochastic amplification effects, inter-individual shedding variability, transfer mechanisms, and persistence dynamics, thereby limiting straightforward inference regarding the timing or mechanism of deposition. The review integrates modern evaluative principles that emphasize the separation of sub-source attribution from activity-level propositions and highlights the interpretive risks associated with transposing conditional reasoning or adopting narrative assumptions in the absence of structured evaluation.

A fingernail-specific hierarchy of propositions and an applied decision matrix for forensic casework are proposed to support proportional interpretation and reporting. Critical research gaps are identified, including the need for controlled prevalence studies across diverse populations, quantitative probabilistic modeling at the activity level, and enhanced practitioner training in structured evaluative reasoning. By shifting the interpretive paradigm from assumption-driven inference toward biologically grounded and probabilistically informed evaluation, this review strengthens the scientific robustness and judicial reliability of fingernail DNA evidence.

Keywords: Forensic genetics; DNA profiling; Fingernail DNA; Subungual space; DNA transfer; DNA persistence

1. Introduction

Trace DNA constitutes a major category of forensic biological evidence and is routinely recovered from crime scenes to support the association of individuals with criminal events [1–7]. Unlike visible biological fluids, trace DNA is typically deposited through everyday contact with surfaces such as tools, door handles, and clothing, either by direct handling or through extended use or wear of an item, and therefore frequently represents the only biological material available for analysis [3,8–10]. In the context of personal items and clothing, trace DNA may originate from the regular user or wearer as well as from indirect contact with other individuals or surfaces, resulting in complex deposition histories. Although

* Corresponding author: Salem K. Alketbi

trace DNA can be highly informative, its recovery and interpretation are characterised by substantial variability in both DNA yield and profile quality. This variability arises from multiple interacting factors, including the physical and chemical properties of the substrate [11–14], exposure to environmental conditions that promote degradation or loss [15–18], and differences in collection strategies employed during scene examination and laboratory processing [11,19–22]. Additional procedural influences include the choice of moistening agent and the number of collection passes or lifts applied, both of which can materially affect recovery efficiency and downstream STR profile quality [23–30]. While trace DNA encompasses a broad range of substrates, this review specifically focuses on DNA recovered from fingernail samples, which present distinct biological and interpretive challenges. In this review, ‘trace DNA’ refers to DNA deposited through contact, whereas ‘DNA evidence’ is used in a broader forensic context to describe biological material considered within evidential evaluation.

Beyond sampling-related factors, interpretive uncertainty is further compounded by variability introduced during extraction and quantification [2,4,12,31–35], risks of contamination, and pronounced inter-individual differences in DNA shedding and transfer behaviour [36–45]. Consequently, selection of an appropriate sampling tool—such as cotton swabs, nylon-flocked swabs, or adhesive tapes—should be informed by the characteristics of the surface being sampled in order to optimise DNA recovery [10,11,23,24]. Smooth, non-porous substrates (e.g., glass and plastic) are generally amenable to swabbing [11,25], whereas porous and fibrous materials, including textiles, often yield improved results when sampled using adhesive tape-lifting approaches [46–51].

In response to the limitations of conventional sampling approaches, a range of alternative and hybrid collection strategies has been proposed. These include combined swab systems compatible with direct amplification workflows, wet-vacuum devices designed for challenging substrates, and chemical formulations intended to enhance DNA detachment and transfer [28,51–53]. The emergence of such approaches reflects a broader shift toward adaptive evidence-collection strategies tailored to substrate type and environmental context rather than uniform application of a single method [54–57]. In parallel, forensic practice has increasingly emphasised flexible investigative models that integrate technological developments with responsive sampling strategies to meet modern casework demands [58,59]. Conventional extraction-based workflows, particularly those reliant on silica-binding chemistry, are also associated with unavoidable sample loss, a limitation that is especially consequential for low-template and environmentally compromised samples [1,60]. Accordingly, direct amplification methods that bypass extraction and quantification have gained attention as a means of preserving limited biological material while reducing analytical turnaround time [21,27,61].

Despite extensive research into swab type, collection motion, and substrate category, a number of practical and interpretive uncertainties persist within trace DNA analysis. Variability in recovery remains especially pronounced for porous substrates, whose absorbency and moisture transport properties differ substantially according to fibre composition, yarn structure, and fabric geometry [62–66]. Hydrophilic fibres retain liquid through fibre swelling and internal reservoirs, whereas hydrophobic synthetic fibres rely primarily on capillary transport within pore spaces, producing distinct wetting and retention dynamics [62–65]. Liquid movement within textiles is governed by capillary forces and pore geometry, which influence both vertical and lateral transport and determine how readily moisture is drawn away from an external source [66–69]. Structural differences, including woven versus knitted constructions and surface finishing, further modulate moisture retention and wicking behaviour [70,71]. When considered in a forensic context, such substrate-dependent liquid transport mechanisms have direct implications for trace DNA recovery, as porous materials may draw liquid away from the swab head during pressure-based sampling, reducing the effective moisture at the swab–substrate interface and limiting mobilisation of epidermal cells and extracellular DNA. Comparable substrate-driven effects on DNA recovery have been observed in studies of trace DNA transfer and persistence on textiles and worn items [10,18,46–49].

In parallel with the extensive study of trace DNA on external surfaces and clothing, fingernail samples have long occupied a distinctive position within forensic practice, particularly in investigations of violent and sexual offences. Fingernail scrapings and clippings are routinely collected under the assumption that they may retain biological material from an assailant following defensive actions such as scratching or gripping. Early work demonstrated the feasibility of recovering DNA from subungual debris [78–81], and subsequent studies have consistently reported that fingernail samples frequently yield mixed DNA profiles rather than single-source profiles [72,75,76]. The prevalence of foreign DNA beneath fingernails has been documented in both casework and experimental contexts, including among cohabiting partners [72], homicide victims and suspects [75], and individuals with no known involvement in assaultive behaviour [74]. These findings indicate that fingernails readily accumulate DNA from multiple contributors through routine daily activities, close interpersonal contact, and indirect transfer pathways.

Experimental and case-based investigations further demonstrate that DNA deposited beneath fingernails may persist for extended periods and is not necessarily removed by washing or environmental exposure. Studies examining digital penetration scenarios have shown that foreign DNA can be transferred to and retained beneath fingernails following brief contact [73], while persistence has been observed even after submersion in water [82]. Collectively, these observations indicate that fingernail samples function less as moment-specific indicators of a particular contact event and more as composite repositories of biological material accumulated over time. As a result, the detection of foreign DNA beneath fingernails cannot be assumed to reflect recent or assault-related contact without careful consideration of alternative deposition and persistence scenarios [72–77].

Despite their routine use in assault investigations, fingernail traces may, in some contexts, be attributed disproportionate evidential weight, often being interpreted as direct indicators of violent struggle or offender contact. This tendency persists in the absence of a dedicated interpretive framework specific to fingernail DNA. While individual studies have examined prevalence, persistence, and transfer of DNA beneath fingernails [72–83], these findings remain dispersed across the literature and are rarely synthesised with explicit attention to activity-level interpretation. Consequently, fingernails are frequently treated analogously to other trace DNA substrates despite their distinct propensity for long-term accumulation, mixture formation, and indirect transfer. The present review therefore aims to consolidate and reinterpret the existing fingernail DNA literature to clarify the mechanisms governing DNA presence beneath fingernails and to evaluate the implications for forensic interpretation. By reframing fingernails as long-term DNA accumulation sites rather than event-specific collectors, this review seeks to support more balanced and scientifically defensible evaluation of fingernail evidence in criminal casework.

2. Fingernails as a unique DNA micro-environment

Fingernail evidence is routinely positioned within the “trace DNA” domain, yet the physical setting in which subungual material accumulates is fundamentally different from most contact substrates. The nail unit forms a semi-enclosed niche where biological and non-biological particulates can be retained and protected from routine environmental loss mechanisms [72–76]. Clinically, the subungual space is recognized as a distinct compartment between the nail plate and nail bed/hyponychium, with limited accessibility and constrained diffusion across the nail plate—features that also explain why subungual disease can be therapeutically difficult to reach by topical agents [84–86]. Imaging-based reviews likewise emphasize the anatomical complexity of the nail unit and the need to understand the structural relationships between nail plate, bed, matrix, folds, and the subungual/hyponychial region when evaluating lesions or processes occurring beneath the nail [85]. In forensic terms, these anatomical barriers and spatial constraints provide a plausible mechanistic basis for why the hyponychium/subungual region behaves as a semi-protected reservoir for trace material, rather than a purely transient contact surface [86].

2.1. Nail anatomy and the subungual space

The nail unit comprises the nail plate and surrounding soft tissues, including the proximal and lateral nail folds, nail matrix, nail bed, and hyponychium. The nail plate is a laminated keratinized structure overlying the nail bed and matrix, with the distal free edge transitioning into the hyponychium at the fingertip [86] (**Figure 1**). The hyponychium and subungual region function as protective interfaces, helping maintain a seal at the distal margin and acting as a barrier-like zone that restricts penetration beneath the plate under normal conditions [86]. From a functional standpoint, this means the subungual space is comparatively sheltered from direct wiping, abrasion, and casual washing. Clinical discussions explicitly frame the subungual space as a distinct and clinically meaningful part of the nail unit—often underappreciated—whose relative inaccessibility shapes both pathology and intervention, reinforcing the notion that it can retain material that is difficult to dislodge or access superficially [84]. Imaging literature complements this by describing how the anatomy of the nail unit and subungual region can be evaluated as a discrete site of processes occurring beneath the plate, again underscoring its compartment-like nature [85].

Forensic pathology literature also treats fingernails as a meaningful site for medicolegal examination, not only for DNA but for the recovery of trace materials and the interpretation of nail-associated findings in violent and sexual offense contexts [87]. Broader anatomical treatments of the hand further support the distinctiveness of nail-associated regions compared with palmar and dorsal skin, highlighting their specialized structural and forensic relevance within hand examinations [88]. While such sources are not DNA-mechanism studies per se, they reinforce the premise that fingernails are routinely examined because the anatomical setting makes them capable of retaining case-relevant material. Extending this logic beyond DNA, evidence from clinical forensic medicine shows that the hyponychium can retain diverse trace types (e.g., environmental and substrate particulates) following scratching and can preserve them for operationally relevant time windows, reinforcing the idea that the subungual region is a protected retention site rather than a simple exposed surface [89].

A parallel line of forensic research on inorganic gunshot residue (GSR) further supports this concept: the hyponychium has been shown to retain particles despite post-event hand cleaning methods that markedly reduce residues on exposed skin surfaces, highlighting the sheltered properties of this niche [90]. Although the material class differs, the retention principle is relevant for conceptualizing why trace biological material—including cellular debris containing DNA—may persist under the free edge of the nail.

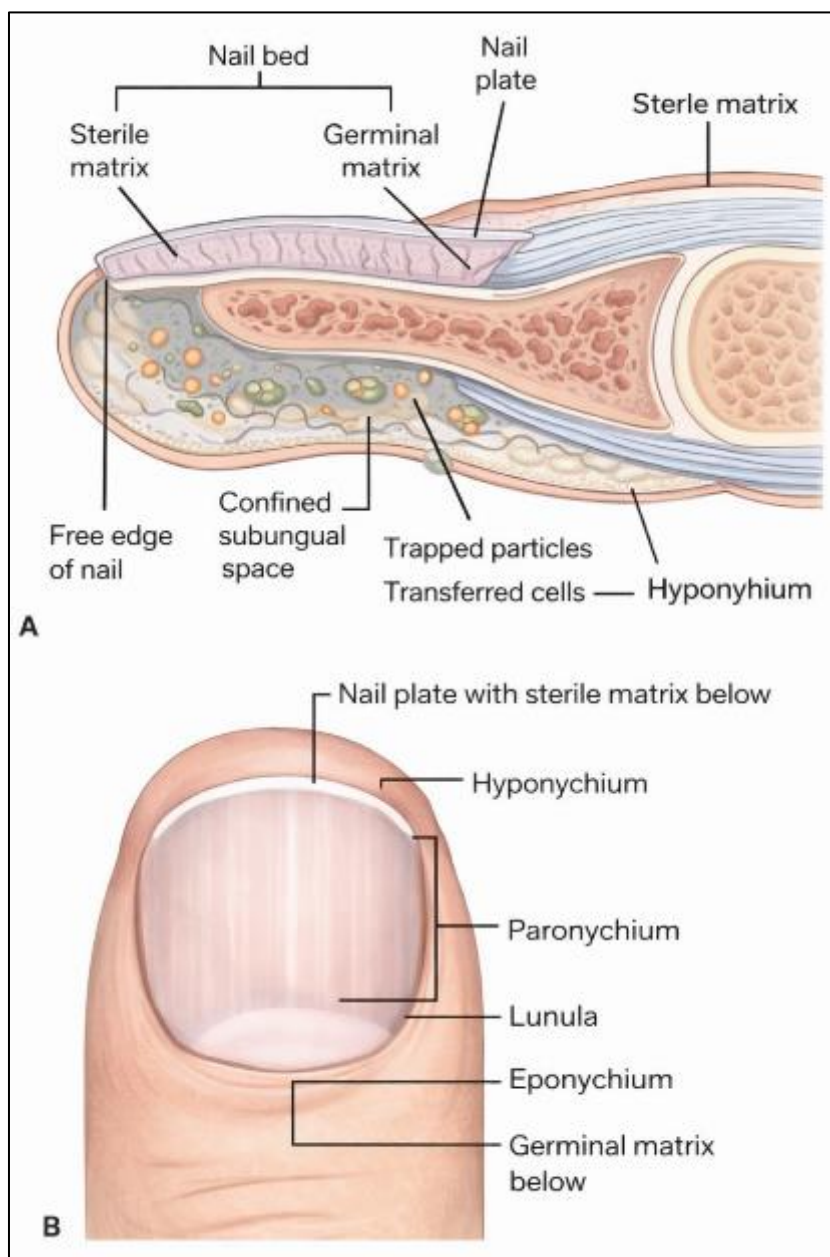


Figure 1 Anatomical structure of the nail unit and subungual space. This figure presents complementary anatomical views of the nail unit to contextualize the subungual region as a distinct forensic substrate. Panel (A) shows a longitudinal cross-sectional schematic of the distal finger, including the nail plate, nail bed, germinal and sterile matrices, and hyponychium, highlighting the confined subungual space beneath the free edge of the nail where biological material may be retained. Panel (B) provides a dorsal view illustrating the nail plate, paronychium, eponychium, lunula, and underlying matrix. Together, these views demonstrate that the subungual space forms a semi-enclosed anatomical niche that is relatively protected from abrasion and routine washing, supporting the accumulation and persistence of biological material relevant to forensic interpretation

2.2. Mechanical trapping versus biological deposition

Two non-exclusive mechanisms plausibly explain why fingernail samples often contain complex DNA mixtures: mechanical trapping and biological deposition. Mechanical trapping refers to the physical capture of particulate matter—epidermal flakes, debris, fibers, and environmental particles—within the confined geometry of the hyponychium/subungual space. Early forensic work established that DNA typing from fingernail debris is feasible and that recoverable biological material can be present beneath nails, consistent with a particulate trapping model [78]. Studies focusing on material obtained by scratching further emphasize that epidermal particles can be recovered through mechanical actions and can yield DNA suitable for typing, linking the mechanism of “scratch-generated debris” to recoverable genetic material [79]. Casework-oriented reports similarly describe the analysis of fingernail debris and clippings as applied to forensic scenarios, again compatible with a model in which particulate matter accumulates and persists under nails [80,81]. Clinical forensic simulations extend the concept beyond DNA by directly demonstrating the retention of non-genetic traces in the hyponychium after scratching different substrates, supporting the view that mechanical retention is a general property of this anatomical site [89]. The GSR persistence findings provide an additional mechanistic analogue: particles are retained preferentially in the hyponychium compared with exposed hand skin after cleaning, consistent with a niche that physically shelters and traps residues [90].

Biological deposition, by contrast, encompasses the direct transfer of cellular and extracellular DNA-containing material during contact events, often derived predominantly from anucleate corneocytes with variable contributions from nucleated cells [4]. In violent or intimate scenarios, biological deposition may include epithelial cells transferred by direct contact, potentially augmented by contact with biological fluids. Experimental work on fingernail DNA in a digital penetration context demonstrates that foreign DNA can be transferred to and persist beneath fingernails following brief but intimate contact, providing a scenario-specific example of biological deposition into the subungual niche [73]. More broadly, the cellular composition of trace (“touch”) deposits is known to be variable, with contributions from shed epidermal cells and other biological material; such variability creates interpretive challenges even before the added complexity of a protected accumulation site is considered [4].

The practical consequence is that fingernail samples frequently exhibit mixtures and background DNA even outside criminal contexts. Volunteer and casework studies consistently report high rates of mixed profiles and foreign DNA under nails, supporting the inference that everyday contact, close interpersonal interaction, and indirect transfer pathways can contribute to the subungual DNA pool [72,74–77]. In cohabiting partners, mixtures and the presence of the partner’s DNA are common, indicating that repeated ordinary contact can seed the subungual reservoir over time [72]. In homicide-related sample sets and other forensic contexts, mixtures remain frequent and foreign components can be detected, reinforcing that subungual DNA is often not single-source and not uniquely event-specific [75,80,81]. Methodological comparisons also indicate that sampling and processing choices influence what is recovered from under nails, which can change the observed balance between self and non-self components and, consequently, the interpretive picture [83].

More recent multidisciplinary approaches using nail material in postmortem contexts (often toenails) highlight that nails can support multiple analytical objectives (DNA profiling, toxicology, isotope/¹⁴C), again consistent with a matrix capable of long-term retention—though such studies primarily speak to the general “accumulation matrix” concept rather than subungual mechanics specifically [91]. For toxicological purposes, nails are explicitly treated as keratinized matrices that accumulate substances over extended periods, providing a conceptual parallel for “time-integrated” incorporation/retention—while acknowledging that drug incorporation pathways and trace DNA deposition are not identical processes [92].

2.3. Comparison with skin, palms, and fingertips

A key justification for treating fingernails as a distinct evidentiary substrate is that their retention dynamics differ from exposed skin surfaces. Palms, fingertips, and dorsal hand skin are open systems: they experience frequent washing, frictional abrasion, continual shedding, and repeated contacts that can rapidly add, redistribute, and remove trace DNA. Empirical studies demonstrate that DNA transfer from hands to common substrates (e.g., glass, fabric, wood) occurs readily, and the resulting profiles are sensitive to contact conditions and subsequent activities [10]. Controlled work on hands shows that activities performed strongly influence DNA transfer and persistence, emphasizing that trace DNA on exposed skin is dynamic and heavily context-dependent [45]. Time since handwashing affects shedding and recoverability, reinforcing that the hand is not a stable reservoir but a fluctuating contributor surface whose DNA output changes over time [44]. These findings are central to modern touch DNA interpretation, where inter-individual variability in shedding (often referred to as “shedder status,” defined as the propensity of an individual to deposit detectable amounts of DNA upon contact) and transfer adds further uncertainty to what a given recovered profile means [1,4,31].

Experimental work on shedder status further indicates that a substantial proportion of DNA deposited from hands originates from previously accumulated material rather than freshly shed cells, reinforcing the notion that exposed skin is subject to continual redistribution of DNA across body surfaces and objects [93]. Systematic reviews of non-intimate skin-cell transfer similarly emphasize the ubiquity of low-level DNA exchange in everyday life, highlighting that background touch DNA is a normal feature of human activity rather than an exceptional occurrence [94].

In violent-contact scenarios involving skin-to-skin contact, recovery outcomes remain highly contingent on sampling strategy and post-event activities. For example, touch DNA deposited on human skin in a strangulation scenario has been evaluated in relation to collection techniques and the practical constraints of sampling an exposed, biologically active surface; such work supports the broader point that recovery from skin is not guaranteed, is method-sensitive, and is temporally fragile compared with sheltered niches [29,30]. This contrast is informative for fingernails: where skin can lose or redistribute trace material rapidly, the subungual region is comparatively sheltered from the same removal forces, making it more likely to retain a time-integrated mixture of deposited and trapped material [84,89,90]. Accordingly, fingernail evidence cannot be treated as equivalent to “touch DNA on skin” or as a simple extension of hand-surface transfer models; rather, it should be conceptualized as a semi-protected micro-environment that can accumulate and retain material across multiple contacts and activities.

Recent work comparing fingernail samples to contemporaneous hand deposits collected after everyday activity provides further support for this distinction: fingernail DNA profiles and hand-deposit profiles can differ in the frequency and composition of non-self DNA, and partner DNA may be commonly represented, highlighting how personal social context can shape both sample types but not necessarily in the same way [95]. Importantly, such findings reinforce two interpretive points that motivate the remainder of this review: (i) non-self DNA under nails is often minor and context-shaped in everyday life, and (ii) results from different “shedder tests” or sampling modalities are not interchangeable, meaning that variability in observed subungual profiles may arise from both biology and methodology [95]. Complementary casework series likewise indicate that foreign DNA may be detected as a minor component in a subset of fingernail samples across criminal cases, broadly consistent with the notion that background/non-self DNA is possible and sometimes expected rather than exceptional [96]. Doctoral research explicitly designed to evaluate transfer, persistence, prevalence, and recovery under fingernails following scratching—including baseline sampling under non-criminal circumstances—further supports the “reservoir” model by showing that relevant profiles can still be obtained after delays, while background acquisition may increase with time, underscoring the need for cautious interpretation [97].

Finally, it is worth emphasizing that fingernails are also valuable forensic substrates beyond DNA (e.g., toxicology, trace particulates, and multidisciplinary profiling) [89,91,92], which reinforces the central conceptual theme of this section: the nail unit—and especially the hyponychium/subungual region—functions as a protected, retention-prone micro-environment. This substrate specificity helps explain why fingernail evidence so often exhibits mixtures and background components [72,74–77,83,95] and why subsequent sections must address prevalence, transfer pathways, persistence, and interpretive pitfalls in a fingernail-specific way rather than by analogy to general touch DNA alone [1,4,31,45].

3. Prevalence of background DNA under fingernails

Fingernail samples are routinely collected in investigations of violent and sexual offences on the assumption that defensive actions such as scratching may lead to the recovery of an assailant’s DNA. However, a substantial body of experimental, volunteer-based, and casework literature demonstrates that foreign DNA is frequently present beneath fingernails in the absence of any criminal activity (**Table 1**). Accordingly, the detection of non-self DNA in subungual material must be interpreted within a broader biological and behavioural context that includes routine social contact, indirect transfer pathways, and cumulative background accumulation processes rather than being treated as inherently assault-specific.

3.1. Frequency of non-self DNA detection

Early population-based studies established that background foreign DNA can be detected under fingernails in individuals with no involvement in crime. In a cohort of 100 volunteers from the general population, Cook and Dixon reported foreign DNA in 13% of fingernail samples, although only a subset yielded reportable mixed profiles [98].

Table 1 Empirical evidence on prevalence, persistence, and recovery of DNA beneath fingernails.

Study	Population / Scenario	Study Type	Sampling Approach	Prevalence / Mixture Findings	Persistence Findings	Methodological Notes	Interpretive Implications
Cook & Dixon, 2007 [98]	General population (100 volunteers)	Prevalence study	Subungual swabs	13% foreign DNA; 6% reportable mixtures	Foreign DNA often linked to contact within 24 h	Qiagen extraction; SGM Plus amplification	Foreign DNA occurs in non-crime contexts; not assault-specific
Malsom et al., 2009 [72]	Cohabiting couples	Volunteer prevalence	Subungual swabs; autosomal + Y-STR	Frequent mixed profiles; partner DNA common	Not temporal	Y-STR increases male detection	Cohabitation strongly influences background DNA
Dowlman et al., 2010 [76]	General population	Prevalence study	Fingernail swabs	Mixed DNA profiles common	Not temporal	Routine activity produces mixtures	Mixtures expected, not exceptional
Nurit et al., 2011 [75]	Homicide victims and suspects	Casework analysis	Subungual swabs	High frequency of mixed profiles	Not primary focus	Complex contributor patterns	Mixtures common even in violent cases
Matte et al., 2012 [74]	General population	Prevalence + persistence	Subungual swabs	Detectable foreign DNA in routine samples	Persistence without assault	Background contributors observed	Non-self DNA biologically plausible without violence
Kettner et al., 2015 [77]	Cohabiting partners (IPV context)	Casework + interpretive	Swabbing	Partner DNA detected without clear injury	Not temporal	Injury-DNA gap observed	DNA under nails ≠ proof of struggle
Goaray et al., 2026 [95]	Everyday activity comparison (hands vs nails)	Controlled volunteer study	Subungual vs hand sampling	Background DNA common under nails	Nails show distinct retention pattern	Nails retain DNA differently from skin	Nails function as retention reservoir
Flanagan & McAlister, 2011 [73]	Digital penetration scenario	Controlled experimental	Subungual swabbing	Transfer demonstrable	Detectable post-contact	Controlled deposition model	Biological plausibility of direct transfer
Damour et al., 2025 [99]	Female scratching male (24 h simulation)	Controlled transfer study	Serial subungual sampling	Male DNA detected immediately	Rapid decline within 3–6 h; background dominates by 24 h	Y-STR profiling	Early collection critical; late sampling vulnerable to background
Zareef et al., 2025 [102]	Drowning simulation	Controlled prosthetic model	Subungual debris recovery	Exogenous DNA persists	Detectable up to 48 h; varies by water type	Environmental medium affects yield	Aquatic exposure modifies but does not eliminate DNA
Harbison et al., 2003 [82]	Submersion experiment	Experimental	Nail debris	DNA persists after water immersion	Detectable post-submersion	Water does not fully remove DNA	Environmental exposure not equal to loss
Wiegand et al., 1993 [78]	Early forensic casework	Case-based	Nail debris	DNA recovered from debris	Not temporal	Clipping-based recovery effective	Debris viable source of DNA
Sanchez-Hanke et al., 1996 [79]	Scratch-derived epidermal particles	Experimental	Debris recovery	Successful PCR typing	Not time-focused	Demonstrated epithelial transfer	Scratching deposits cellular material
Fernández-Rodríguez et al., 2003 [80]	Casework fingernail debris	Applied casework	Clippings/debris	STR typing successful	Not temporal	Debris analysis viable	Forensic applicability established
Piccinini, 2003 [81]	5-year homicide review	Retrospective casework	Clippings	Variable recovery rates	Not systematic	Case-dependent outcomes	Recovery varies by context
Hebda et al., 2014 [83]	Comparative sampling methods	Experimental comparison	Swab vs clipping	Recovery differs by method	Not time-focused	Method affects yield	Sampling influences interpretation
Bozzo et al., 2015 [96]	Criminal case samples	Case-based	Swabbing	DNA profiles obtained; mixtures common	Not temporal	Complex contributor patterns	Multi-source profiles typical
Iuvaro, 2020 [97]	Scratch experiment	Controlled + applied	Subungual debris	Transfer demonstrated	Temporal aspects explored	Detailed debris analysis	Supports activity-level evaluation

Note. Percentages and detection outcomes are reported as described in the original studies and may reflect differences in sampling method (e.g., swabbing, scraping, clipping), analytical strategy (autosomal STR, Y-STR, probabilistic genotyping), reporting thresholds, and population characteristics. “Foreign DNA” refers to detectable non-self DNA beneath the fingernails. “Mixtures” indicate profiles containing genetic material from two or more contributors. Variability across studies reflects differences in volunteer versus casework populations, time since contact, environmental exposure, cohabitation status, and analytical sensitivity. Collectively, the data demonstrate that the presence of non-self DNA beneath fingernails is not uncommon in non-criminal contexts and that mixture profiles should be considered expected rather than exceptional findings.

Importantly, most individuals exhibiting foreign DNA had experienced recent physical contact, highlighting that routine social interactions are sufficient to introduce non-self DNA into the subungual environment.

Subsequent studies consistently reported higher frequencies of foreign DNA detection, particularly when more sensitive STR systems and Y-STR approaches were employed. Matte et al. observed foreign DNA beneath fingernails in a high proportion of volunteers, with detection rates varying depending on sampling and analytical conditions, and demonstrated that such DNA could persist for several hours or longer despite routine handwashing [74]. Dowlman et al. similarly found that mixed DNA profiles were common on fingernail swabs, reinforcing that single-source profiles are not the default outcome [76].

Everyday activity studies further support these findings. Goray et al. showed that non-self DNA was present in fingernail samples collected after unrestricted daily activities, with partners being the most frequent contributors [95]. Doctoral work by Iuvaro, which incorporated baseline sampling prior to any simulated assault, demonstrated that male DNA could already be detected under female volunteers' fingernails under normal living conditions [97]. Collectively, these studies demonstrate that background foreign DNA beneath fingernails is a recurrent and measurable phenomenon rather than an exceptional finding.

3.2. Number of contributors commonly observed

Fingernail samples are characteristically prone to mixture formation. Studies involving cohabiting couples consistently show that two-person mixtures are common and that partner DNA is frequently detected as a minor component [72,77]. In homicide-related case series, mixed DNA profiles were also prevalent in both victims and suspects, with foreign contributors regularly detected alongside the individual's own DNA [75,81].

Casework-oriented evaluations report similar trends. Bozzo et al. found that approximately 13% of criminal case fingernail samples contained foreign DNA as a minor contributor, with most profiles dominated by the individual's own DNA [96]. Hebda et al. demonstrated that the observed mixture composition varied depending on sampling and analytical strategy, underscoring that methodological choices can influence whether minor contributors are detected [83].

Recent experimental simulations reinforce these observations. Damour et al. showed that immediately after scratching, the offender's DNA dominated the subungual profile, but within hours this contribution decreased rapidly and was progressively replaced or masked by background DNA from unknown sources [99]. After 24 h, a substantial proportion of detected Y-STR profiles matched pre-existing background DNA rather than the scratched individual, illustrating how contributor composition evolves over time. Thus, fingernail DNA profiles typically reflect a composite signal derived from multiple contributors accumulated across different time points rather than a snapshot of a single contact event.

3.3. Influence of intimate contacts and cohabitation

The role of intimate and repeated contact is particularly well documented. Malsom et al. showed that cohabiting partners frequently contribute detectable DNA beneath each other's fingernails, even in the absence of violence [72]. Kettner et al. similarly demonstrated that scratches between intimate partners produced profiles that overlapped substantially with background DNA arising from cohabitation [77].

Simulated assault studies confirm that intimate or forceful contact can transfer DNA efficiently. Digital penetration experiments demonstrated that male DNA could be recovered beneath fingernails following brief genital contact and could persist for several hours [73]. However, both Matte et al. and Iuvaro showed that such foreign DNA is not exclusive to assault scenarios and can also arise from casual interactions, self-contact, and routine social behaviour [74,97].

Damour et al. provided a mechanistic explanation for these observations by demonstrating that background male DNA may persist or be newly introduced after an assault simulation, especially when individuals live together or engage in regular close contact [99]. These findings highlight that cohabitation and intimacy significantly bias the subungual DNA reservoir, increasing the likelihood that foreign DNA originates from non-criminal interactions.

3.4. Comparison between victims and non-victims

Comparative analyses indicate that while victims of violent crime may exhibit higher rates of foreign DNA under their fingernails, non-victims also commonly show foreign contributors. In homicide case series, mixed profiles were detected in both victims and suspects, with no absolute distinction between forensic and non-forensic contexts [75,81]. Dowlman et al. reported that fingernail mixtures occurred in individuals without any reported assault history, further blurring the distinction between forensic and everyday contexts [76]. Controlled simulations illustrate this overlap. Flanagan and McAlister showed that offender DNA could be detected shortly after digital penetration, but Matte et al. and Damour et al. demonstrated that background DNA increasingly dominates with time [73,74,99]. Goray et al. likewise found that everyday activity could produce profiles comparable in complexity to those observed in casework fingernail samples [95]. These findings indicate that fingernail DNA does not inherently encode whether an assault occurred. Instead, it reflects a balance between recent contact events and accumulated background material, with substantial overlap between victim and non-victim populations.

3.5. Implications for interpretation

The consistent observation of foreign DNA beneath fingernails in non-crime contexts has profound implications for forensic interpretation. Buckleton et al. formalised this problem by developing activity-level likelihood ratio frameworks for fingernail DNA evidence, demonstrating that the probative value of a detected contributor is highly sensitive to assumptions about prior social contact, scratching behaviour, and the presence of unknown contributors [100]. Their results showed that fingernail DNA often provides only modest support for prosecution propositions when social interaction cannot be excluded. Mechanistic studies on secondary transfer further support this cautious approach. Zoppis et al. demonstrated that sebaceous skin areas facilitate DNA transfer and secondary deposition, explaining how indirect transfer pathways can populate the subungual environment without any violent interaction [101]. Environmental persistence studies, including work on submerged bodies, confirm that exogenous DNA can remain detectable under extreme conditions, further complicating temporal inference [102].

Taken together, the literature supports a unified conclusion: the presence of foreign DNA beneath fingernails is common in everyday life, mixtures are the norm, and contributor composition evolves rapidly over time. Fingernail DNA should therefore be interpreted as evidence of contact history rather than direct proof of assault. This justifies the need for fingernail-specific interpretive frameworks that explicitly incorporate background prevalence, mixture formation, and activity-level reasoning rather than relying solely on sub-source attribution.

4. Transfer mechanisms relevant to fingernail samples

Interpretation of DNA recovered from fingernail samples requires an explicit understanding of the multiple transfer mechanisms by which biological material may enter and persist within the subungual space. Unlike many exposed contact surfaces, fingernails are embedded within a semi-protected anatomical niche that facilitates the accumulation and retention of DNA originating from diverse activities and temporal contexts (Section 2). Consequently, DNA detected beneath fingernails cannot be assumed to arise from a single event, and its evidential significance must be evaluated at the activity level rather than inferred solely from sub-source attribution. The principal transfer mechanisms relevant to fingernail samples include primary, secondary, and tertiary transfer pathways, as well as grooming-mediated deposition, all of which may operate concurrently or sequentially (**Figure 2**).

4.1. Primary transfer: direct physical contact

Primary transfer refers to the direct deposition of biological material from one individual to another during physical contact. In the context of fingernail evidence, this most commonly involves scratching or gripping during violent or sexual assaults, whereby epithelial cells, blood, or other biological material from the assailant may be introduced into the hyponychium. Experimental and case-based studies have repeatedly demonstrated that such direct contact can result in the recovery of foreign DNA beneath fingernails, particularly when sampling is conducted shortly after the alleged event [73,75,77,99].

Controlled simulations of scratching have shown that foreign DNA may be readily detectable immediately following contact, with recovery rates declining as time elapses and as competing activities occur [99,102]. Importantly, however, even under conditions designed to model direct assault-related transfer, fingernail samples frequently yield mixed DNA profiles rather than single-source profiles, reflecting the contribution of pre-existing background DNA within the subungual space [72,74–76,98]. These findings indicate that while primary transfer can introduce probative DNA, it does not occur in isolation from other transfer and persistence processes.

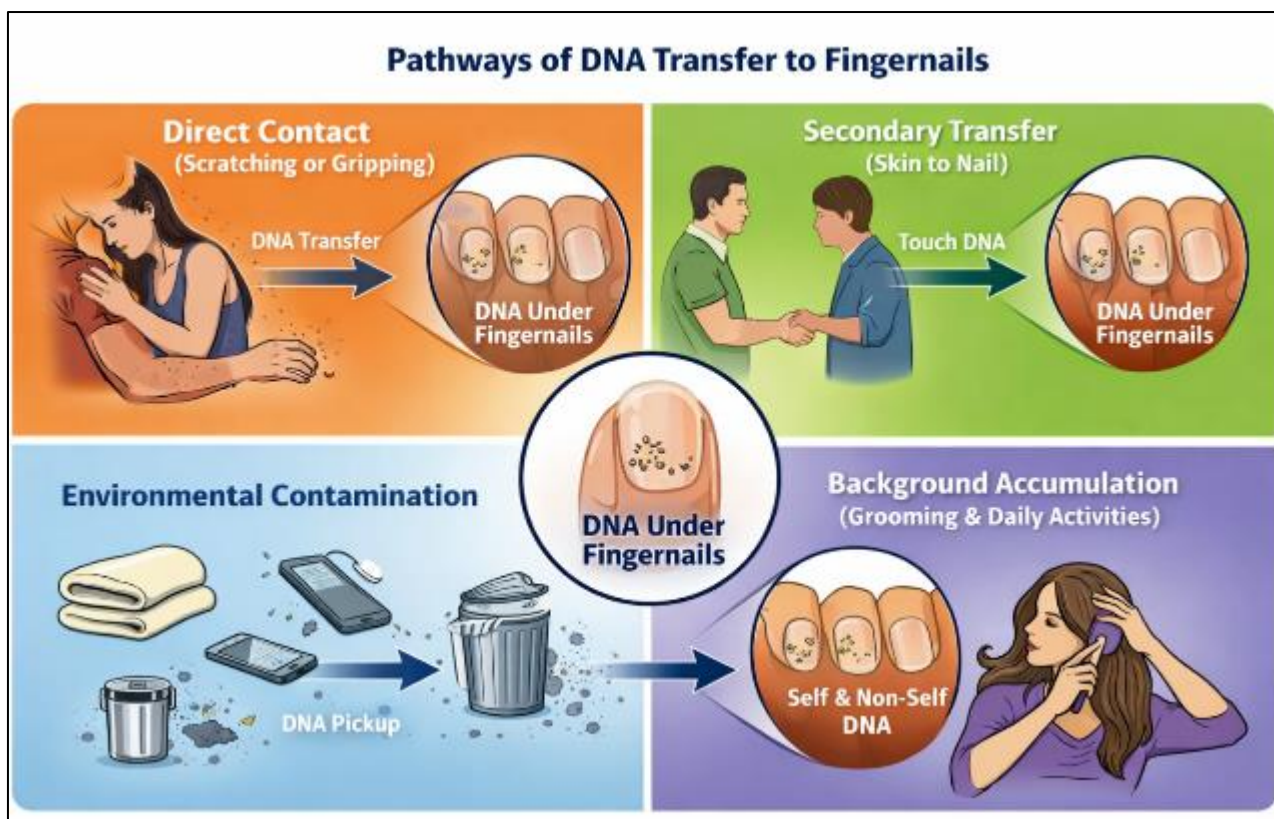


Figure 2 Pathways of DNA transfer to fingernails. This conceptual diagram illustrates the principal mechanisms by which DNA may be deposited and retained within the subungual space. Primary transfer occurs through direct contact (e.g., scratching or gripping), secondary transfer involves indirect movement of DNA from skin surfaces during routine contact, and tertiary transfer occurs via intermediary objects or surfaces. Background accumulation reflects the time-integrated incorporation of self and non-self DNA through everyday activities such as grooming and environmental contact. The figure is schematic and not intended to represent DNA as visible material, but to illustrate mixed-origin DNA arising from multiple overlapping transfer pathways relevant to activity-level interpretation.

4.2. Secondary transfer: skin-to-nail pathways

Secondary transfer involves the movement of DNA from skin surfaces to the fingernails without direct contact between the fingernails and the original donor. Hands are highly dynamic DNA vectors, acquiring and redistributing biological material through routine social interactions, object handling, and self-contact [10,45,93,94]. DNA present on the palmar surfaces or fingertips may subsequently be transferred to the subungual region during everyday activities such as nail grooming, scratching one's own skin, or incidental contact between fingers.

Studies on touch DNA transfer demonstrate that indirect transfer from person to person is common and influenced by skin properties, sebaceous secretions, and individual shedding variability [4,93,101]. Experimental work further shows that secondary transfer can occur rapidly and may produce detectable profiles even in the absence of direct contact with the original donor [101]. In the context of fingernails, this mechanism provides a plausible explanation for the frequent detection of foreign DNA in non-criminal settings and among individuals reporting recent social or domestic contact [72,74,98].

4.3. Tertiary transfer: object-mediated pathways

Tertiary transfer refers to the indirect movement of DNA via intermediary objects, such as when biological material is transferred from a person to an object and subsequently from that object to another individual. Numerous studies have established that common surfaces readily acquire and redistribute touch DNA and that profiles recovered from hands often reflect cumulative contact with multiple objects rather than a single source [10,31,45].

Given the hands' central role in object manipulation, tertiary transfer provides an additional pathway by which foreign DNA may be introduced into the subungual space. DNA acquired from shared objects (e.g., clothing, furniture, tools, personal devices) may be transferred to the hands and subsequently deposited beneath fingernails during routine

movements or grooming behaviors. Although tertiary transfer to fingernails has been less frequently isolated experimentally, its plausibility is supported by broader touch DNA research demonstrating complex transfer chains and bidirectional exchange between skin and surfaces [4,31,94].

4.4. Grooming-mediated transfer and background accumulation

Grooming behaviors represent a distinct but underappreciated mechanism contributing to fingernail DNA profiles. Activities such as touching the face, scalp, hair, or clothing can introduce both self and non-self DNA to the hands, which may then be transferred to the subungual space. Studies on skin area-dependent DNA shedding and secondary transfer highlight the role of sebaceous regions and grooming-related contact in facilitating DNA movement across the body surface [101].

Over time, repeated primary, secondary, and tertiary transfer events lead to the gradual accumulation of biological material beneath fingernails. This process results in what may be conceptualized as a time-integrated DNA reservoir, containing contributions from multiple individuals and activities rather than reflecting a single discrete event [72,74–76,98,102]. Evidence from volunteer studies, cohabiting partner research, and post-event simulations consistently shows that background DNA may persist beneath fingernails even when no recent assault-related activity has occurred [72,74,98].

4.5. Implications for forensic interpretation

The coexistence of multiple transfer mechanisms has significant implications for the interpretation of fingernail DNA evidence. Activity-level models demonstrate that the evidential value of subungual DNA is strongly modulated by contextual factors such as prior social interaction, grooming behaviors, elapsed time, and the presence of unknown contributors [99,100]. The detection of foreign DNA beneath fingernails may therefore provide support, limited support, or no support with respect to competing activity-level propositions depending on the activity framework under consideration rather than the mere presence or absence of a person of interest's DNA. Figure 2 synthesizes these transfer pathways and illustrates how direct and indirect mechanisms converge within the subungual micro-environment. This conceptual framework reinforces the need to treat fingernail DNA as a composite product of multiple biological and behavioral processes, and cautions against assuming assault-specific origin in the absence of robust activity-level evaluation [72–76,98–100,102].

5. Persistence and temporal dynamics of DNA under fingernails

The probative value of fingernail DNA evidence is not determined solely by the presence or absence of foreign genetic material, but by its persistence over time and its susceptibility to modification through routine activities and environmental exposure. As summarized in Section 3 and synthesized in **Table 1**, foreign DNA is frequently detected beneath fingernails in non-criminal contexts. Accordingly, the evidential significance of any detected profile depends not only on its source but also on when and under what circumstances it was deposited. Unlike exposed skin surfaces, the subungual region constitutes a partially sheltered micro-environment (Section 2), which alters both the rate and pattern of DNA loss, retention, and replacement. As illustrated in **Figure 3**, the temporal dynamics of DNA beneath fingernails are characterized by an early phase in which recently transferred DNA may predominate, followed by a progressive transition toward mixed or background-dominated profiles as time elapses. Consequently, DNA persistence under fingernails differs fundamentally from touch DNA persistence on hands or external substrates and must be evaluated within a time-dependent, activity-level framework when assessing evidential significance.

5.1. Persistence immediately after contact versus delayed sampling

Experimental and casework-based studies consistently demonstrate that the probability of detecting offender DNA beneath fingernails is highest immediately following physical contact, particularly in scenarios involving scratching or forceful interaction [73,75,99]. Early experimental work showed that DNA transferred under fingernails during intimate or violent contact can be detected shortly after deposition and may persist for several hours under controlled conditions [73]. More recent controlled simulations reinforce this finding, indicating that Y-STR profiles of scratched individuals are most frequently detected in samples collected immediately or within the first few hours following the event [99]. However, these same studies also demonstrate a rapid temporal decline in the relative contribution of offender DNA. Damour et al. reported a marked reduction in male DNA quantities within the first three hours post-scratching, with compatible offender profiles rarely detected beyond 6 h and absent at later time points (12–24 h), despite the continued presence of other foreign DNA [99]. This temporal pattern underscores an important interpretive principle: early detection does not equate to long-term persistence, and the absence of offender DNA in delayed samples cannot be equated with absence of contact.

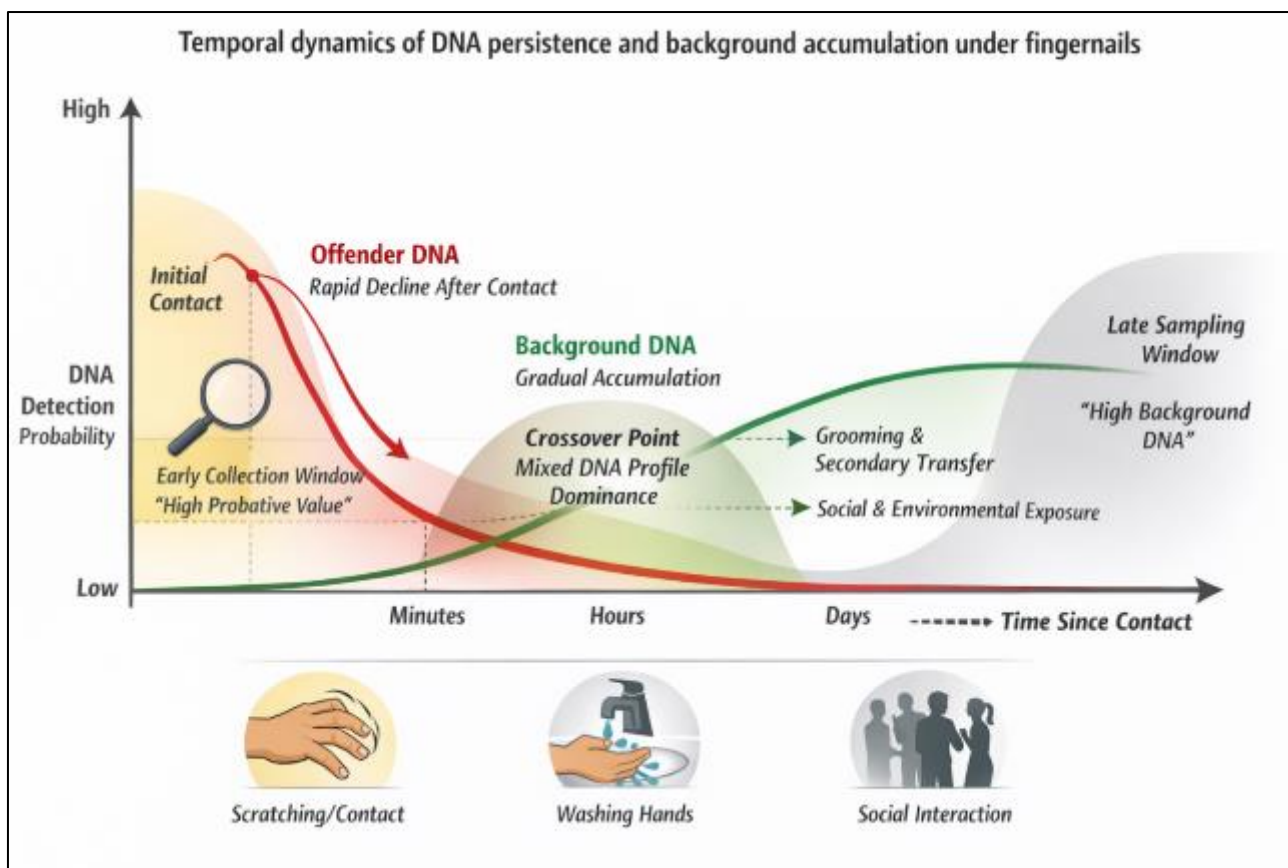


Figure 3 Temporal dynamics of DNA persistence and background accumulation beneath fingernails. This conceptual illustration depicts changes in the relative detectability of event-associated (e.g., offender-derived) DNA and background DNA within the subungual space as a function of time since contact, based on experimental and casework studies [73,75,99]. Immediately following contact (e.g., scratching), DNA from the contacted individual is expected to have a high probability of detection, defining an early sampling window of greatest evidential value. Over time, routine activities—including handwashing, grooming, environmental contact, and social interactions—contribute to the decline of event-associated DNA and the accumulation or replacement by background DNA. This shift increases the likelihood of mixed profiles and non-specific findings. The crossover phase represents the transition from event-related to background-dominated DNA, highlighting the importance of prompt sampling and activity-level interpretation.

Persistence studies involving extreme conditions further support this distinction. DNA has been shown to remain detectable under fingernails following prolonged submersion in water, including freshwater and polluted environments, although recovery efficiency varies substantially with exposure conditions [82,102]. These findings demonstrate that fingernail DNA may persist physically while undergoing compositional change, with quantitative loss and qualitative profile evolution occurring simultaneously. These data collectively argue against binary interpretations based on delayed sampling outcomes. Fingernail DNA evidence should instead be evaluated within a time-dependent framework, recognizing that the likelihood of detecting offender DNA decreases rapidly, while background or previously accumulated DNA may remain detectable for substantially longer periods.

5.2. Effects of washing, grooming, and routine hand activity

A common assumption in forensic practice is that handwashing or personal hygiene substantially reduces or eliminates DNA under fingernails. Empirical evidence does not support such a simplistic view. While washing effectively reduces DNA on exposed skin surfaces [44,45], its effect on the subungual region is more limited and inconsistent.

Submersion experiments have shown that DNA can persist under fingernails even after extended immersion in water, suggesting that mechanical washing alone does not reliably clear subungual material [82]. Controlled scratching simulations further demonstrate that routine activities performed after an event—without deliberate nail cleaning—may reduce offender DNA while simultaneously introducing new background DNA through secondary transfer [99].

This pattern reflects selective loss rather than complete removal, driven by differential exposure and accessibility within the nail unit.

Routine grooming behaviors introduce additional complexity. Touching the face, scalp, or hair can facilitate secondary transfer of DNA to the hands and subsequently to the nails, particularly via sebaceous secretions that act as effective DNA vectors [101]. Individual variability in shedding behavior further modulates this process, influencing both the amount and persistence of DNA under fingernails over time [93].

From a practical standpoint, these findings indicate that washing does not reset the subungual DNA environment. Instead, fingernail DNA profiles evolve through a combination of partial loss and ongoing acquisition. Claims that post-event washing necessarily invalidates fingernail evidence are scientifically unsustainable and should be avoided in forensic reporting.

5.3. Environmental exposure and extreme conditions

Environmental exposure represents an additional modifier of fingernail DNA persistence, particularly in cases involving immersion, burial, or extended postmortem intervals. Experimental work on submerged fingernail samples demonstrates that DNA can remain recoverable for at least 48 h, with recovery rates strongly influenced by water type and contamination level [102]. Freshwater environments generally permit higher DNA recovery than polluted or sewage waters, although complete loss is not inevitable even under adverse conditions.

Earlier studies similarly demonstrated persistence of DNA under fingernails following submersion, reinforcing the concept that the subungual niche affords a degree of protection not observed on exposed skin [82]. These findings align with broader observations that fingernails function as retention matrices capable of preserving biological material under conditions that would rapidly degrade DNA elsewhere.

Importantly, persistence under harsh conditions does not imply evidential specificity. Environmental exposure may preserve DNA physically while eroding its activity-level informativeness, particularly if prolonged intervals permit competing deposition or background accumulation. Expert interpretation must therefore distinguish physical survival from forensic relevance, especially in delayed or postmortem contexts.

5.4. Competitive deposition and profile evolution over time

Perhaps the most critical—and often underappreciated—aspect of fingernail DNA persistence is the phenomenon of competitive deposition. Multiple studies demonstrate that fingernail profiles are rarely static; instead, they evolve as new DNA is introduced and previously deposited material is diluted or displaced [72,74,98,99].

Volunteer studies involving individuals from the general population have shown that foreign DNA is present under fingernails even in the absence of criminal activity, with mixed profiles detected in a measurable proportion of samples [98]. Cohabitation and close social contact further increase the likelihood of persistent non-self DNA beneath fingernails, complicating attribution to specific events [72,77]. Casework-based investigations similarly report high frequencies of mixed profiles in victims and suspects alike, reinforcing the non-exceptional nature of background DNA in this substrate [75,76,96].

Recent comparative work highlights that fingernail samples and contemporaneous hand deposits may differ in both contributor composition and persistence patterns, reflecting their distinct micro-environmental properties [95]. Activity-level modelling approaches explicitly account for these dynamics, demonstrating that evidential weight is often modest unless sampling occurs promptly and contextual information strongly constrains alternative explanations [100].

Fingernail DNA should be understood as a time-integrated biological record rather than a snapshot of a single interaction. The presence of offender DNA shortly after an event may support activity-level propositions, but delayed samples are increasingly dominated by background and competing contributors. Failure to account for this temporal evolution risks overstating evidential value and misrepresenting scientific uncertainty.

Collectively, the evidence demonstrates that persistence under fingernails is governed by a dynamic interplay between retention, loss, and replacement [72–76,99,102]. Offender DNA is most likely to be detected shortly after contact, declines rapidly, and may be masked or replaced by background DNA over time [99]. Washing and environmental exposure do not guarantee removal, while routine activities continue to modify the subungual DNA pool [82,99,102]. Fingernail DNA evidence cannot be interpreted reliably without explicit consideration of time since contact, intervening

activities, and background accumulation processes [72–76,98,100]. These factors must be integrated into activity-level evaluation frameworks to ensure scientifically defensible conclusions [100].

6. Mixtures, Dominance, and Interpretive Traps

The interpretation of DNA recovered from beneath fingernails presents one of the most analytically demanding scenarios in forensic biology. As established in Sections 2 through 5, the subungual region functions as a semi-protected micro-environment capable of accumulating biological material through repeated primary, secondary, and tertiary transfer events. Empirical prevalence data summarized in **Table 1** demonstrate that foreign DNA and mixed profiles are frequently detected beneath fingernails even in the absence of criminal activity. The presence of non-self DNA is therefore not an inherently crime-specific observation, but rather a biologically plausible consequence of routine human contact, indirect transfer, and background accumulation processes [72–76,98].

Despite this empirical foundation, fingernail DNA evidence remains vulnerable to over-interpretation. Three interpretive domains are particularly susceptible to analytical distortion: the expectation of mixtures, the evidential meaning attributed to dominant contributors, and the narrative inference that subungual DNA necessarily implies defensive struggle. These domains do not operate independently; they interact through stochastic amplification dynamics, transfer variability, and cognitive influences that may subtly shape interpretive judgments. **Figure 4** provides a structured conceptual framework for understanding these interacting layers of complexity. It illustrates how biological reality, analytical factors, activity-level modeling, and cognitive risk operate hierarchically yet interdependently in the interpretation of fingernail DNA. A critical examination of these mechanisms is therefore essential to preserve evidential proportionality and to prevent interpretive conclusions from exceeding the constraints imposed by biological variability and statistical uncertainty.

6.1. Mixtures as the Baseline Condition

Mixtures in fingernail samples should be regarded as biologically expected rather than exceptional. Early casework observations and controlled studies consistently demonstrated a high frequency of mixed DNA profiles in subungual samples from both victims and suspects [72–76]. Dowlman et al. [76] and Malsom et al. [72] reported frequent detection of multiple contributors even among cohabiting individuals in non-criminal contexts. Nurit et al. [75] further showed that mixtures are common in homicide investigations, yet their presence alone did not discriminate between assault-related and background deposition.

Cook and Dixon [98] provided particularly important baseline data by examining fingernail samples from 100 volunteers in the general population. Foreign DNA was detected in 13% of samples, and reportable mixtures were present in 6% despite the absence of any alleged assault. A substantial proportion of mixed profiles involved male contributors, and most participants reported physical contact within 24 hours prior to sampling. These findings directly challenge the assumption that foreign DNA beneath fingernails is intrinsically indicative of violent activity.

The biological explanation is consistent with transfer research more broadly. Fingernails interact continuously with sebaceous and non-sebaceous skin surfaces, hair, fabrics, and objects. Zoppis et al. [101] demonstrated that sebaceous secretions act as effective vectors for DNA transfer, facilitating secondary deposition. Szkuta et al. [45] showed that DNA readily transfers and persists on hands during routine activities, providing a reservoir from which material may subsequently accumulate under nails. Given the frequency of hand-to-face, hand-to-hair, and interpersonal contact events in daily life, repeated secondary and tertiary transfer to the subungual region is inevitable. The persistence of mixture profiles under fingernails should not be viewed as evidential complexity requiring special explanation. Rather, a single-source subungual profile in an adult individual may in some circumstances be more biologically unusual than a mixed profile. The expectation of mixtures must therefore be embedded as a baseline interpretive assumption.

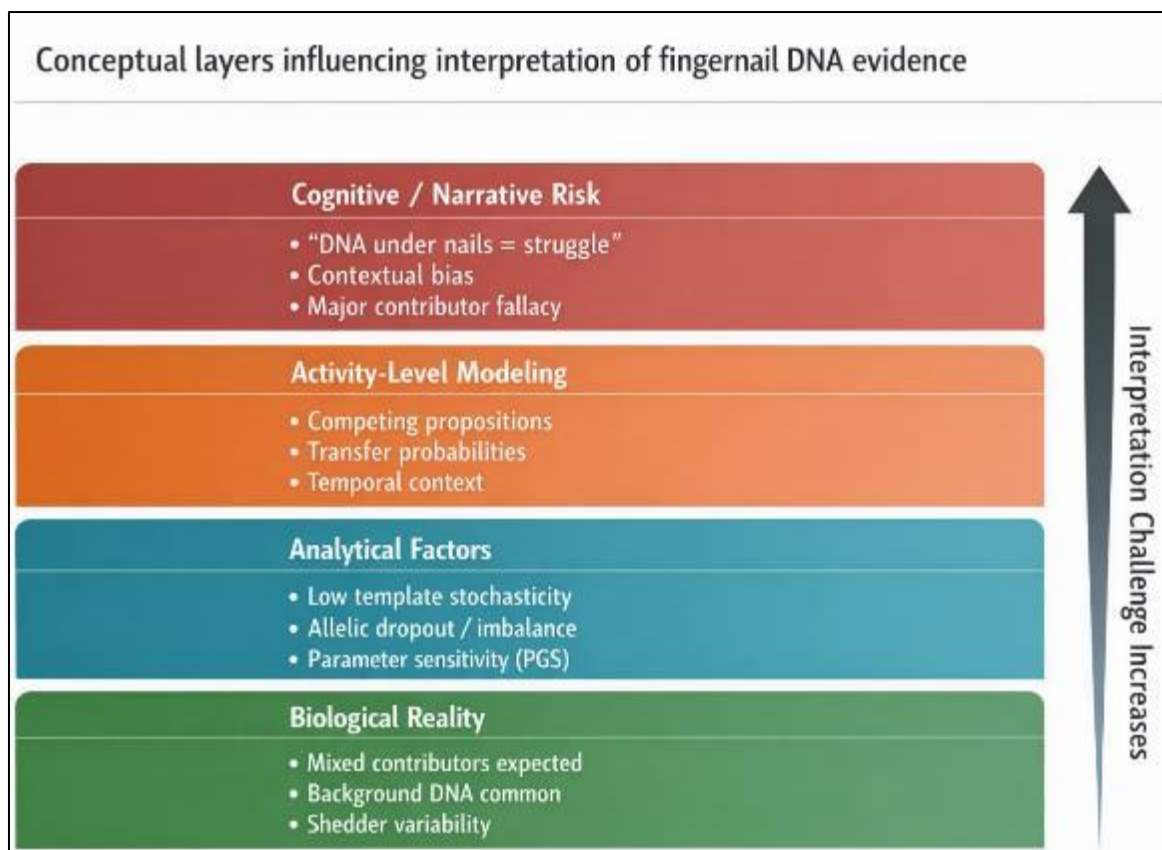


Figure 4 Conceptual framework for the interpretation of fingernail DNA evidence. This schematic presents a hierarchical model illustrating the biological, analytical, evaluative, and cognitive dimensions influencing the interpretation of DNA recovered from fingernails. The framework comprises four interconnected layers. “Biological Reality” reflects empirically established properties of subungual material, including mixture prevalence, background DNA accumulation, and variability in shedding and retention. “Analytical Factors” encompass technical influences associated with low-template DNA, such as stochastic effects, allelic dropout, degradation, and probabilistic genotyping parameters. “Activity-Level Modeling” emphasizes evaluation under competing propositions, integrating transfer mechanisms, persistence, and temporal context. “Cognitive and Narrative Risk” highlights interpretive vulnerabilities, including contextual bias and inferential errors. The hierarchical structure reflects increasing interpretive complexity and underscores the need for integrated, activity-level evaluation

6.2. Dominant Contributors and the Illusion of Temporal Priority

A recurring interpretive error in fingernail casework is equating the major contributor in a mixture with the most recent or most forceful depositor. This reasoning assumes that contributor proportions directly reflect deposition chronology. Empirical evidence does not reliably support such simplification, as contributor dominance may be influenced by stochastic effects, transfer variability, and persistence dynamics [99,103,104].

Low-template samples are inherently vulnerable to stochastic amplification effects [103]. Timken et al. [103] demonstrated that allelic imbalance and dropout in reduced template dilutions can be accurately modeled using pre-PCR Poisson sampling dynamics. Minor contributors may be disproportionately lost due to stochastic dropout, artificially inflating the apparent dominance of remaining contributors. Thus, peak height ratios do not necessarily reflect original cellular proportions.

Costa et al. [104] extended this complexity by demonstrating that likelihood ratios derived from probabilistic genotyping software can vary dramatically depending on parameter choices, including drop-in rates, stutter modeling, and analytical thresholds. In some cases, altering a single parameter resulted in LR differences exceeding 10,000-fold, occasionally supporting opposing hypotheses. This underscores that contributor dominance is not solely a biological phenomenon but partly an artifact of modeling assumptions.

Degradation adds further instability. Duke and Myers [105] showed that degradation modeling within STRmix™ can significantly influence evidential weight calculations. When DNA is differentially degraded, peak height patterns may distort contributor ratios. In fingernail samples exposed to environmental stressors, such as washing, abrasion, or water immersion, differential degradation of contributors is plausible.

Ido et al. [106] demonstrated that establishing amplification thresholds for low template DNA materially affects profile informativeness. Adjusting laboratory cut-offs reduced workload while retaining most informative profiles, but also altered dropout frequencies. Consequently, dominance in a fingernail mixture may reflect laboratory decision thresholds rather than deposition magnitude.

The presence of a major contributor beneath fingernails should not be equated with chronological priority in the absence of independent corroborative evidence. Apparent dominance may arise from differential shedding propensity, stochastic sampling effects, dropout of minor contributors, degradation dynamics, or assumptions embedded within probabilistic modeling systems. Consequently, contributor ranking must be interpreted with caution, particularly in low-template contexts that are characteristic of many subungual samples.

6.3. Shedder Status and Retention Dynamics

The concept of “shedder status” has been extensively explored in touch DNA literature [1,4,93]. Individuals vary in the amount of DNA they deposit upon contact. However, deposition propensity does not guarantee retention beneath fingernails.

Damour et al. [99] provided controlled scratch simulations demonstrating that male DNA transferred during scratching was readily detectable immediately and up to six hours post-event, with a marked decrease after three hours and absence at 12–24 hours. Notably, background male DNA reappeared at later time points, suggesting replacement rather than persistence. These findings illustrate the dynamic turnover of subungual DNA.

Zareef et al. [102] further demonstrated environmental modulation of persistence. Using prosthetic fingers in submersion scenarios, they showed that DNA yield varied significantly depending on water type. Freshwater samples retained higher concentrations than sewage water after 48 hours. Although subungual regions provide partial shelter, they are not immune to environmental degradation.

The interaction between shedding and retention is underappreciated. A high shedder may deposit substantial DNA during contact, but routine activities—handwashing, abrasion, grooming, and subsequent contacts—may replace or dilute that deposit rapidly. Conversely, a moderate shedder whose DNA becomes mechanically entrapped in the hyponychium during a specific event may persist longer than expected. Thus, retention dynamics may override deposition propensity. This distinction is critical when interpreting mixed subungual profiles. Without temporal context and prompt recovery, contributor presence cannot be reliably mapped onto specific activity events.

6.4. Narrative Fallacy and Cognitive Bias

Perhaps the most pervasive interpretive trap in fingernail casework is the implicit narrative equation: “DNA under nails equals defensive struggle.” This inference is psychologically compelling but scientifically fragile.

Buckleton et al. [100] emphasized the importance of activity-level propositions when evaluating fingernail DNA. Their modeling demonstrated that likelihood ratios vary substantially depending on prior social interaction between complainant and person of interest. In scenarios involving prior contact, evidential support may decrease to modest levels even when suspect DNA is present.

Taylor et al. [107] further showed how site-to-site transfer can be incorporated into Bayesian networks during activity-level evaluations. Transfer modeling must account for indirect routes, including packaging, transport, and cross-contact. Failure to incorporate plausible transfer pathways risks non-exhaustive propositions.

Cognitive bias literature reinforces this concern. Curley et al. [108] reviewed contextual bias in forensic decision-making, highlighting the influence of task-irrelevant information. In assault investigations, knowledge of alleged scratching or visible injuries may subconsciously increase confidence in DNA findings, even when background prevalence data suggest caution. Fingernail evidence should not confirm a narrative; it should be evaluated against competing hypotheses. The scientifically defensible question is not whether a struggle occurred, but whether the observed DNA findings are more probable under one activity-level proposition than another, given known transfer, persistence, and background mechanisms.

6.5. Toward a Structured Interpretive Approach

Given the complexities discussed, fingernail DNA evidence demands a structured interpretive framework integrating biological understanding, statistical rigor, and activity-level reasoning.

First, biological literacy is essential. Evaluators must understand transfer pathways [45,101], background prevalence [72-76,98], and retention dynamics [99,102]. Second, statistical discipline is required. Low-template stochasticity [103], parameter sensitivity [104], degradation modeling [105], and threshold effects [105] must be explicitly considered when evaluating contributor proportions and likelihood ratios. Third, activity-level reasoning must be applied. Bayesian modeling approaches [100,107] provide formal mechanisms to incorporate transfer probabilities, temporal factors, and alternative scenarios. Fourth, contextual discipline is necessary. Awareness of cognitive bias [108] protects against narrative overreach.

A defensible interpretive stance for fingernail evidence is one of calibrated neutrality. The presence of foreign DNA beneath fingernails may provide meaningful evidential support when samples are collected promptly and evaluated within a robust activity-level framework. However, in the absence of such contextualization, the weight attributed to the findings should be moderated to reflect biological complexity, transfer variability, and stochastic uncertainty inherent to low-template and mixed DNA profiles.

Fingernails represent time-integrated, mixed-source biological micro-environments rather than single-event trace collectors. Mixtures are expected. Major contributors may be stochastic artifacts. Shedder status does not guarantee retention. Background DNA is common. Activity-level propositions must be formally modeled rather than narratively assumed. The interpretive strength of subungual DNA lies not in its dramatic association with struggle, but in its disciplined evaluation within biological, statistical, and probabilistic boundaries. When approached with rigor, fingernail DNA evidence can contribute meaningfully to forensic reconstruction. When approached narratively, it risks exceeding its empirical foundation.

7. Implications for Activity-Level Interpretation

The evidential evaluation of DNA recovered from beneath fingernails presents a distinctive challenge at the activity level. As established in Sections 2 through 6, and supported by prevalence data summarized in **Table 1**, the subungual region constitutes a semi-protected, time-integrated micro-environment in which biological material may accumulate through repeated primary, secondary, and tertiary transfer events. Foreign DNA and mixed profiles are frequently observed even in non-criminal contexts. While the detection of non-self DNA may be consistent with a physical altercation, it is equally compatible with routine social contact, indirect transfer pathways, and background persistence. Consequently, fingernail DNA rarely resolves competing activity propositions in isolation. The hierarchical relationship between laboratory findings and evaluative conclusions in such cases is illustrated in **Figure 5**, which situates sub-source attribution within the broader logical framework required for activity-level reasoning.

Modern evaluative frameworks emphasize that the weight of forensic findings must be assessed relative to clearly articulated, mutually exclusive propositions addressing the issue in dispute [109,110]. In many cases involving fingernail evidence, the source of the DNA is not the primary issue. Instead, the dispute concerns how and when the material was deposited. This distinction is critical. A high sub-source likelihood ratio indicating that the DNA originated from a person of interest does not, by itself, determine whether that DNA was deposited during an alleged assault, during a prior consensual interaction, or via indirect transfer. Carrying sub-source conclusions into activity-level inference without structured evaluation risks transposing the conditional and overstating the probative value of the evidence [110].

7.1. Fingernail DNA and Competing Activity Propositions

When fingernail DNA is presented in court, the competing narratives frequently involve contrasting accounts of contact. For example, the prosecution may allege that the complainant scratched the accused during a violent encounter, whereas the defense may assert prior consensual contact, routine cohabitation, or innocuous interaction. In such scenarios, the relevant propositions are activity-based rather than source-based.

Research on activity-level modeling has demonstrated that the formulation of propositions substantially affects the evaluation of DNA evidence [109]. If the alleged criminal activity itself is disputed, the presence or absence of unknown DNA may be largely irrelevant to the weight assigned to the DNA of the accused. Conversely, if the activity is conceded but the identity of the actor is disputed, the evaluative focus shifts accordingly. These structural considerations must be addressed before any likelihood ratio is assigned.

Empirical studies reinforce this caution. Background foreign DNA has been documented under fingernails in individuals without any criminal context [72–76,98]. Controlled scratching simulations demonstrate that while offender DNA may be highly detectable shortly after contact, its quantity decreases rapidly over time and may be replaced or masked by background DNA through subsequent activity [99]. Similarly, activity-level evaluation models show that the presence of unknown contributors can substantially alter likelihood ratios, especially when prior social interaction cannot be excluded [100]. Taken together, these findings indicate that fingernail DNA rarely functions as a binary indicator of struggle. A common interpretive error is the implicit assumption that the presence of a suspect’s DNA beneath a complainant’s nails equates to defensive scratching. While this inference may be plausible in certain circumstances, it is not inherently supported by biological evidence alone. Without contextual integration, the observation remains compatible with multiple plausible activities.

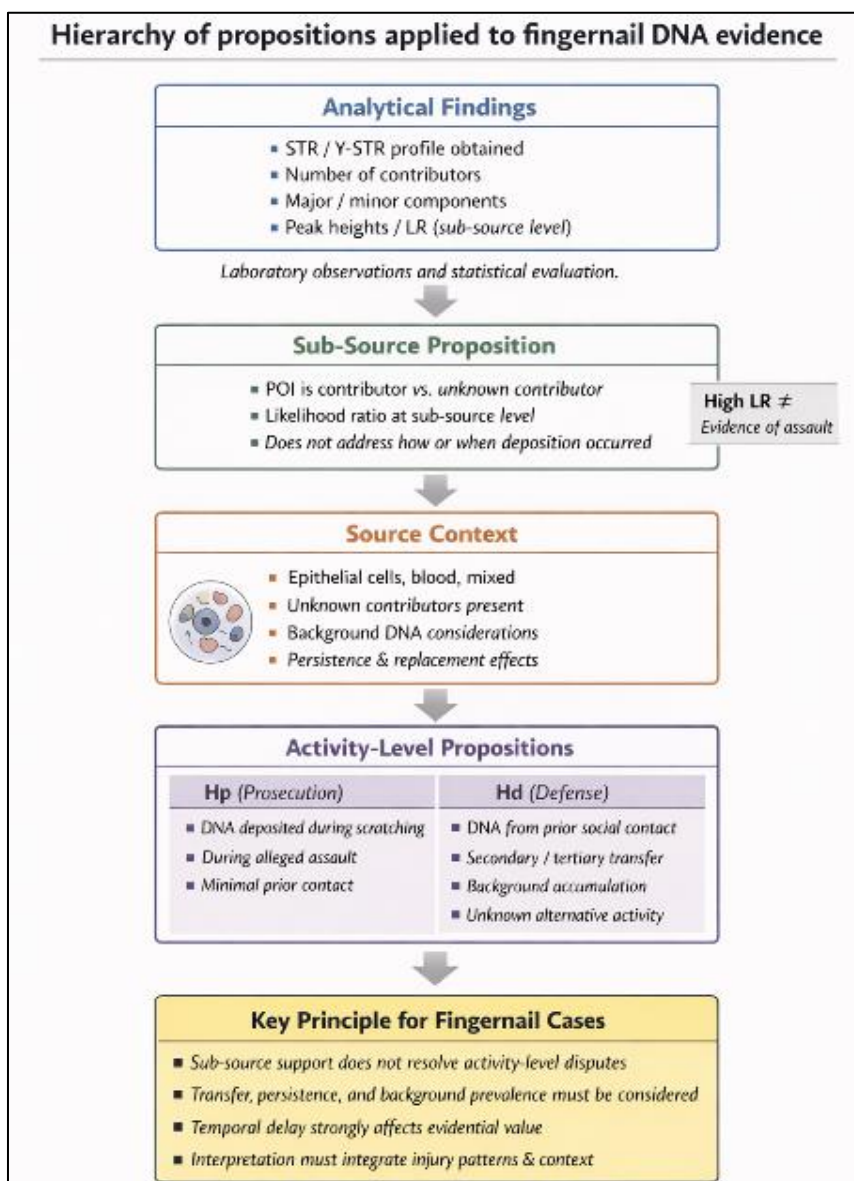


Figure 5 Hierarchy of propositions applied to fingernail DNA evidence. This schematic illustrates the progression from analytical findings to evaluative conclusions in fingernail DNA interpretation. Interpretation begins at the sub-source level, where STR or Y-STR results, contributor number, peak heights, and likelihood ratios (LRs) address whether a Person of Interest (POI) is a contributor to the DNA mixture. These findings do not, however, determine how or when the DNA was deposited. Evaluation at the activity level requires consideration of competing propositions, such as deposition during an alleged assault (Hp) versus alternative explanations including prior contact, secondary or tertiary transfer, or background accumulation (Hd). The framework emphasizes that strong sub-source support does not, in isolation, resolve activity-level questions, and that interpretation must integrate transfer mechanisms, persistence, background prevalence, and case-specific context

7.2. Integration of Injury Patterns

The biological plausibility of an alleged scratching event should be evaluated in conjunction with documented injury patterns. The presence of linear abrasions, defensive wounds, or consistent anatomical correspondence between fingernail contact and visible injuries may increase the likelihood of direct primary transfer. Conversely, the absence of such injuries does not necessarily negate transfer but may reduce the probability of forceful scratching as the deposition mechanism.

Activity-level evaluation literature emphasizes that forensic findings must be assessed in light of case circumstances, including injury documentation [109,110]. DNA evidence does not operate independently of physical examination findings. A coherent evaluation should consider whether the pattern, distribution, and severity of injuries align with the proposed transfer mechanism.

Integrating injury analysis with DNA findings requires caution. Minor abrasions may occur through numerous mechanisms unrelated to assault, and some violent encounters leave minimal visible marks. Therefore, injury absence should not be treated as dispositive, but rather as one factor within a probabilistic framework. The key principle is proportionality: DNA findings should neither override nor be detached from medical evidence.

7.3. Temporal Considerations and Case Timeline

Temporal dynamics are particularly influential in fingernail interpretation. As illustrated in **Figure 3**, offender DNA detection probability declines over time, while background DNA may accumulate or re-emerge. Controlled experimental data indicate that offender-derived Y-STR profiles are most reliably detected immediately after scratching and decrease substantially within hours [99]. After 12–24 hours, background or unrelated male DNA may predominate.

These dynamics underscore the importance of documenting the interval between alleged contact and sample collection. Delayed sampling increases the likelihood that transfer, persistence, and replacement processes have altered the DNA landscape beneath the nails. In such cases, absence of suspect DNA cannot be equated with absence of contact, and presence of foreign DNA cannot be confidently attributed to a specific time point.

Activity-level frameworks advocate explicit consideration of timing within proposition formulation [109,110]. Rather than asking whether the suspect's DNA is present, the appropriate question becomes whether the observed findings are more probable if the alleged activity occurred at the specified time than if an alternative activity occurred at a different time.

In practice, failure to incorporate timeline information is a frequent source of misinterpretation. Laboratory reports that omit reference to sampling delay may inadvertently invite the trier of fact to assume temporal proximity between alleged events and DNA deposition.

7.4. Victim and Suspect Activities

Routine behaviors significantly influence the interpretive landscape. Cohabitation, intimate relationships, occupational contact, sports participation, grooming habits, and hand hygiene practices all affect transfer and persistence probabilities [72–76,93,99]. Activity-level evaluation therefore requires pre-assessment of such contextual factors before assigning evidential weight [110].

Models incorporating site-to-site transfer and secondary transfer mechanisms demonstrate that DNA may relocate across surfaces and between individuals through packaging, transport, or indirect contact [107]. In the context of fingernails, secondary transfer from hands, hair, clothing, or shared objects is biologically plausible and empirically supported [72–76,101].

From a professional perspective, one of the most important safeguards in fingernail casework is resisting narrative alignment with investigative hypotheses. The DNA result must be evaluated against both prosecution and defense propositions, not merely interpreted within a single storyline. Bayesian frameworks provide structured tools for this evaluation, but their reliability depends on accurate modeling assumptions and transparent communication of uncertainty [100,110].

7.5. Reporting Language and Communicative Discipline

Given the complexity outlined above, careful attention to reporting language is essential. Certain formulations risk overstating the evidential significance of fingernail DNA. Assertions that DNA “confirms” a struggle or that its presence

“proves” that scratching occurred may misrepresent the limits of scientific inference. Similarly, presenting source-level likelihood ratios without explicitly clarifying their restriction to sub-source propositions can lead to inappropriate activity-level interpretation. A failure to distinguish between the presence of DNA and the mechanism or timing of its deposition further increases the risk of misinterpretation.

Reporting should therefore clearly articulate the level of proposition being addressed, specify the assumptions underlying the evaluation, and transparently acknowledge the limitations imposed by transfer variability, mixture complexity, and persistence dynamics [110].

Cognitive bias literature further supports structured safeguards in interpretation and reporting [111,112]. DNA mixture interpretation involves discretionary decisions regarding number of contributors, thresholds, and model parameters. Awareness of contextual influence and implementation of independent review procedures can reduce the risk of inadvertent bias.

An appropriately calibrated report might state that the DNA findings are more probable under one activity proposition than another, given specified assumptions and considering the timing and background context. Where the data do not discriminate between activities, this limitation should be stated explicitly. Neutral findings should not be framed as implicitly incriminating or exculpatory.

7.6. Expert Perspective: Calibrated Neutrality in Practice

In professional practice, fingernail DNA evidence should be approached with calibrated neutrality. The presence of foreign DNA beneath fingernails may provide meaningful support for a proposition when collection is prompt, injuries are consistent, and alternative transfer routes are limited. However, in the absence of such contextual reinforcement, evidential weight should be moderated to reflect biological complexity and stochastic variability. This does not diminish the value of fingernail evidence. Rather, it situates the evidence within a scientifically defensible framework. Fingernail samples can be highly informative, particularly in early-collected cases involving clear injury patterns and minimal prior contact. Yet they are also among the most susceptible evidence types to narrative oversimplification.

The most defensible evaluative stance is therefore one that:

- Recognizes the routine prevalence of background DNA under fingernails.
- Distinguishes sub-source from activity-level conclusions.
- Integrates medical, temporal, and behavioral context.
- Communicates uncertainty transparently.
- Avoids transposing conditional probabilities.
- Applies structured review to mitigate cognitive bias.

By adhering to these principles, forensic practitioners can ensure that fingernail DNA evidence contributes meaningfully to judicial decision-making without exceeding its biological and statistical limits.

8. Practical Considerations for Forensic Casework

The preceding sections have demonstrated that DNA recovered from beneath fingernails occupies a complex evidential position. The subungual space functions as a semi-protected, time-integrated micro-environment in which biological material may accumulate through multiple primary, secondary, and tertiary transfer events, and in which background DNA is common even in non-criminal contexts [72–77,98,95]. At the same time, controlled experimental studies confirm that defensive scratching during physical assault can result in detectable foreign DNA, particularly when samples are collected promptly [73,99,102]. The practical challenge for forensic casework is therefore not whether fingernail DNA can be informative—it clearly can—but under what circumstances it meaningfully discriminates between competing activity-level propositions, and how its limitations should be articulated in reporting and testimony. To facilitate structured casework application, **Table 2** provides an applied decision matrix summarizing common investigative scenarios, the expected evidential contribution of fingernail sampling, and the principal interpretive risks associated with each context.

8.1. When Fingernail Sampling Is Most Informative

Fingernail sampling is most probatively valuable when biological, temporal, and contextual factors converge in a manner consistent with a specific transfer event. Empirical data demonstrate that foreign DNA deposited through direct

scratching can be detected at high frequency immediately following contact, with decreasing detectability over time [99]. In controlled simulations, male Y-STR profiles were frequently detectable beneath female fingernails immediately after scratching and remained detectable for several hours, with a rapid decline thereafter [99]. These findings reinforce the importance of prompt sampling in cases alleging defensive actions.

Accordingly, fingernail evidence is most informative under the following general conditions:

- The allegation includes direct physical contact involving scratching or gripping.
- Visible defensive injuries or corroborative medical findings are present.
- Sampling occurs within a short temporal window following the alleged event.
- The complainant and the person of interest (POI) do not have frequent prior intimate or cohabiting contact.

The resulting DNA profile is single-source or exhibits a dominant contributor consistent with the alleged assailant, without substantial background complexity.

In such scenarios, the presence of the POI's DNA beneath the fingernails may provide meaningful support for propositions alleging physical altercation, particularly when evaluated within a structured activity-level framework [100,109,110]. Importantly, this support derives not merely from the presence of DNA but from its congruence with injury patterns, timing, and absence of plausible alternative transfer routes.

However, even in these circumstances, the interpretation must remain proportionate. The presence of a POI's DNA does not, in isolation, establish the specific mechanics of transfer. Rather, it increases the probability of propositions involving direct contact relative to those excluding such contact, and the magnitude of that increase must be assessed in light of known transfer variability and background prevalence [72–76,98].

Fingernail sampling approaches also influence DNA recovery and subsequent interpretation. Common methods include fingernail clippings followed by downstream extraction, as well as direct swabbing of the subungual region during examination or autopsy. Each approach presents distinct advantages and limitations: clippings may retain physically trapped material within the nail structure, whereas swabbing may preferentially recover more accessible surface-associated DNA. Variability in swab type, moistening strategy, and sampling technique can further affect recovery efficiency. In addition, casework practices may differ in whether samples are collected and processed separately for each hand or combined, which can influence mixture complexity and contributor interpretation. These methodological considerations should be acknowledged when evaluating fingernail DNA results, as they may affect both the quantity and composition of recovered DNA and, consequently, the weight assigned at the activity level [72–76,83].

Table 2 Applied decision matrix for fingernail DNA evidence in casework.

Scenario	Expected Evidential Value	Interpretation Risk	Recommended Approach
Immediate sampling (<6 h) after alleged scratching with corroborated injury patterns	Potentially high activity-level relevance if POI DNA detected without significant unknown contributors	Overinterpretation if background contributors ignored	Integrate injury documentation, timeline, and mixture structure before drawing activity-level conclusions
Sampling within 6–24 h after alleged assault	Moderate; detection probability declines and background contribution increases	Background male DNA may be mistaken for offender DNA	Consider persistence data and temporal decay; avoid equating presence with timing
Delayed sampling (>24 h) with routine daily activity	Limited activity-level discrimination	Replacement and secondary transfer likely; mixed profiles expected	Treat results as contextual; emphasize uncertainty in reporting
Cohabiting partners / prior social contact	Low discriminatory power at activity level even if POI DNA detected	Narrative fallacy (“DNA under nails = struggle”)	Evaluate under explicit competing propositions; consider background prevalence studies
Absence of POI DNA but presence of unknown DNA	Potentially exculpatory at sub-source level	False reassurance if transfer or sampling limitations ignored	Consider sampling efficiency, stochastic effects, and degradation before exclusionary inference
Highly complex mixture (≥ 3 contributors) with low template features	Reduced clarity; interpretation heavily model-dependent	Stochastic imbalance, dropout, parameter sensitivity	Use validated probabilistic genotyping; conduct sensitivity analyses where appropriate
Presence of dominant contributor in mixture	Limited standalone meaning	Major contributor may reflect retention, not primary actor	Avoid equating dominance with aggressor status without contextual support
Submerged or environmentally exposed body	Persistence possible but variable	Environmental effects may alter mixture composition	Interpret alongside environmental persistence literature and recovery conditions

Note. POI = Person of Interest. “Sub-source level” refers to propositions addressing whether a particular individual contributed DNA to a sample, whereas “activity level” refers to propositions concerning how and under what circumstances the DNA was deposited. “Dominant contributor” denotes the contributor with the highest relative peak heights in a mixed DNA profile and does not necessarily imply primary actor status.

8.2. When Fingernail Evidence Adds Minimal or Ambiguous Value

Conversely, there are numerous scenarios in which fingernail DNA adds limited discriminatory power. Volunteer and casework studies have repeatedly shown that mixed DNA profiles and non-self DNA beneath fingernails are common in everyday contexts, including among cohabiting partners and individuals with routine social contact [72–77,98,95]. The detection of foreign DNA alone is therefore not an assault-specific observation.

Fingernail evidence may add minimal value when:

- There is a substantial delay between the alleged incident and sample collection.
- The parties have ongoing intimate or social contact.
- The DNA profile is highly mixed, with multiple unknown contributors.
- The POI’s DNA is detected alongside substantial background DNA consistent with prior social interactions.
- No injuries consistent with scratching are observed.
- The alleged competing activities are biologically similar (e.g., consensual physical contact versus assault).

Under such circumstances, the evidential findings may be equally compatible with competing activity propositions, thereby limiting their discriminative capacity at the activity level [109,110]. Moreover, as demonstrated in persistence studies, background or previously transferred DNA may remain detectable even after several hours or routine activities

[99], and new background DNA may accumulate over time [95]. In these contexts, the risk of over-attribution increases substantially.

From a practical standpoint, fingernail DNA should not be treated as a standalone indicator of struggle. Instead, it should be regarded as context-sensitive evidence whose probative weight depends on its integration with medical, temporal, and relational information. When interpreted without such integration, its apparent strength may be misleading.

8.3. Interpretation Safeguards in Reporting and Testimony

Given the analytical and contextual complexities outlined in Sections 4 through 7, several safeguards are essential in the practical handling of fingernail evidence.

8.3.1. Reporting Language

Reports should avoid narrative statements that implicitly equate subungual DNA with defensive struggle. Expressions such as “the DNA under the fingernails indicates a struggle” or “consistent with defensive scratching” are inappropriate unless explicitly evaluated under competing activity-level propositions. As emphasized in logical evaluative frameworks, sub-source conclusions must not be transposed into activity-level assertions without structured reasoning [110].

Instead, reporting should:

- Clearly distinguish sub-source findings (e.g., likelihood ratios regarding contribution) from activity-level considerations.
- Explicitly state that the presence of DNA does not by itself establish the mechanism or timing of deposition.
- Identify plausible alternative transfer routes where supported by the case context.
- Use balanced evaluative language reflecting relative support rather than definitive conclusions.
- Such disciplined reporting reduces the risk of transposing the conditional and preserves the proportionality of the evidence [110].

8.3.2. Integration with Case Context

Activity-level evaluation of fingernail DNA should incorporate:

- Injury patterns and anatomical distribution of abrasions.
- Case timeline, including delay to sampling.
- Relationship history between complainant and POI.
- Statements regarding scratching or physical interaction.
- Presence or absence of alternative transfer opportunities.

Bayesian evaluative frameworks provide a structured method for integrating these elements under mutually exclusive propositions [109,100]. When fingernail findings are evaluated in isolation from these contextual factors, the resulting inference may lack logical coherence.

8.3.3. Analytical Safeguards

Because fingernail samples often constitute low-template or complex mixtures, laboratories should implement safeguards addressing stochastic and mixture interpretation issues [103–106]. These include:

- Appropriate analytical thresholds.
- Consideration of allelic dropout and peak imbalance.
- Laboratory-specific validation of probabilistic genotyping parameters.
- Documentation of modeling assumptions.
- Independent technical and administrative review.

Low-template stochastic effects can distort apparent contributor ratios and influence likelihood ratio outputs [103,104,105]. Awareness of these phenomena is particularly important in subungual samples, where DNA quantity and contributor complexity are highly variable.

8.3.4. Bias Mitigation

Finally, fingernail evidence is particularly susceptible to contextual bias due to its strong narrative association with defensive struggle. Studies have demonstrated that forensic interpretation, including DNA mixture assessment, is not immune to cognitive influences [108,111,112]. Laboratories should therefore adopt context management strategies, ensure blind or sequential unmasking procedures where feasible, and reinforce awareness of cognitive bias during training and review processes. The goal is not to eliminate expert judgment but to structure it within transparent and reproducible evaluative frameworks.

8.4. Expert Perspective on Casework Application

Fingernail DNA represents a complex category of forensic evidence, characterized by both significant evidential potential and inherent interpretive limitations. It can, under appropriate conditions, capture biological traces associated with direct physical contact. However, the same biological environment that enables retention also facilitates accumulation, mixture formation, and replacement over time.

In practice, fingernail evidence should be treated as context-amplifying rather than context-defining. It may strengthen an interpretation already supported by injury patterns, timelines, and corroborative findings. It rarely, however, resolves activity-level disputes in isolation.

The most defensible casework approach therefore combines:

- Prompt and properly documented sampling,
- Rigorous mixture interpretation grounded in validated probabilistic methods,
- Explicit activity-level proposition framing,
- Careful, neutral reporting language,
- And integration with broader evidentiary context.

When these elements are present, fingernail DNA can meaningfully contribute to the evaluation of alleged assaults. When they are absent, restraint in evidential claims is not a weakness but an expression of scientific integrity.

9. Conclusions and Future Research Needs

The interpretation of DNA recovered from beneath fingernails occupies a uniquely complex position within forensic biology. As demonstrated throughout this manuscript, the subungual region constitutes a semi-protected anatomical niche capable of accumulating biological material through repeated primary, secondary, and tertiary transfer events [72–77,101]. Foreign DNA beneath fingernails is not an inherently assault-specific finding; rather, it is a biologically plausible consequence of routine human contact, cohabitation, grooming behaviors, and environmental interaction [72–76,95,98]. At the same time, controlled studies confirm that defensive scratching during physical altercation can result in detectable foreign DNA, particularly when sampling occurs promptly after the event [73,99,102].

This dual reality—common background presence alongside demonstrable assault-related transfer—creates an evidential tension that cannot be resolved through sub-source attribution alone. High likelihood ratios at the sub-source level establish contributor status but do not, in isolation, determine the mechanism or timing of deposition [100,109,110]. The probative value of fingernail DNA therefore depends on structured activity-level evaluation, contextual integration, and proportional interpretation.

The findings and analysis presented herein support three overarching conclusions. First, mixtures beneath fingernails should be regarded as expected rather than exceptional findings [72–76,95,98]. Second, dominance within a mixture is not a reliable proxy for temporal recency or primary involvement, given the combined influence of stochastic amplification effects, variable shedding status, and persistence dynamics [93,103–106]. Third, narrative inference—particularly the assumption that “DNA under the nails implies defensive struggle”—constitutes a recurrent interpretive risk unless constrained by formal evaluative frameworks [109,110,111].

While significant progress has been made in understanding transfer and persistence mechanisms, several scientific and operational gaps remain. Addressing these gaps will be essential to advancing the evidential reliability of fingernail DNA in future casework.

9.1. Need for Robust Controlled Prevalence Studies

Existing research has established that foreign DNA is frequently detected beneath fingernails in both crime and non-crime contexts [72–77,98]. However, many prevalence studies remain limited by small cohort sizes, short sampling intervals, or scenario-specific designs. There remains a need for large-scale, population-based prevalence research that systematically examines:

- Variation across age groups, occupations, and hygiene behaviors
- Cohabiting versus non-cohabiting individuals
- Gender-paired interaction patterns
- Quantitative DNA amounts rather than binary presence/absence outcomes
- Longitudinal persistence beyond 24–48 hours

Such datasets would provide empirical priors for Bayesian activity-level modeling and reduce reliance on qualitative assumptions. Without robust baseline prevalence distributions, evaluative frameworks risk being underpowered when confronted with alternative transfer explanations.

Future research should prioritize multi-center, standardized protocols to generate reproducible quantitative datasets. Importantly, studies should integrate DNA quantity, mixture complexity, and contributor ratio metrics rather than limiting analysis to detection rates. The transition from descriptive prevalence to probabilistic parameterization represents a critical next step for the field.

9.2. Advancing Probabilistic Modeling at the Activity Level

Modern forensic interpretation increasingly recognizes the necessity of distinguishing sub-source and activity-level propositions [109,110]. While probabilistic genotyping software has significantly improved mixture interpretation at the sub-source level [104,105], equivalent formalization at the activity level remains comparatively underdeveloped. Fingernail evidence presents an ideal context in which to advance activity-level modeling. It combines:

- High prevalence of background mixtures
- Variable transfer mechanisms
- Time-dependent persistence
- Stochastic amplification instability
- Competing legitimate-contact explanations

Structured Bayesian network approaches have demonstrated the feasibility of incorporating transfer and persistence into evaluative reasoning [107,109]. However, fingernail-specific parameterization remains limited. Future research should focus on:

- Modeling background accumulation rates beneath fingernails.
- Quantifying the probability of dominance under competing transfer mechanisms.
- Conducting sensitivity analyses for mixture ratio variability.
- Integrating quantitative DNA amount data into activity-level frameworks.
- Evaluating model robustness across laboratory-specific parameter settings.

Sensitivity analyses are particularly important, as recent research demonstrates that parameter variation in probabilistic systems can meaningfully alter likelihood ratio outcomes in complex mixtures [104]. Transparent reporting of modeling assumptions and convergence diagnostics will therefore be essential to maintaining judicial confidence.

In this context, fingernail DNA represents both a challenge and an opportunity: it exposes the limitations of simplistic inferential shortcuts while providing a structured test bed for refined probabilistic reasoning.

9.3. Integration of Biological, Clinical, and Contextual Evidence

Another research priority lies in interdisciplinary integration. Fingernail sampling rarely occurs in isolation; it is typically part of a broader forensic examination that may include injury documentation, trace recovery, toxicological analysis, and timeline reconstruction [87–92].

Future work should explore combined evaluative models that integrate:

- Injury morphology and scratch pattern documentation
- Microscopic debris characterization
- Inorganic trace persistence (e.g., gunshot residue) [90]
- Environmental exposure variables
- Behavioral reconstruction evidence

Such integrative modeling may improve discrimination between competing activity-level propositions by situating DNA findings within a multi-modal evidential context. The value of fingernail DNA is maximized when interpreted as one component within a convergent evidential matrix rather than as an isolated determinant.

9.4. Practitioner Training and Interpretive Safeguards

Advancement of scientific methodology must be accompanied by corresponding evolution in practitioner education. Cognitive bias research has demonstrated that forensic interpretation, including DNA mixture assessment, is not immune to contextual influence [108,111,112]. The hierarchical separation of sub-source and activity-level reasoning must therefore be explicitly reinforced in training and reporting practices [110]. In addition, practitioners should remain aware that DNA recovery and profile characteristics may vary depending on substrate properties, environmental conditions, and collection approaches, all of which can influence downstream interpretation [113,114].

Future initiatives should prioritize:

- Formal activity-level interpretation training
- Structured case pre-assessment procedures
- Explicit statement of competing propositions in reports
- Clear articulation of limitations and alternative transfer mechanisms
- Continued professional development in probabilistic modeling

Interpretive discipline is particularly critical in fingernail cases, where intuitive narratives of struggle may arise from the mere presence of foreign DNA. Education programs should emphasize that high statistical support for contributor status does not equate to confirmation of assault-related deposition. Maintaining calibrated neutrality protects both evidential integrity and judicial fairness.

9.5. Toward Evidential Proportionality

The cumulative evidence indicates that fingernail DNA is neither inherently incriminating nor inherently trivial. It is evidentially conditional. Its probative strength depends on the timing of collection, biological context, mixture complexity, transfer plausibility, and the structure of the competing propositions.

Future research must therefore move beyond the binary question of whether foreign DNA is present and toward quantitative, model-based evaluation of how and when it is likely to have been deposited. The development of standardized reporting language, expanded prevalence datasets, and validated activity-level models will be central to this progression.

In conclusion, fingernail DNA evidence should be interpreted within a rigorously structured framework that integrates anatomy, transfer science, persistence dynamics, stochastic amplification effects, and hierarchical reasoning. When evaluated proportionally and transparently, fingernail DNA can provide meaningful support within an activity-level framework. When interpreted without contextual discipline, however, it carries substantial risk of overstatement. The continued refinement of probabilistic modeling, empirical parameterization, and practitioner training will determine the extent to which this form of evidence fulfills its scientific and judicial potential.

Compliance with ethical standards

Acknowledgments

The author gratefully acknowledges the professional environment and institutional support of the Biology and DNA Section, General Department of Forensic Science and Criminology, Dubai Police, which fosters ongoing scientific inquiry and critical evaluation in forensic genetics. Appreciation is also extended to colleagues and academic collaborators for constructive discussions that contributed to the development of the conceptual framework presented in this review.

The interdisciplinary exchange between forensic practitioners and academic researchers continues to play a vital role in advancing evidence-based interpretation within forensic biology.

Disclosure of conflict of interest

The author declares no conflicts of interest, financial or otherwise, that could have influenced the content or conclusions of this review.

Funding

This review received no external funding and was conducted without financial support from public, commercial, or not-for-profit funding agencies.

Data Availability Statements

No new data were generated or analyzed in support of this review. Data sharing is therefore not applicable.

Statement of ethical approval

Not applicable. This article is a review of previously published literature and did not involve the collection or analysis of new human or animal data.

Author Contributions

S.K.A. conceptualized the review, conducted the literature search and critical analysis, developed the conceptual frameworks and figures, drafted and revised the manuscript, and approved the final version for publication.

References

- [1] Alketbi SK. The affecting factors of touch DNA. *J. Forensic Res.* 2018, 9, 424.
- [2] Aidarous NI, Alketbi SK, Abdullahi AA, Alghanim HJ, Alawadhi HM, Alrazouqi AM, Alsabhan AF, Alshehhi SM, Alsaadi AM, Aldabal NI. Investigating touch DNA success rates in vehicle sites for hit-and-run casework. *Perspect. Leg. Forensic Sci.* 2025, 2, 10008.
- [3] Alketbi SK. Analysis of Touch DNA. Doctoral thesis, University of Lancashire, Preston, UK, 2023. Available online: <https://knowledge.lancashire.ac.uk/id/eprint/46154/> (accessed on 29 October 2025).
- [4] Burrill J, Daniel B, Frascione N. A review of trace “touch DNA” deposits: Variability factors and an exploration of cellular composition. *Forensic Sci. Int. Genet.* 2019, 39, 8–18.
- [5] Alketbi SK. The role of DNA in forensic science: A comprehensive review. *Int. J. Sci. Res. Arch.* 2023, 9, 814–829.
- [6] Recipon M, Agniel R, Kunemann P, Ponche A, Carreiras F, Hermitte F, Leroy-Dudal J, Hubac S, Gallet O, Kellouche S. Detection of invisible biological traces in relation to the physicochemical properties of substrate surfaces in forensic casework. *Sci. Rep.* 2024, 14, 13271.
- [7] Alketbi SK. Emerging technologies in forensic DNA analysis. *Perspect. Leg. Forensic Sci.* 2024, 1, 10007.
- [8] Pfeifer CM, Wiegand P. Persistence of touch DNA on burglary-related tools. *Int. J. Leg. Med.* 2017, 131, 941–953.
- [9] Alketbi SK. Collection of touch DNA from rotten banana skin. *Int. J. Forensic Sci.* 2020, 5, 000204.
- [10] Daly DJ, Murphy C, McDermott SD. The transfer of touch DNA from hands to glass, fabric, and wood. *Forensic Sci. Int. Genet.* 2012, 6, 41–46.
- [11] Alketbi SK, Goodwin W. The effect of surface type, collection, and extraction methods on touch DNA. *Forensic Sci. Int. Genet. Suppl. Ser.* 2019, 7, 704–706.
- [12] Verdon TJ, Mitchell RJ, Van Oorschot RAH. Swabs as DNA collection devices for sampling different biological materials from different substrates. *J. Forensic Sci.* 2014, 59, 1080–1089.
- [13] Singh VS, Alketbi SK, Sharma PA. Influence of surface material, cleaning frequency, and swab type on touch DNA recovery from entrance door handles: A simulated study. *Int. J. Forensic Sci.* 2025, 10, 000449.
- [14] Salleh HM, Alketbi SK. Touch DNA recovery from edible surfaces: Forensic implications for crime scene evidence collection. *J. Forensic Allied Sci.* 2026, 2, 1–16.

- [15] Alketbi SK, Goodwin W. The effect of sandy surfaces on touch DNA. *J. Forensic Leg. Investig. Sci.* 2019, 5, 034.
- [16] Martin B, Kaesler T, Kirkbride KP, Linacre A. The influences of dusty environments on the STR typing success of post-detonation touch DNA samples. *Forensic Sci. Int. Genet.* 2022, 57, 102651.
- [17] Alketbi SK, Goodwin W. The effect of time and environmental conditions on touch DNA. *Forensic Sci. Int. Genet. Suppl. Ser.* 2019, 7, 701–703.
- [18] Alketbi SK, Goodwin W. Evaluating the impact of sandy surface contamination on trace DNA recovery from wearable fabrics: A comparative study of collection methods and extraction kits. *World J. Adv. Res. Rev.* 2025, 26, 2399–2410.
- [19] Comte L, Manzanera M. Touch DNA collection – Performance of four different swabs. *Forensic Sci. Int. Genet.* 2019, 43, 102113.
- [20] Alketbi SK, Goodwin W. Enhancing trace DNA recovery from disposable face masks: Insights from the COVID-19 era and beyond. *Int. J. Leg. Med.* 2025.
- [21] Alketbi SK, Goodwin W. Collection methods for touch DNA direct amplification. *J. Forensic Leg. Investig. Sci.* 2023, 9, 072.
- [22] Tozzo P, Mazzobel E, Marcante B, Delicati A, Caenazzo L. Touch DNA sampling methods: Efficacy evaluation and systematic review. *Int. J. Mol. Sci.* 2022, 23, 15541.
- [23] Alketbi SK, Goodwin W. Validating touch DNA collection techniques using cotton swabs. *J. Forensic Res.* 2019, 10, 445.
- [24] Stoop B, Defaux PM, Utz S, Zieger M. Touch DNA sampling with SceneSafe Fast™ minitapes. *Leg. Med.* 2017, 29, 68–71.
- [25] Alketbi SK, Goodwin W. Touch DNA collection techniques for non-porous surfaces using cotton and nylon swabs. *J. Sci. Tech. Res.* 2021, 36, 28608–28612.
- [26] Aloraer D, Hassan NH, Albarzinji B, Goodwin W. Improving recovery and stability of touch DNA. *Forensic Sci. Int. Genet. Suppl. Ser.* 2017, 6, e390–e392.
- [27] Alketbi SK. An innovative solution to collect touch DNA for direct amplification. *J. Forensic Sci. Crim. Investig.* 2022, 16, 555928.
- [28] Schulte J, Rittiner N, Seiberle I, Kron S, Schulz I. Collecting touch DNA from glass surfaces using different sampling solutions and volumes: Immediate and storage effects on genetic STR analysis. *J. Forensic Sci.* 2023, 68, 1133–1147.
- [29] Alketbi SK. Collection techniques of touch DNA deposited on human skin following a strangulation scenario. *Int. J. Leg. Med.* 2023, 137, 1347–1352.
- [30] Alketbi SK, Carta L. Uncovering the persistence of touch DNA on human skin and its implications for violent crime investigations. *World J. Biol. Pharm. Health Sci.* 2025, 21, 234–244.
- [31] Nimbkar PH, Bhatt VD. A review on touch DNA collection, extraction, amplification, analysis, and determination of phenotype. *Forensic Sci. Int.* 2022, 336, 111352.
- [32] Francisco DO, Lopez LF, Gonçalves FT, Fridman C. Casework direct kit as an alternative extraction method to enhance touch DNA samples analysis. *Forensic Sci. Int. Genet.* 2020, 47, 102307.
- [33] Alketbi SK, Goodwin W, Alghanim HJ, Sanqoor SH, Alshehhi SA, Almheiri MM, AlJanaahi NS, Sanqoor AN, Altamimi FJ, Sajwani MM. Comparing extraction and direct amplification methods for enhanced touch DNA profiling. *30th Congr. Int. Soc. Forensic Genet.* 2025, 1035–1042.
- [34] Aljanahi NS, Alketbi SK, Almheiri MM, Alshehhi SA, Sanqoor AN, Alghanim HJ. Enhancing trace DNA profile recovery in forensic casework using the amplicon RX post-PCR clean-up kit. *Sci. Rep.* 2025, 15, 3324.
- [35] Alketbi SK. An evaluation of the performance of two quantification methods for trace DNA casework samples. *J. Forensic Sci. Crim. Investig.* 2023, 16, 555950.
- [36] Mehta AA, Alketbi SK. Touching without contact: Glove-mediated secondary DNA transfer in forensic casework. *J. Forensic Allied Sci.* 2025, 1, 056–072.
- [37] Alketbi SK. Maintaining the chain of custody: Anti-contamination measures for trace DNA evidence. *Int. J. Sci. Res. Arch.* 2023, 8, 457–461.

- [38] Ballantyne KN, Salemi R, Guarino F, Pearson JR, Garlepp D, Fowler S. DNA contamination minimisation – finding an effective cleaning method. *Aust. J. Forensic Sci.* 2015, 47, 428–439.
- [39] Alketbi SK. Preventing DNA contamination in forensic laboratories: An illustrated review of best practices. *Am. J. Biomed. Sci. Res.* 2024, 24, 7–16.
- [40] Khan AA, Alketbi SK. Integrating DNA and chemical profiling to trace illicit drug manufacture and distribution. *Perspect. Leg. Forensic Sci.* 2025, 2, 10009.
- [41] Alketbi SK. DNA contamination in crime scene investigations: Common errors, best practices, and insights from a survey study. *Biomed. J. Sci. Tech. Res.* 2024, 58, 50970–50982.
- [42] Basset P, Castella V. Positive impact of DNA contamination minimization procedures taken within the laboratory. *Forensic Sci. Int. Genet.* 2019, 38, 232–235.
- [43] Alketbi SK, Carta L. Safeguarding DNA integrity: The critical role of PPE in preventing contamination in forensic laboratories. *J. Forensic Sci. Crim. Investig.* 2025, 19, 556010.
- [44] Alketbi SK, Goodwin W. Temporal assessment of DNA shedding from human hands after handwashing: Implications for touch DNA recovery. *Biomed. J. Sci. Tech. Res.* 2024, 59, 51977–51985.
- [45] Szkuta B, Ballantyne KN, Van Oorschot RAH. Transfer and persistence of DNA on the hands and the influence of activities performed. *Forensic Sci. Int. Genet.* 2017, 28, 10–20.
- [46] Alketbi SK. The impact of collection method on touch DNA collected from fabric. *J. Forensic Sci. Crim. Investig.* 2022, 15, 555922.
- [47] Alketbi SK, Goodwin W. The impact of deposition area and time on touch DNA collected from fabric. *Forensic Sci. Int. Genet. Suppl. Ser.* 2022, 8, 45–47.
- [48] Verdon TJ, Mitchell RJ, Van Oorschot RAH. Evaluation of tapelifting as a collection method for touch DNA. *Forensic Sci. Int. Genet.* 2014, 8, 179–186.
- [49] Alketbi SK, Goodwin W. The impact of area size and fabric type on touch DNA collected from fabric. *J. Forensic Sci. Crim. Investig.* 2022, 16, 555926.
- [50] Kanokwongnuwut P, Kirkbride KP, Linacre A. An assessment of tape-lifts. *Forensic Sci. Int. Genet.* 2020, 47, 102292.
- [51] Alketbi SK, Alsoofi S. Dual recovery of DNA and fingerprints using minitapes. *J. Forensic Sci. Crim. Investig.* 2022, 16, 555929.
- [52] Blackmore L, Cabral de Almada CH, Poulsen F, Prasad E, Kotzander J, Paton K, Hitchcock C, Nadort A. Evaluation of the microbial wet-vacuum system (M-Vac®) for DNA sampling from rough, porous substrates, and its compatibility with fully automated platforms. *Forensic Sci. Int.* 2024, 361, 112079.
- [53] Radgen-Morvant I, Curty C, Kummer N, Delémont O. Effects of chemical and biological warfare agent decontaminants on trace survival: Impact on DNA profiling from blood and saliva. *Forensic Sci. Int.* 2024, 364, 112206.
- [54] Zaarour L, Padula M, Van Oorschot RAH, McNevin D. Mass spectrometry-based proteomics for source-level attribution after DNA extraction. *Forensic Sci. Int. Genet.* 2025, 74, 103168.
- [55] Bibbo E, Taylor D, Van Oorschot RAH, Goray M. Air DNA forensics: Novel air collection method investigations for human DNA identification. *J. Forensic Sci.* 2024.
- [56] Goray M, Taylor D, Bibbo E, Patel D, Fantinato C, Fonnelløp AE, Gill P, Van Oorschot RAH. Up in the air: Presence and collection of DNA from air and air conditioner units. *Electrophoresis* 2024, 45, Special Issue: Innovation in Forensic Analysis.
- [57] Noor S, Akhtar S, Khan MF, Rehman RA, Salman M, Nazir S, Munawar A. Preliminary study on mitochondrial DNA analysis from different sports items. *Forensic Sci. Int.* 2024, 361, 112077.
- [58] Alketbi SK. A journey into the innovations and expertise of Dubai Police and the General Department of Forensic Science and Criminology. *World J. Adv. Res. Rev.* 2024, 22, 1391–1399.
- [59] Alketbi SK, Goodwin W, Alghanim HJ, Abdullahi AA, Aidarous NI, Alawadhi HM, Alrazouqi AM, Alsaadi AM, Alshehhi SM, Alsabhan AF, Aldabal NI, Sajwani MM, Almheiri MA. Trace DNA recovery: Insights from Dubai Police casework. *Perspect. Leg. Forensic Sci.* 2025, 2, 10001.

- [60] Barta JL, Monroe C, Teisberg JE, Winters M, Flanigan K, Kemp BM. One of the key characteristics of ancient DNA, low copy number, may be a product of its extraction. *J. Archaeol. Sci.* 2014, 46, 281–289.
- [61] Alketbi SK, Goodwin W. Evaluation of microFLOQ™ Direct Swab for touch DNA recovery. *Forensic Leg. Investig. Sci.* 2024, 10, 093.
- [62] Wallenberger FT. The effect of absorbed water on the properties of cotton and fibers from hydrophilic polyester block copolymers. *Text. Res. J.* 1978, 48, 1005.
- [63] Sawhney P, Allen C, Reynolds M, Slopek R, Condon B. Whiteness and absorbency of hydroentangled cotton-based nonwoven fabrics of different constituent fibers and fiber blends. *World J. Eng.* 2013, 10, 125–132.
- [64] Wada O, Takatera Y. Physical properties and wear test of water absorbent polyester fibers. *J. Text. Mach. Soc. Jpn.* 1984, 30, 91–99.
- [65] Karthik P, Arunkumar HR, Sugumar S. Moisture management study on inner and outer layer blended fleece fabric. *Int. J. Eng. Res. Technol.* 2012, 1.
- [66] Hsieh YL. Liquid transport in fabric structures. *Text. Res. J.* 1995, 65, 299–307.
- [67] Lieboldt M, Mechtcherine V. Capillary transport of water through textile-reinforced concrete applied in repairing and/or strengthening cracked RC structures. *Cem. Concr. Res.* 2013, 52, 53–62.
- [68] Raja D, Ramakrishnan G, Sampath MB. Comparison of different methods to measure the transverse wicking behaviour of fabrics. *J. Ind. Text.* 2012.
- [69] Chatterjee A, Singh P. Studies on wicking behaviour of polyester fabric. *J. Text.* 2014, 379731.
- [70] Hussain A, Goel A. Fabric geometry and its effect on insulation properties. *Man-Made Text. India* 2007, 50, 169.
- [71] Kim M, Park Y. High sensitive CNT imbedded knit fabrics for heat comfort. *Fibers Polym.* 2018, 19, 2112–2120.
- [72] Malsom S, Flanagan N, McAlister C, Dixon L. The prevalence of mixed DNA profiles in fingernail samples taken from couples who co-habit using autosomal and Y-STRs. *Forensic Sci. Int. Genet.* 2009, 3, 57–62.
- [73] Flanagan N, McAlister C. The transfer and persistence of DNA under the fingernails following digital penetration of the vagina. *Forensic Sci. Int. Genet.* 2011, 5, 479–483.
- [74] Matte M, Williams L, Frappier R, Newman J. Prevalence and persistence of foreign DNA beneath fingernails. *Forensic Sci. Int. Genet.* 2012, 6, 236–243.
- [75] Nurit B, Anat G, Michal S, Lilach F, Maya F. Evaluating the prevalence of DNA mixtures found in fingernail samples from victims and suspects in homicide cases. *Forensic Sci. Int. Genet.* 2011, 5, 532–537.
- [76] Dowlman EA, Martin NC, Foy MJ, Lochner T, Neocleous T. The prevalence of mixed DNA profiles on fingernail swabs. *Sci. Justice* 2010, 50, 64–71.
- [77] Kettner M, Cappel-Hoffmann S, Makuch D, Schmidt P, Ramsthaler F. IPV – bridging the juridical gap between scratches and DNA detection under fingernails of cohabitating partners. *Forensic Sci. Int. Genet.* 2015, 14, 110–115.
- [78] Wiegand P, Bajanowski T, Brinkmann B. DNA typing of debris from fingernails. *Int. J. Leg. Med.* 1993, 106, 81–83.
- [79] Sanchez-Hanke M, Püschel K, Augustin C, Wiegand P, Brinkmann B. PCR typing of DNA extracted from epidermal particles won by scratching. *Proc. ISFH Congr.* 1996.
- [80] Fernández-Rodríguez A, Iturralde MJ, Fernández de Simón L, Capilla J, Sancho M. Genetic analysis of fingernail debris: Application to forensic casework. *Int. Congr. Ser.* 2003, 1239, 921–924.
- [81] Piccinini A. A 5-year study on DNA recovered from fingernail clippings in homicide cases in Milan. *Int. Congr. Ser.* 2003, 1239, 929–932.
- [82] Harbison SA, Petricevic SF, Vintiner SK. The persistence of DNA under fingernails following submersion in water. *Int. Congr. Ser.* 2003, 1239, 809–813.
- [83] Hebda LM, Doran AE, Foran DR. Collecting and analyzing DNA evidence from fingernails: A comparative study. *J. Forensic Sci.* 2014, 59, 1343–1350.
- [84] Canavan TN, Graham LV, Elewski BE. Subungual space: The next frontier. *Skin Appendage Disord.* 2018, 5, 50–51.

- [85] Rodriguez-Takeuchi SY, Villota V, Renjifo M. Anatomy and pathology of the nail and subungual space: Imaging evaluation of benign lesions. *Clin. Imaging* 2018, 52, 356–364.
- [86] de Berker D. Nail anatomy. *Clin. Dermatol.* 2013, 31, 509–515.
- [87] Wankhede AG. The role of fingernails in death investigation. *Am. J. Forensic Med. Pathol.* 2024, 45, 215–223.
- [88] Hackman L, Black S. Forensic examination of the hand. *J. Anat.* 2023, 29, 116–131.
- [89] Caccia G, Re L, Caccianiga M, et al. Traces under nails in clinical forensic medicine: Not just DNA. *Int. J. Leg. Med.* 2021, 135, 1709–1715.
- [90] Akçan R, Yıldırım MŞ, Demircioğlu D, et al. Persistence of inorganic gunshot residue in the hyponychium: Tackling post-shooting hand cleaning challenges. *Med. Sci. Law* 2025.
- [91] van der Hulst R, Gerretsen RRR, Kootker LM, Palstra SWL, Kal AJ, Ammer STM, Verschoor SP, Borra LCP, van Leeuwen CSM, Miranda. A multidisciplinary approach to forensic biological profiling on a single tooth and nail sample. *Int. J. Leg. Med.* 2025, 139, 361–374.
- [92] Solimini R, Minutillo A, Kyriakou C, Pichini S, Pacifici R, Busardo FP. Nails in forensic toxicology: An update. *Curr. Pharm. Des.* 2017, 23, 5468–5479.
- [93] Jansson L, Swensson M, Gifvars E, Hedell R, Forsberg C, Ansell R, Hedman J. Individual shedder status and the origin of touch DNA. *Forensic Sci. Int. Genet.* 2022, 56, 102626.
- [94] Saxena G, Saini V. A systematic review of non-intimate skin-cell touch DNA. *J. Indian Acad. Forensic Med.* 2025, 47, 184–189.
- [95] Goray M, Linacre A, Van Oorschot RAH, Taylor D, Murton K. Comparison of DNA profiles from samples collected from underneath fingernails and hand deposits following everyday activity. *Forensic Sci. Int. Genet.* 2026, 81, 103367.
- [96] Bozzo WR, Colussi AG, Ortíz MI, Laborde L, Pilili JP, Carini G, Lojo MM. Analysis of DNA from fingernail samples in criminal cases. *Forensic Sci. Int. Genet. Suppl. Ser.* 2015, 5, e601–e602.
- [97] Iuvaro A. Forensic analysis of fingernail debris after a scratch experiment and its applications in violence against women investigation. Doctoral thesis, University of Bologna, Bologna, Italy, 2020. Available online: <https://amsdottorato.unibo.it/id/eprint/9419> (accessed on 8 January 2026).
- [98] Cook O, Dixon L. The prevalence of mixed DNA profiles in fingernail samples taken from individuals in the general population. *Forensic Sci. Int. Genet.* 2007, 1, 62–68.
- [99] Damour G, Basset P, Samie L, Hall D. Tracking male DNA transfer and survival under female victim fingernails: Insights from a 24-h scratch simulation. *Forensic Sci. Int. Genet.* 2025, 78, 103280.
- [100] Buckleton J, Taylor D, Curran J, Gittelsohn S, Kalafut T. Interpreting DNA under fingernails given activity level propositions. *J. Forensic Sci.* 2025, 70, 1973–1984.
- [101] Zoppis S, Muciaccia B, D'Alessio A, Ziparo E, Vecchiotti C, Filippini A. DNA fingerprinting secondary transfer from different skin areas: Morphological and genetic studies. *Forensic Sci. Int. Genet.* 2014, 11, 137–143.
- [102] Zareef I, Rathore AW, Zaheen U, Riaz A, Rakha A, Munawar A. A model research study on persistence, recovery and analysis of trace DNA under fingernails of drowned bodies. *Forensic Sci. Int.* 2025, 377, 112649.
- [103] Timken MD, Klein SB, Buoncristiani MR. Stochastic sampling effects in STR typing: Implications for analysis and interpretation. *Forensic Sci. Int. Genet.* 2014, 11, 195–204.
- [104] Costa C, Figueiredo C, Costa S, Ferreira PM, Amorim A, Prieto L, Pinto N. The impact of parameter variation in the quantification of forensic genetic evidence. *Sci. Rep.* 2025, 15, 2524.
- [105] Duke KR, Myers SP. Systematic evaluation of STRmix™ performance on degraded DNA profile data. *Forensic Sci. Int. Genet.* 2020, 44, 102174.
- [106] Ido A, Kirshenbaum L, Waiskopf O, Voskoboinik L. Optimizing amplification threshold of low template DNA. *J. Forensic Sci.* 2025, 70, 1521–1526.
- [107] Taylor D, Volgin L, Kokshoorn B. Accounting for site-to-site DNA transfer on a packaged exhibit in an evaluation given activity level propositions. *Forensic Sci. Int. Genet.* 2024, 73, 103122.

- [108] Curley LJ, Munro J, Lages M, MacLean R, Murray J. Assessing cognitive bias in forensic decisions: A review and outlook. *J. Forensic Sci.* 2020, 65, 354–360.
- [109] Kokshoorn B, Blankers BJ, de Zoete J, Berger CEH. Activity level DNA evidence evaluation: On propositions addressing the actor or the activity. *Forensic Sci. Int.* 2017, 278, 115–124.
- [110] Hicks T, Buckleton J, Castella V, Evett I, Jackson G. A logical framework for forensic DNA interpretation. *Genes* 2022, 13, 957.
- [111] Dror IE, Hampikian G. Subjectivity and bias in forensic DNA mixture interpretation. *Sci. Justice* 2011, 51, 204–208.
- [112] Jeanguenat AM, Budowle B, Dror IE. Strengthening forensic DNA decision making through a better understanding of the influence of cognitive bias. *Sci. Justice* 2017, 57, 415–420.
- [113] Chahal RB, Alketbi SK. Touch DNA on wood: Effects of surface morphology, humidity, and adaptive recovery strategies on forensic DNA yield. *Int. J. Forensic Sci.* 2026, 11, 000453.
- [114] Alketbi SK, Ali MS, Khan SA. Managing porous substrate wicking in trace DNA collection: Impact of swab wetting volume on fabric evidence. *Med. Res. Arch.* 2026, 14, 1–16.