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IMPACT OF FABRIC TYPE AND ENVIRONMENTAL EXPOSURE ON DNA DETECTION IN SEMINAL AND BLOODSTAINS: A COMPREHENSIVE REVIEW

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ABSTRACT
Biological stains, such as blood and semen, forms the basis of forensic DNA profiling; nevertheless, the forensic evidence provided by these stains is dependent on the longevity of the DNA under different conditions, on various fabric substrates. Although research into the field of genomics continues to be refined, the interpretation of results remains constrained by substrate effects and degradation kinetics. The current study critically analyzes the forensic literature in an attempt to explore the longevity of DNA in blood and semen stains under different environmental conditions on fabric substrates. A narrative review was conducted based on multidisciplinary databases from 2010 to 2025. The findings revealed that DNA survival depends on several factors and is a function of the matrix-textile interactions. Notable among the findings was the concept of '*Micro-Environmental* Shielding', whereby the porosity structure of natural fibers traps and protects DNA from destructive by Ultra Violet (UV) rays and microbes. Conversely, synthetic fibers leave biological material more exposed, increasing vulnerability to external stressors. The study further identifies the seminal DNA typically exhibits higher environmental resilience than blood- derived DNA. This review concludes that forensic interpretation must shift from viewing textiles as passive surfaces to active biological preservers. Therefore, adopting a substrate aware frame work for optimizing evidence prioritization and interpreting negative results in complex casework, ensuring that recovery variations are not misinterpreted as biological loss.

KEYWORDS: Forensic DNA analysis, bloodstains, seminal stains, fabric substrates, environmental exposure, DNA Persistence.

KEY POINTS
- A critical analysis reveals that forensic DNA survivability is not a passive deposition surface but rather a dynamic result of textile-fluid matrix interactions.
- Explains the idea of "*Micro-Environmental Shielding*," showing how natural fibbers' porous structure actively captures and shields biological material from UV rays and microbial deterioration.
- Identifies that biological traces are left exposed on the surface of synthetic textiles (like polyester0 due to their low fluid absorption and high susceptibility to mechanical loss and environmental deterioration.
- Establishes that seminal stains exhibit higher environmental resilience than blood-derived DNA across diverse substrates due to a dense, compact chromatin structure.
- Highlights critical methodological heterogeneity in recent research and advocates for multidisciplinary, multi-factor environmental modeling to enhance the forensic evidence's scientific and legal validity.

1. INTRODUCTION
Biological stains are among the most crucial types of physical evidence in criminal investigations, particularly in cases involving violence, sexual assault and interpersonal contact. Blood and seminal stains are the most widespread substrates for DNA profiling. In specialized situations, such as veterinary forensic investigations, semen analysis can also be critical [1]. These biological materials allow identification of individuals, link suspects to crimes scenes, and assist in re-creating incidents [2]. The development of the next-generation sequencing (NGS) driven by the evolution of forensic DNA typing and the integration of Single Nucleotide Polymorphism (SNP) microarrays has significantly expanded the capabilities of forensic investigations [3-5]. The emergence of forensic "*omics*", which incorporates genomics, transcriptomics, and proteomics into casework interpretation, represents a significant shift in the broader forensic landscape [6,7].

Consequently, biological material and the comprehensive analysis of its molecular components have emerged as critical pillars of judicial decision-making [8].

Latest developments in forensic epigenetics are advancing investigative intelligence by offering novel individual biological signatures, specifically histone modifications and DNA methylation tags, applicable to post-mortem interval estimation and trace evidence examination [9]. Genomic methods such as population-based databases and environmental epigenetic surveillance, highlight the expanding dimension of molecular forensic examination [10,11]. However, the reliability of these advanced methods remains fundamentally dependent on the integrity and stability of DNA and associated proteins in biological stains. Consequently, understanding the multi-matrix degradation kinetics of biological stains remains a paramount challenge. Up until 2025, there have been significant paradigm shifts from yield- focused analysis to thorough structural and molecular degradation tracking. In order to determine baseline survival boundaries, modern forensic procedures increasingly examine how alternative molecular targets scale under extreme environmental stress by com paring extraction efficiency across complex, processed biological matrices [12,13].

Although biological stains hold significant evidentiary value, they are infrequently stored under optimal conditions, often remaining on garments or fabric substrates exposed to different types of the environments. Extensive research shows that the temperature, humidity, and radiation have a significant impact on the stability of DNA [14,15]. These *post-depositional* factors significantly impact DNA persistence frequently resulting in degradation, inhibition, or the generation of partial genetic profiles [16].

Environmental exposure increases hydrolytic and oxidative processes, as well as microbial activity, which decrease the amount of amplifiable DNA. Furthermore, studies on DNA transfer, prevalence, persistence, and recovery indicate that environmental variables significantly impact the trace evidence interpretation [17]. In addition to environmental degradation, research into behavioural and biometric data indicates that new privacy aspects regarding genetic data management are arising within forensic systems [18]. The molecular behaviour and stability of DNA in blood and semen stains differ with respect to their biological makeup. Blood has nucleated leukocytes, while semen consists of spermatozoa that have condensed, protamine-filled chromatin structure [19]. This structural difference contributes to higher DNA persistence in seminal stains compared to those derived from blood [20].

Mitochondrial DNA (mtDNA) represents an important secondary target for forensic genetics because of its higher copy numbers and improved stability against degradation than nuclear DNA [21]. However, its preservation is highly dependent on environmental conditions, and mitochondrial DNA profiling should be considered a complementary, rather than a replacement method for nuclear profiling [22]. Studies on time since deposition show that the process of degradation has different dynamics depending on whether the sample is blood or semen [23]. Similarly, vibrational spectroscopy has been considered for estimating the age of deposited bloodstains [24]. DNA recovery and storage is determined by the fabric substrate. Materials that are porous in nature like cotton and wool provide better penetration of bodily fluids into the deeper layer of the fibrous material, which gives better resistance to environmental factors [25]. However, non-porous or synthetic fabrics provide surface retention of the fluid, making them more susceptible to environmental damage secondary transmission [26].

Recent studies show that the composition of fabrics, color and surface chemistry play a large role in the visualization and recovery of biological traces [27]. Furthermore, the detectability of invisible biological stains in forensic casework is determined by the specific physicochemical properties of substrates [28]. Additionally, environmental and airborne DNA studies show that environmental sampling has the potential to collect human genomic material, bringing substantial interpretative, privacy, and ethical concerns [29,30].

The rapid development of environmental DNA (eDNA) monitoring technologies and biosensor platforms, provides the opportunity to monitor and detect genetic material at a mega scale [31]. Furthermore, the growth of biodiversity genomics and the combination of reference databases are expanding the forensic applications of environmental genetic data [32]. Recent experimental population level genomic studies demonstrate how environmental can effectively characterize patterns of species abundance and persistence [33]. Despite advancements in forensic technology, interpreting biological traces on textiles within context remains crucial. Laundering and cleaning agents significantly impact DNA persistence due to combined mechanical and chemical exposure. Specifically, washing with detergents, oxidants, and repeated washing decrease the DNA yield and increases the risk of secondary transfer [34]. Research on touch DNA focuses on the fact that sampling strategy and interaction with the surface have been the key factors defining recovery efficiency [35,36].

Despite the substantial body of research on the factors affecting biological stain degradation, significant methodological heterogeneity exists, with differences in the choice of substrate, environment modeling, and analytical techniques restrict the universalization of studies [37-38]. Although new techniques like immunochromatographic methods, vibrational spectroscopy, microfluidics, and integrated DNA-based devices are promising, they require extensive validation prior to their use in forensic investigations [39-42]. Moreover, forensic examination becomes even more difficult due to considerations like secondary transfer, arson risk, and contamination from other forms of trace evidence [38]. Therefore, the study of fabric characteristics and environment interaction is essential for enhancing the accuracy of time-since-deposition estimation, stain age, and body fluid identification [43-46].

As a result of the absence of comprehensive scientific research, there are no proper guidelines to help forensic scientists manage biological evidence that have been collected from different fabrics. This study analyzes current literature related to the detection of forensic DNA in blood and semen stains on various fabrics exposed to different environmental conditions. With the help of the synthesized information provided, this study goes beyond the realm of summarization to identify fabric-fluid combinations, such as blood on non-porous synthetic substrates, where sample loss is most noticeable. The purpose of this analysis is to examine trends in the persistence of forensic DNA, strengths and weaknesses of each

method used, as well as practical recommendations for collecting and sampling evidence [47,48]. The result of such integration is to aid evidence-based forensic practices and strengthen the reliability of forensic evidence in courts of law.

2. METHODOLOGY

This paper offers an extensive review of the literature on forensic examination of DNA from blood and seminal stains on different fabric substrates under varied exposure to the environment. The literature was sourced from major multidisciplinary and forensic scientific databases, specifically PubMed, ScienceDirect, Scopus, and Google Scholar. The search strategy utilized structured Boolean operators with thematic keyword groupings covering: ('forensic DNA' OR 'DNA Persistence' OR 'environmental degradation') AND (fabric OR 'textile materials') And (blood OR semen OR 'biological stains'). The primary focus of literature search was on papers published from 2010 to 2025, which is the publication period of the selected article, though early literature was included if it served some methodological purpose.

The methodology for the search aimed to gather a broad range of relevant literature. To ensure the approach was robust and unbiased, studies were included if they provided empirical, methodological or analytical information regarding blood or seminal stains deposited on natural, synthetic or blended fabric subjected to one or more factors; temperature variation, humidity, radiation, laundering or chemical treatment (Fig. 1). This was achieved by incorporating various types of studies such as experiments, observations, and review papers. The exclusion criteria for selecting the studies included those that did not employ textile surfaces, failed to incorporate environmental or post-deposition conditions, and focused on only the analytical or population genetic aspects without addressing fabric stain survivability. Data were summarized using a structured extraction system covering substrates, exposure conditions, and analytical methods, allowing for the identification of common patterns, comparisons, and methodological issues pertinent to forensic practice.

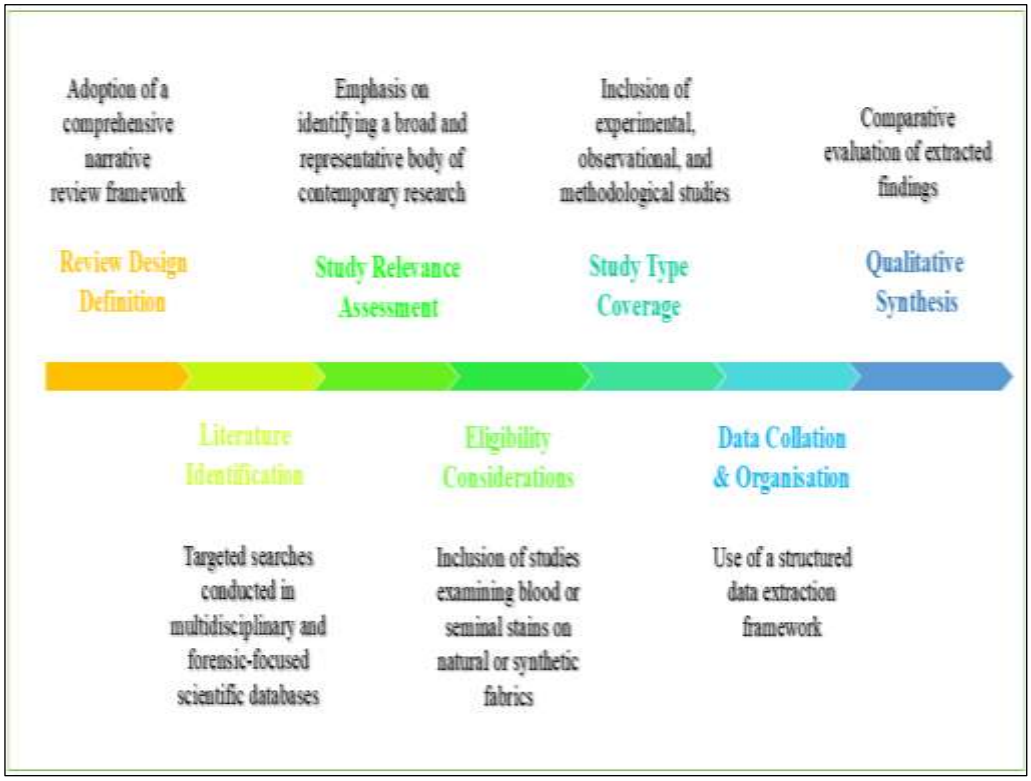

Figure 1. Schematic Workflow of the Comprehensive Narrative Review on DNA Detection in Fabric-Based Biological Stains

3. RESULTS

3.1 Fabric substrate effects

The fabric type and its structure have a considerable effect on the DNA retention as well as its detectability. The comparative studies between natural, man-made and mixed fabrics showed that the fabric absorbency, fiber structure, weave density, and chemical properties play an important role in the penetration depth and retention of biological materials [49]. As indicated in Table 1 below, natural fibers (e.g., cotton, wool, linen) often have a higher content of DNA due to their porosity and may absorb it through a capillary action. Whereas DNA deposited on synthetic fabrics (e.g., polyester, nylon) were more likely to be remain on the surface, thus making it more susceptible to loss during disturbances [50].

Cotton produced the most reliable identification of blood and seminal stains under dry and moderately humid conditions, whereas wool demonstrated moderate results dependent on the fiber density and intensity of laundering. In many cases, linen was found to exhibit reduced recovery of DNA after a long period of exposure to the environment or age. Conversely, polyester due to its low absorbency and increased susceptibility to wash-off, exhibited significant amount of DNA loss after laundering and chemical exposure. Nylon behaved intermediately, preserving DNA under dry conditions, yet experiencing rapid loss upon water exposure. Finally, blended fabrics revealed unpredictable results, influenced by fiber proportion, weave type, and treatments history [50-52].

Table 1. Fabric types dependent DNA recovery trends

Fabric / Condition[a]	Recovery Pattern[b]	Limiting Factor	Evidence
Cotton	High, stable	Moisture	[52]
Wool	Moderate	Laundering	[53]
Linen	Low	Aging	[54]
Polyester	Low	Detergents	[50-52]
Nylon	Moderate	Water	[50]
Blended fabrics	Variable	Fiber ratio	[51]
Washed fabrics	Reduced	Oxidants	[55]
Enhanced stains	Variable	Reagent effects	[56]
Presumptive-tested	Reduced yield	Chemical interference	[57]

[a] "Variable" suggests that recovery is significantly dependent on the textile weave and the proportion of natural and man-made materials.
[b] The recovery patterns are qualitative judgements based on the literature.

3.2 Environmental degradation

Environmental exposure consistently affects DNA persistence, fragmentation and amplification success of substrates. Thermal stress promotes fragmentation, while humidity increases the enzymatic and microbial degradation, decreasing the amplifiable DNA yields, especially on exposed or porous substances [50]. Furthermore, ultraviolet and solar radiation caused strand breaks and spectral changes in stains, making downstream interpretation and detection less favourable [58]. Experimental evidence also suggests that the DNA quality can be measurably decreased upon exposure to sunlight [59].
Chemical exposure (cleaning agents and oxidants) and laundering cause significant loss of DNA and a risk of changed stain distribution or secondary transfer, making it difficult to interpret evidence source and survival [55]. Furthermore, DNA recoverability may also be affected by the laundering parameters such as cycle type and household washing conditions [60]. Spectroscopic evaluation of chemically washed stains of blood and semen confirms that cleaning agents alter the detectable composition of these samples [61]. The degradation of DNA quantity and quality in stains exposed to decomposition-linked contexts is supported by insect activity and decomposition fluids, further confirmed that the *post-depositional* environment is multidimensional interaction between contaminants and substrate properties [52,62]. Finally, exposure to water might permit survival of cellular material but often led to poorer DNA quality and less successful profiling, based on the duration and the type of substrate [52].

3.3 Blood vs semen challenges

Blood and semen are the most frequently analysed biological stains, holding paramount importance in violent crime and sexual offence casework. Comparative studies showed fluid-specific variations in DNA persistence, which are linked to cellular composition and chromatin structure [22,63]. As illustrated in the comparative analysis of degradation kinetics (Fig. 2), seminal DNA exhibits significantly greater resistance to environmental stress blood-based DNA. This stability is primarily attributed to the dense, compact chromatin structure, and the tougher penetration into porous fabrics, reducing both physical loss from the surface and exposure to environmental degradation [22].
Conversely, blood DNA degradation often occurring more rapidly, especially under high-temperature and light exposure, leading to subsequent decreases in amplifiable template [64]. Molecular time-course analyses have shown a gradual loss of blood-related RNA/DNA markers relative to semen, highlighting the crucial need to consider the specific biological material when interpreting persistence and time-dependent change [65]. Moreover, determining the particular stain matrix is a crucial operational requirement prior to using downstream microbiome and biomarker-based techniques [66,67]. This sequence is crucial because distinct nucleic acid degradation pathways are governed by biological matrices; attempting to compute time-since deposition using generalized molecular clocks without prior fluid attribution introduces significant analytical bias, a procedural dependency that remains largely un addressed in current comparative literature.

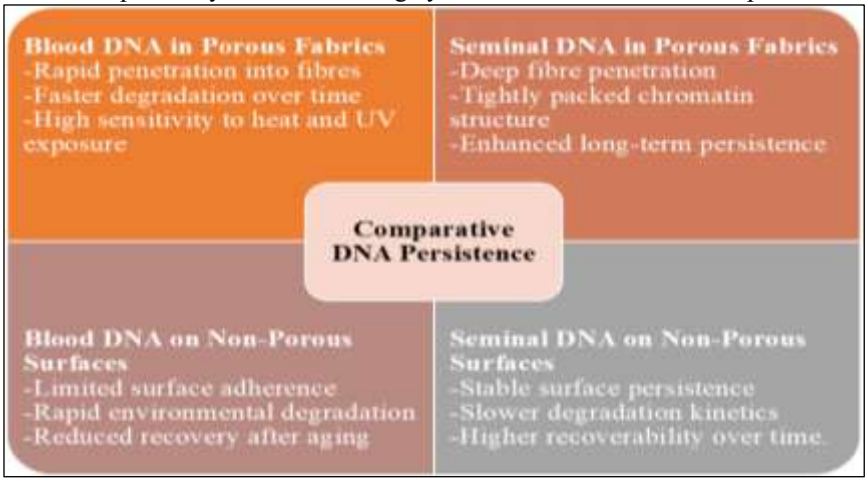

Figure 2: Comparative degradation kinetics of blood versus seminal DNA under environmental stress

3.4 Analytical challenges

The success of forensic DNA analysis being highly dependent on the substrate type, moisture content, appearance of the stain, and the presence of Polymerase Chain Reaction (PCR) inhibitor. Sampling efficiency, which affect the amount of recovered DNA and profile fullness, is also influenced by the types of surfaces and wet/dry conditions of the stains [17, 36]. While presumptive testing and enhancement reagents are operationally useful for locating or screening stains, they can introduce chemical interference that reduces the yield of downstream DNA, depending on their type, substrate and exposure time [56,59]. Rapid DNA systems reduced turnaround time to support operational workflows but showed lower sensitivity for low-template, degraded, or inhibitor-rich samples, limiting their effectiveness for environmentally compromised stains [68].

3.5 Emerging technology

Beyond standard Short Tandem Repeat (STR) profiling, recent studies have expanded toward techniques designed to improve the detection, localization, and interpretation of degraded or low-template evidence. Imaging-based approaches enabled large-area localization of trace evidence prior to sampling, particularly useful for stains that are aged or not readily visible [69]. Furthermore, spectroscopic methods (e.g., attenuated total reflectance Fourier transform infrared [ATR-FTIR] and Raman Spectroscopy) support non-destructive detection and differentiation of biological stains, including stains subjected to environmental exposure or aging [70-71]. Deep ultraviolet Raman approaches have also-been reported for detecting oral-fluid stains on fabrics [72]. Advanced spectroscopic strategies are increasingly utilized to complement conventional body-fluid identification [73]. Emerging molecular approaches particularly epigenetic and epigenomic profiling have expanded the potential for body-fluid discrimination and contextual inference, offering investigative intelligence beyond traditional identity profiling [74]. Innovations in chemical analysis of fingermarks are expanding the range of recoverable forensic intelligence from trace evidence [75]. Furthermore, nanotechnology-based probes and signal-enhancement strategies are also reported as promising for improving detection sensitivity and stability under challenging conditions, indicating a shift toward more integrative, time-efficient forensic workflow [68].

Furthermore, the incorporation of forensic microbiomics has resulted in a significant methodological change in the state-of-the-art in body fluid identification with in the past several years. Characterization is no longer exclusively dependent on delicate human messenger RNA (*mRNA)* or protein markers because biological stains contain unique, localized microbial communities. Recent developments have proven that, even in cases when the host human DNA has seen significant environmental deterioration, sequencing particular core microbial species offers a highly stable, alternative taxonomy for recognizing severely degraded blood, saliva, and semen stains [6,7]. The shift to microbial-matrix profiling is an essential tool for overcoming the traditional constrains of impaired trace evidence recovery.

3.6 Methodological limitation

In the reviewed studies, the methodological differences hindered the direct comparison of findings across different laboratories and substrates. Variations in the deposition volume, ageing period, laundering protocols, and environmental exposure regimes (including UV dose, humidity and temperature) led to inconsistent recoveries. Furthermore, differences in sampling tools, extracting chemistry, and quantification thresholds resulted in unreliable reporting of success metrics [55,76].

Traditional forensic validation studies have primarily focused on blood and semen, with significantly fewer studies addressing saliva, touch DNA, mixed stains and the complex histories of substrates, which restricts the extrapolation of results to real-world, mixed-evidence scenarios [22,77]. Although advanced biomarkers (such as *mRNA*, methylation, coagulation-related markers) necessitated higher template quality and are sensitive to environmental degradation creating practical limitations for direct implementation in forensic casework [64, 74, 78, 79].

Table 2 provides a comparative overview of these diverse methodological approaches and the specific environmental or substrate- related factors influencing their forensic efficacy.

Table 2. Methodological factors influencing DNA detection

Method Category	Technique[a]	Advantage[c]	Fabric/ Substrate Tested	Environmental Conditions Tested[b]	References
Imaging	MA-XRF	Large-area detection	Cotton, denim, wool, blends, leather	Aged stains (>4 months); repeated scans	[69]
Presumptive Tests	KM / Hemastix	Rapid blood screening	Filter paper, fabric strips, metal	Overnight drying; 5-week indoor/outdoor sun exposure	[57]
Enhancement	Luminol	Detects washed blood	Denim fabric, tufted carpet	Washing (10–60°C); UV/rain outdoor ageing (0–14 *d*)	[55]
Rapid DNA	ANDE 6C System	Fast STR profiling	Cotton/denim stains; tiles, knife, gum	Overnight drying; storage up to 12 months; inhibitors tested	[68]
Epigenetics	DNA methylation	Fluid ID, investigative leads	Body fluid DNA extracts	Applicable to aged/damaged	[80]

				evidence; lifestyle exposure effects	
RNA Markers	*mRNA* degradation	TSD estimation	Fitzco cards, Dacron swabs	Dark room-temp storage; aging 0–360 *d*	[65]
Spectroscopy	ATR-FTIR/Raman	Non-destructive detection	Cotton, polyester, denim, wool	Aging up to 8 months; outdoor exposure; reduced after washing	[70]
Nanotechnology	CQDs probes	Signal enhancement	Fibers; glass/metal/plastic surfaces	UV/chemical stability; pH/ionic effects	[82]

[a] MA-XRF-Marco Area X-ray Fluorescence; TSD- Time Since Deposition; CQDs- Carbon Quantum Dots.
[b] Environmental variations evaluate the degradation mechanics across exposure timelines and ambient stressors.
[c] The success factors of these studies are largely dependent on the specific extraction techniques and quantification thresholds used.

4. DISCUSSION

Cumulative evidence examined in this study suggests that the DNA recovery from fabric-related blood and seminal stains is a dynamic process influenced by the interaction between the biological matrix, substrate type, environmental factors, and the analytical procedure. However, a comparative analysis shows that there is a significant methodological variance across studies that prevents the development of consistent interpretative guidelines.

Rivers and Geiman [76] highlighted that insect artifacts and *post-depositional* biological interference the morphology of the stains and the distribution of the DNA, proving that the environmental exposure is not limited to the abiotic factors like temperature and humidity. Conversely, many literature studies kept just only a single environmental parameter such as heat or ultraviolet radiations. This methodological discrepancy likely explains why the degradation kinetics of Abdel Hady *et al*. [16] do not agree with the ones in the long-term environmental simulation's studies of Poetsch *et al*. [15]. The latter focused on progressive degradation during changing conditions of environmental oscillations, whereas the former focused on fast thermally induced fragmentation. These results represent different modelling approaches to environmental exposure. This is the major limitation in the field due to the lack of standardized multi-factor environmental simulations.

Interpretative variability is a significant challenge in the biological comparison of matrices. While Shrivastava *et al*. [19] and Zarczynska *et al*. [20] experimentally found increased DNA persistence in seminal stains with the compact chromatin structure of sperm cells, Sacco *et al*. [23] have found that the time-since-deposition patterns diffuse greatly, based on substrate and environmental exposure. Taken altogether, it becomes clear that the DNA persistence patterns cannot be generalized among different biological fluids without the control of substrates type and the environmental conditions. However, there remains a critical gap in the literature, as few studies directly compares blood, seminal stains, and other body fluids under comparable experimental conditions.

Progressive advancements in analytical technologies can paradoxically complicate the only-interpretation of forensic DNA results. Studies by Jager [78] and Staadig *et al*. [79] demonstrate that whole genome amplification and SNP genotyping technologies (utilizing ancient DNA methodologies) can significantly increase profile recovery from highly degraded samples that fail conventional STR analysis. In a similar way, Larnane *et al*. [80] highlight that improved sequencing systems and library preparation methods, make it possible to study even those DNA traces that were difficult to characterize before. However, such studies often highlight a crucial point of difference higher profiling success rates can be the result of being analytically sensitive, rather than improved biological DNA preservation. As Haddrill [81] indicates, forensic genomics has lowered the limit for the detection of DNA, thereby changing the concept of viable evidence in criminal investigation. The lack of differentiation between the two aspects makes the conclusions concerning the effect of substrates on DNA persistence may be confounded by advancements in analytical capacity.

Variations in temporal inference frameworks highlight deep-seated methodological inconsistencies in current forensic workflows. Kubo *et al*. [82] and Liu *et al*. [83] independently reported the rapid response of the RNA amplification systems for the identification of body fluids, emphasizing speed and field compatibility. In contrast, Manis *et al*. [84] used hyperspectral imaging (HIS) for non-destructive stain age estimation, rather than molecular amplification, and temporal inference. In the meantime, Wallis *et al*. [85] revealed that presumptive immunochromatographic testing an impact downstream DNA yield, thereby affecting interpretative reliability. Comparing these approaches, it is clear that detection sensitivity, temporal inference, and profiling success represents partially independent analytical frameworks. There is a paucity of studies that incorporates these technologies into comparative experimental studies to determine the effect of non-destructive screening on the posterior DNA persistence measurement.

Another aspect of variability in forensic evidence analysis is the DNA transfer dynamics. Woollacott *et al*. [17] highlighted the interrelationship between transfer, prevalence, persistence, and recovery whereas Schwender [86] showed that individual's shedder status fundamentally impacts DNA transfer and persistence outcomes. Sessa *et al*. [87] also established that the use of antibacterial soaps and sanitizers alters transfer dynamics, thus changing the persistence pattern upon environmental exposure. Notwithstanding these findings, the majority of the fabric-based persistence studies fail to model contributors' variability, hygiene status and transfer probability within their experimental models. This omission can be one of the factors why there is inconsistency in reported recovery rates and represents a significant gap in ecological validity.

Environmental and microbial factors are often inadequately incorporated into DNA persistence modeling. Dass *et al*. [88] emphasized the potential usefulness of the microbial analysis process in determining the body fluid due to the role of microbial activity in acting as both a degradation and inference factor. Despite the fact that, as shown by Cao *et al*. [89] digital PCR is more effective in optimizing the measurement of degradation of nucleic acids during biodegradation, quantitative approaches have not been fully utilized in studies of fabrics. Through the incorporation of high-resolution quantification technologies, it would be easier to make distinctions between partial degradation and amplification failure, thereby reducing methodological ambiguity.

Another major confounding factor that is usually not considered in forensic DNA analyses is the effect of the extraction process. According to Comparisons conducted by Ren *et al*. [12] and Kamilari *et al*. [13] extraction methods had a considerable effect on the amount of DNA extracted and degradation. However, forensic fabric studies often assume extraction as a standardized, background process that does not affect DNA persistence. Consequently, current explanations of textile-dependent DNA persistence are rather hypothetical lacking comparative analysis of extraction strategies applied across same substrate and environmental conditions.

As reviewed by Cozens *et al*. [90], technological innovation in sensor-based detection systems offers a quick multiplexed, in-field screening. Nevertheless, as demonstrated by Pandey *et al*. [91] using atomic force microscopy surface visualization may not always be a predictor of amplifiable DNA retrieval. The gap between the detection, the visualization, and the successful genotyping remains under-researched. Supporting this, Vitosevic *et al*. [46] emphasized that establishing unified genotyping standards is necessary to ensure judicial reliability.

A synthesis of the substrate- matrix interaction is crucial to understanding that DNA persistence is not merely a function of the biological fluid or the environment, but rather a product of the '*Micro-Environmental* Shielding' provided by the textile's architecture. The seeming paradox of the fast decay seen in acute heat tests [16] versus stability seen in longitudinal tests [15] can perhaps be explained by the fact that the natural fibers have an inherent ability to store DNA in the hollow cavities of the fibers and thus protect it from UV light and surface bacteria. Polyester fibers do not provide such protection; hence the DNA remains on the surface and is easily retrievable by swabbing. By understanding that the textile matrix acts as a biological stabilizer, forensic investigators can make better sense of 'negative' results. This approach will change the way forensics experts view the fabric matrix from being nothing more than a passive substrate to an actively involved agent in the degradation process. Addressing this '*Shielding Effect*' through standardized extraction-as highlighted by Ren et al. [12] is the necessary next step to ensure that recovery variations are not mistaken for biological loss.

A review of current comparative analyses highlights several critical gaps in forensic research. Specifically, there is a lack of comprehensive studies modelling the combined effects of thermal stress, ultraviolet radiation, microbial activity, laundering, and environmental exposure. There is a paucity in direct comparative studies regarding the degradation of blood, seminal stains as well as other biological fluids at the same substrate conditions. Research to date has not sufficiently integrated the advanced genomic tools, digital quantification of stain persistence and standardized extraction comparisons into fabric-based studies. Finally, experimental designs rarely account for the variability of contributors, hygiene, and environmental background DNA, limiting the applicability of findings to real-world scenarios.

Therefore, future research must shift from purely descriptive studies towards the integrative, interdisciplinary designs. These approaches should concurrently assess the biological matrix type, textile properties, combined environmental exposures, variability of contributors, extraction method and multi-platform genomic analysis. It is only by means of such intensive comparative modelling can robust, standardized findings regrading DNA persistence in fabric-associated biological stains be established. Such transformation from mere reporting into a systematic, comparison is important for increasing the scientific and judicial validity of the forensic DNA evidence.

5. CONCLUSION

This paper highlights forensic literature on the stability, recovery, and detection of DNA that was left behind on blood and semen stains on various types of fabrics. The findings indicate that there is no single factor which is decisive in determining the recovery rate of DNA evidence. Instead, it is the result of several interactions among fabric properties, environmental conditions, and stain types methodological limitations. Based on the various studies, it can be seen that natural fabrics (especially those that are porous and absorbent fabrics) provided better and deeper penetration and greater retention of the biological stain; however, synthetic materials were more susceptible to DNA degradation and loss due to surface exposure, laundering, and environmental degradation. *Post-depositional* stressors (heat, humidity, ultraviolet/solar radiation, water exposure, and chemical agents), increases the intensity of these substrate-driven patterns across experimental conditions. There results demonstrate the importance of using appropriate methods for different materials and settings. The fabric type, history of the specimen, and analysis techniques should be taken into account when devising methods to extract evidence and obtain samples that will provide maximum yields of DNA and maintain interpretative reliability.

Other individual challenges were also observed between blood and semen stains. Seminal DNA is known to be more stable because it is protected by chromatin structure and also has a high affinity for porous textiles. In contrast, DNA from blood is more vulnerable thermal and UV degradation, making profiling standards susceptible and inferential to time.

Innovations like imaging techniques, non-destructive spectroscopy, and epigenetic/biomarker methods, could provide promising avenues for improving the recovery and interpretation of degraded or low-template DNA samples. Despite this, the practical use of forensic science is restricted by its lack of consistency in technique and standardization.

Overall, forensic interpretation can be strengthened and employed to improve accurate courtroom interpretations by incorporating fabric and environment-specific considerations within protocols development, validation experiments and training of practitioners.

Statements and Declarations

Ethical approval and consent to participate: As this is a narrative review of previously published literature, it does not involve original research with human participants or animals performed by the authors. All secondary data cited were obtained from primary sources that reported their own institutional ethical approvals and informed consent protocols.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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