Nexus Global Research Journal of Medical Sciences
Journal Homepage: https://nexusglobalresearch.com/index.php/ngrjms

Review Article:

Environmental and Tissue-Specific Determinants of DNA Degradation in Forensic Evidence: A Systematic Literature Review of Temperature, Moisture, and pH Effects

Aditya Suman [1], Wilma Manisha Picardo [2], Devesh Chawariya[3], Saptarshi Mandal [4*]

[1-3] B.Sc Forensic Science, Department of Forensic Science, Govt. Holkar Science College, Indore (M.P.) 452001
[2]Assistant Professor, School of Social Work, Roshini Nilaya, Mangalore
[4]Research Scholar, Department of Forensic Medicine and Toxicology, Kasturba Medical College, Manipal Academy of Higher Education, Manipal, Karnataka-576104, India

ABSTRACT:
DNA evidence remains one of the most powerful tools in forensic science; however, its evidential value is highly dependent on the preservation of genetic material following deposition or death. DNA degradation is a complex process influenced by both environmental conditions and the intrinsic biological characteristics of the tissue from which DNA is recovered. This systematic review examines the combined effects of temperature, moisture, and pH on DNA degradation and understands how preservation patterns differ among major forensic tissue types, including blood, saliva, soft tissues, bone, teeth, hair, and nails. DNA degradation occurs through multiple molecular pathways, including hydrolytic cleavage, depurination, oxidative damage, nuclease activity, microbial decomposition, and ultraviolet radiation-induced strand breakage. [1,2]
Available evidence demonstrates that elevated temperatures significantly accelerate the DNA degradation by increasing rates of depurination, strand fragmentation, and oxidative damage, particularly under prolonged exposure conditions.[3,4] Likewise, extreme acidic or alkaline environments destabilise the DNA molecule and contribute to the breakdown of phosphodiester bonds and nucleobases.[5] Moisture further increases degradation by promoting hydrolysis and facilitating microbial proliferation, leading to increased nuclease-mediated DNA destruction.[6,7] In contrast, cool, dry, and near-neutral pH environments consistently provide the most favourable conditions for long-term DNA preservation.[3,6] Marked differences in DNA preservation are observed among biological tissues. Soft tissues such as liver, spleen, and brain generally undergo rapid post-mortem degradation due to autolysis, high enzymatic activity, and microbial invasion.[8] On the other hand, mineralised tissues such as bone and teeth provide physical protection against environmental insults and often retain recoverable DNA for extended periods, making them valuable sources in highly decomposed or skeletal remains.[9,10] Hair roots may yield substantial quantities of nuclear DNA when present, whereas hair shafts and keratinised tissues frequently contain limited and degraded genetic material.[11,12]
The reviewed literature further indicates that progressive DNA degradation adversely affects forensic DNA profiling by reducing template quantity, increasing fragmentation, and increasing the risk of allelic dropout, particularly for larger short tandem repeat (STR) loci. [3,13] These effects may compromise individual identification and influence interpretations relating to post-mortem interval estimation and evidential reliability. Although substantial evidence exists regarding individual environmental factors, comparatively few studies have investigated their combined or synergistic effects under realistic forensic conditions. Methodological heterogeneity, variation in tissue types, and limited long-term experimental studies remain significant challenges within the field.
Understanding the interactions between environmental stressors and tissue-specific preservation characteristics is essential for optimising evidence collection, storage, laboratory processing, and interpretation of forensic DNA profiles. Future research should focus on integrated degradation models, standardised experimental designs, and the development of improved analytical approaches for highly degraded biological evidence.
Keyword: DNA degradation; forensic genetics; temperature; moisture; pH; tissue preservation; STR profiling; allelic dropout; post-mortem interval; forensic biology.

Citation: Suman, A., Picardo, W. M., Chawariya, D., & Mandal, S. (2026). Environmental and tissue-specific determinants of DNA degradation in forensic evidence: A systematic literature review of temperature, moisture, and pH effects. *Nexus Global Research Journal of Medical Sciences, 2*(9), 292–310.

***Corresponding Author:** Saptarshi Mandal, **Email:** saptarshimandal9748@gmail.com
Received: 20 Aug 2026 | **Accepted:** 09 Sep 2026 | **Published:** 15 Sep 2026
Copyright © 2026 The Author(s): This work is licensed under a Creative Commons Attribution- Non-Commercial-No Derivatives 4.0 (CC BY-NC-ND 4.0) International License

INTRODUCTION

Since its introduction in the mid-1980s, DNA profiling has become one of the most powerful and reliable methods for human identification, criminal investigation, kinship analysis, and disaster victim identification. The ability to generate individual genetic profiles from biological evidence has revolutionized forensic practice and significantly enhanced the evidential value of biological traces recovered from crime scenes. However, the success of forensic DNA analysis depends not only on the sensitivity of laboratory techniques but also on the quantity and quality of DNA preserved within biological samples. [14,15]

DNA is inherently unstable and undergoes continuous degradation through both endogenous and exogenous processes. Even under optimal conditions, spontaneous chemical reactions such as hydrolysis, oxidation, and depurination contribute to the gradual breakdown of the DNA molecule. [1] The phosphodiester backbone and nitrogenous bases are susceptible to chemical modification, leading to strand breaks, base loss, cross-linking, and fragmentation. These molecular alterations can compromise the integrity of genetic material and reduce the effectiveness of downstream forensic analyses. [1,5]

Following deposition at a scene of crime or after death, biological samples are exposed to a wide range of environmental conditions that can accelerate DNA degradation. Temperature is among the most influential factors affecting DNA preservation, as elevated temperatures increase the rates of hydrolytic and oxidative reactions and facilitate microbial growth.[3,6] Similarly, moisture promotes degradation by enhancing hydrolysis and creating favourable conditions for bacterial and fungal proliferation, which may introduce extracellular nucleases capable of rapidly degrading DNA molecules.[6,7,8] Additionally, environmental pH influences DNA stability by altering the chemical structure of nucleic acids; highly acidic conditions promote depurination, whereas strongly alkaline environments may induce denaturation and cleavage of phosphodiester bonds.[5] Collectively, these factors contribute to varying rates of DNA degradation across different environmental contexts.

The forensic significance of DNA degradation extends beyond simple reductions in DNA quantity. Fragmentation of DNA molecules can adversely affect short tandem repeat (STR) profiling, particularly when larger amplicons are targeted. Degraded samples frequently exhibit reduced amplification efficiency, peak imbalance, stochastic effects, and allelic dropout, all of which may compromise profile interpretation and the evidential value. [3,13,15] As a result, understanding the mechanisms and patterns of DNA degradation remains essential for the accurate interpretation of forensic genetic evidence.

In environmental influences, the biological source of DNA plays a critical role in determining preservation outcomes. Different tissues exhibit substantial variation in cellular composition, DNA content, structural protection, and susceptibility to decomposition. Blood and saliva are among the most commonly encountered forensic samples and often provide sufficient quantities of DNA for profiling, but they are highly exposed to environmental degradation following deposition. [15] Soft tissues such as liver, spleen, brain, and muscle contain abundant cellular DNA but undergo rapid post-mortem autolysis and microbial decomposition. On the other hand, mineralised tissues such as bone and teeth provide a protective microenvironment that can preserve DNA for extended periods despite prolonged environmental exposure. [4,9,10] Hair and nails show additional challenges because of their keratinised structure, low nuclear DNA content, and varying susceptibility to environmental damage. [11,12]

Although numerous studies have independently examined the effects of temperature, moisture, pH, or specific tissue types on DNA preservation, comparatively few reviews have integrated these factors within a unified forensic framework. Existing literature frequently focuses on isolated environmental variables or individual sample types, limiting broader understanding of how environmental stressors interact with tissue-specific characteristics to influence DNA survival. Such integration is increasingly important as forensic investigators encounter biological evidence across diverse environmental conditions ranging from tropical climates and aquatic environments to buried remains and highly decomposed skeletal material.

The present systematic review therefore seeks to provide a comprehensive synthesis of current knowledge regarding environmental and tissue-specific determinants of DNA degradation in forensic contexts. Specifically, this review aims to: (i) examine the molecular mechanisms responsible for DNA degradation; (ii) evaluate the effects of temperature, moisture, and pH on DNA stability; (iii) compare preservation patterns among major forensic tissue types, including blood, saliva, soft tissues, bone, teeth, hair, and

nails; (iv) assess the potential synergistic interactions between environmental stressors and biological substrates; and (v) discuss the implications of DNA degradation for forensic identification, STR profiling, and evidence interpretation. Through the integration of molecular biology, forensic genetics, and decomposition research, this review aims to provide a comprehensive evidence-based framework for understanding DNA preservation and degradation across a wide range of forensic scenarios.

METHODS (PRISMA SUMMARY)

Search Strategy and Information Sources

This systematic review investigates the forensic applications of DNA, with a focus on DNA degradation and fragmentation, the effects of heat on DNA, tissue preservation strategies, and the estimation of the post-mortem interval. The review drew on major scientific databases, including Google Scholar, PubMed, and Scopus. The literature search employed the following keywords: DNA, DNA degradation, forensic genetics, biology, forensics, and post-mortem interval.

Eligibility Criteria

Studies were included if they met one or more of the following criteria:

1. Reported experimental or observational data concerning DNA degradation under known environmental conditions.
2. Examined the influence of temperature, moisture, humidity, pH, ultraviolet radiation, microbial activity, burial conditions, or related environmental variables on DNA preservation.
3. Compared DNA recovery, degradation, or profiling success among different tissue or biological sample types.
4. Provided mechanistic insights into molecular pathways of DNA degradation relevant to forensic science.
5. Reported measurable outcomes such as DNA yield, degradation indices, quantitative PCR results, STR recovery rates, allele retention, fragment length distribution, or amplification success.

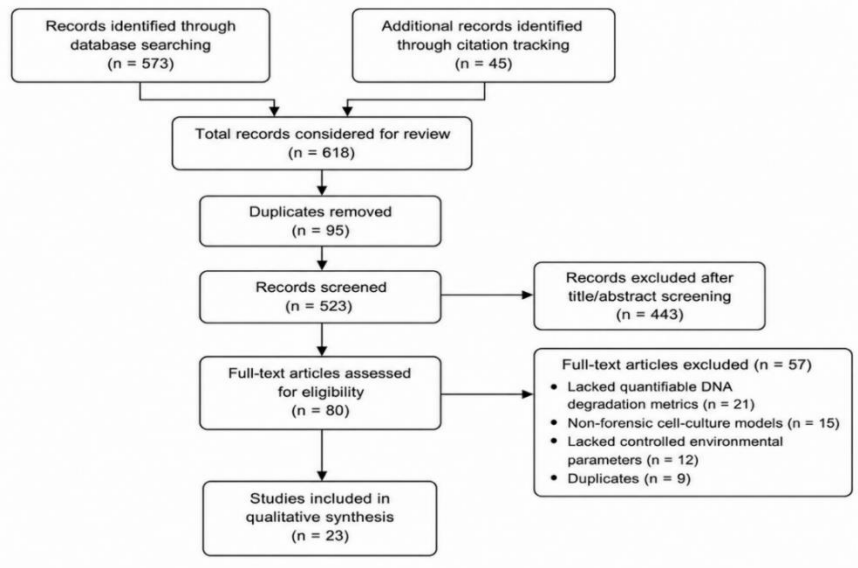
Studies were excluded if they:

1. Not available in English.
2. Focused exclusively on molecular biology techniques without relevance to forensic DNA preservation.
3. Lacked sufficient methodological detail or quantifiable outcomes.
4. Consisted solely of conference abstracts, editorials, opinion pieces, or non-peer-reviewed material.
5. Addressed synthetic, cell-culture, or laboratory-generated DNA systems without forensic applicability.

Study Selection

All records identified through database searching and supplementary sources were screened in a stepwise manner. Duplicate records were removed before title and abstract screening. Potentially relevant articles were subsequently evaluated through full-text assessment. Studies meeting all eligibility criteria were included in the final qualitative synthesis.

A total of 573 records were initially identified through database searching, with an additional 45 records obtained through citation tracking. This resulted in 618 documents being considered for review in total. After removing 95 duplicate records, 523 unique records remained for screening. Following the title and abstract evaluation, more than 443 records were excluded because they were unrelated to the study objectives or failed to meet the predefined eligibility criteria. The remaining 80 articles underwent full-text assessment, 57 were excluded (21 lacked quantifiable DNA degradation metrics, 15 focused on non-forensic cell-culture models, 12 lacked controlled environmental parameters, and 9 were duplicates). Ultimately, 23 studies satisfied all inclusion criteria and were incorporated into the final qualitative synthesis.



PRISMA Flow Summary

Data Extraction and Synthesis

Data were systematically extracted from each eligible study using a standardized framework. The following information was recorded whenever available:

- Author(s) and year of publication.
- Biological sample or tissue type.
- Environmental conditions investigated.
- Temperature and exposure duration.
- Relative humidity or moisture conditions.
- pH values and substrate characteristics.
- Presence of ultraviolet radiation or microbial activity.
- DNA extraction and analytical methods.
- DNA yield and concentration.
- Quantitative PCR results.
- STR profiling success.
- DNA degradation indices.
- Fragment size distribution and evidence of allelic dropout.

Where numerical data were available, findings were compared across studies and summarized descriptively. Due to substantial heterogeneity in experimental designs, environmental conditions, tissue types, analytical methods, and reported outcome measures, a quantitative meta-analysis was not performed. Conversely, results were synthesized narratively to identify consistent trends in DNA degradation patterns across environmental conditions and biological substrates.

Quality Assessment

Studies were evaluated based on methodological transparency, experimental design, environmental control, sample characterization, analytical methods, and reporting of DNA quality metrics. Greater weight was given to studies applying controlled experimental conditions, validated forensic methodologies, and quantitative measures of DNA degradation. Findings were interpreted in the context of methodological limitations and potential sources of bias.

The synthesized evidence was subsequently organized into thematic sections addressing the molecular mechanisms of DNA degradation, environmental influences on DNA stability, tissue-specific preservation patterns, synergistic interactions among degradation factors, and their implications for forensic identification and evidence interpretation.

Molecular Mechanisms of DNA Degradation

The preservation of DNA is fundamental to successful forensic identification; however, DNA is inherently unstable and continuously undergoes degradation through a combination of chemical, physical, and biological processes. Following deposition at a crime scene or after death, the integrity of genetic material progressively declines as environmental stressors interact with endogenous cellular mechanisms and external microbial communities. [1,3]Understanding these

molecular pathways is essential for interpreting forensic DNA evidence, particularly when analysing aged, environmentally exposed, or highly decomposed biological samples.

Hydrolytic Damage

Hydrolysis is one of the most important mechanisms responsible for DNA degradation under natural conditions. Water molecules can attack the chemical bonds within DNA, resulting in the cleavage of N-glycosidic bonds that connect nitrogenous bases to the sugar-phosphate backbone. This process leads to depurination and depyrimidination, producing abasic (apurinic/apyrimidinic) sites that destabilise the DNA molecule and increase susceptibility to strand breakage. [1,5]

Depurination occurs more frequently than depyrimidination and represents one of the most common spontaneous forms of DNA damage. Lindahl demonstrated that DNA continuously undergoes spontaneous hydrolytic decay under physiological conditions, highlighting the intrinsic instability of genetic material even in living cells. [1] Once an abasic site is formed, subsequent hydrolytic reactions may cleave the phosphodiester backbone, generating single-strand breaks that can ultimately develop into double-strand breaks if complementary strands are simultaneously affected. These lesions reduce the average fragment size of DNA and significantly impair forensic amplification success.

Environmental conditions strongly influence hydrolytic damage. Elevated temperatures, increased moisture levels, and prolonged exposure times accelerate the rate of hydrolysis, making biological samples deposited in warm and humid environments particularly susceptible to degradation. [3,6]

Oxidative Damage

Oxidative damage constitutes another major pathway of DNA degradation. Reactive oxygen species (ROS), including superoxide radicals, hydroxyl radicals, and hydrogen peroxide, can attack both DNA bases and the deoxyribose sugar backbone. Oxidative stress may arise from normal cellular metabolism, post-mortem biochemical processes, environmental exposure, and microbial activity.[1,5]

The interaction of ROS with DNA can result in base modifications, strand scission, cross-link formation, and structural distortions. Among the most often reported oxidative lesions is the formation of oxidised guanine derivatives, which may interfere with DNA polymerase activity during amplification. Persistent oxidative damage contributes to fragmentation and decreases the probability of recovering complete genetic profiles from forensic samples. [3]

The effects of oxidative damage become increasingly pronounced in decomposing tissues, where cellular breakdown and microbial metabolism generate reactive chemical species that accelerate DNA degradation. [6,8]

Nuclease-Mediated Degradation

After death, cellular homeostasis rapidly stops, initiating autolytic processes that contribute substantially to DNA degradation. During autolysis, lysosomal membranes lose integrity and intracellular enzymes are released into surrounding tissues. Among these enzymes are endogenous nucleases, which catalyse the cleavage of phosphodiester bonds within DNA molecules.[3,8]

As decomposition progresses, microbial colonisation further intensifies DNA destruction. Bacteria and fungi produce extracellular nucleases that digest nucleic acids as nutrient sources. Environmental microorganisms may infiltrate tissues through natural body openings, damaged skin, soil contact, or aquatic exposure. Once established, these microbial communities accelerate the breakdown of both soft tissues and genetic material. [7,8]

The combined effects of endogenous and microbial nucleases frequently account for the rapid loss of amplifiable DNA observed in soft tissues such as liver, spleen, and brain. On the other hand, mineralised tissues such as bone and teeth often provide a physical barrier that limits microbial penetration and slows enzymatic degradation. [4,9,10]

DNA Cross-Linking and Structural Modifications

Along with fragmentation, DNA molecules may undergo structural modifications that hinder successful forensic analysis. Chemical cross-linking can occur between DNA strands or between DNA and proteins, resulting in complex molecular structures that are difficult to denature and amplify during polymerase chain reaction (PCR) analysis. [1,3]

Cross-linking may arise from oxidative reactions, environmental contaminants, decomposition products, and interactions with aldehydes generated during tissue breakdown. Although cross-linked DNA may remain physically present within a sample, its forensic utility is often reduced because amplification enzymes cannot efficiently access damaged template regions. Hence,

DNA quantity measurements may overestimate the amount of usable genetic material available for profiling.

Ultraviolet Radiation-Induced Damage

Ultraviolet (UV) radiation is an electromagnetic radiation (EMR) represents an important environmental source of DNA damage, particularly in biological evidence exposed to direct sunlight. UV photons can induce photochemical reactions between adjacent pyrimidine bases, resulting in the formation of cyclobutane pyrimidine dimers and other photoproducts. These lesions distort the DNA helix and interfere with replication and amplification processes. [3]

Extended UV exposure may also generate reactive oxygen species that contribute to secondary oxidative damage and strand breakage. Outdoor biological stains exposed to sunlight therefore often exhibit accelerated degradation compared with samples protected from ultraviolet radiation. The cumulative effects of UV-induced lesions, oxidation, and thermal stress can significantly reduce STR profiling success and increase the likelihood of incomplete genetic profiles. [3,13]

Fragmentation and Forensic Consequences

The ultimate consequence of most degradation mechanisms is DNA fragmentation. Hydrolysis, oxidation, nuclease activity, and UV-induced damage collectively reduce DNA molecules to progressively smaller fragments. As fragment length decreases, amplification of larger STR loci becomes increasingly difficult, resulting in peak imbalance, locus drop-out, and partial DNA profiles. [3,13]

Forensic laboratories frequently observe preferential amplification of smaller loci in degraded samples, a phenomenon that forms the basis of degradation scores showed in quantitative PCR analysis. Highly degraded samples may contain sufficient DNA quantity but insufficient DNA quality to generate complete genetic profiles. Hence, DNA integrity rather than absolute DNA concentration often represents the critical determinant of forensic success.

Interaction of Degradation Mechanisms

Although hydrolysis, oxidation, nuclease activity, cross-linking, and ultraviolet damage are often discussed separately, these mechanisms rarely occur in isolation. Instead, they operate simultaneously and interact synergistically within forensic environments. Elevated temperature may accelerate hydrolysis and oxidation, moisture may facilitate microbial proliferation and nuclease activity, and extreme pH conditions may destabilise DNA structure and increase sensitivity to chemical attack. [3,5,6]

The cumulative action of these degradation pathways ultimately determines the persistence of genetic material within biological evidence. Understanding their molecular basis provides the foundation for interpreting the environmental and tissue-specific patterns of DNA preservation discussed in subsequent sections of this review.

Temperature Effects on DNA Preservation

Temperature is widely recognised as one of the most important environmental factors influencing DNA preservation and degradation in forensic evidence. The stability of DNA is fundamentally dependent on the rate of chemical and biological processes that act upon the molecule, and temperature directly affects both. Elevated temperatures accelerate hydrolytic and oxidative reactions, increase enzymatic activity, promote microbial proliferation, and enhance tissue decomposition, all of which contribute to progressive DNA fragmentation and loss of amplifiable genetic material.[1,3,6]

DNA degradation under elevated temperatures is primarily governed by chemical kinetics. As temperature increases, molecular motion increases, resulting in a greater frequency of molecular collisions and an increased likelihood of chemical reactions capable of damaging nucleic acids. Hydrolysis, one of the principal mechanisms of DNA degradation, occurs more rapidly at higher temperatures and leads to the cleavage of N-glycosidic bonds between bases and the sugar-phosphate backbone. This process generates apurinic and apyrimidinic sites, which destabilise the DNA molecule and increase susceptibility to strand breakage. [1,5] Simultaneously, oxidative reactions become more frequent, producing modified bases and strand lesions that further compromise DNA integrity.[1,3]

The influence of temperature extends beyond direct chemical damage. Elevated temperatures also facilitate biological degradation by enhancing microbial growth and enzymatic activity. After death or deposition, endogenous nucleases released during autolysis begin degrading cellular DNA. As decomposition progresses, environmental microorganisms inhabit biological tissues and produce extracellular nucleases that accelerate DNA destruction. [7,8] Because most decomposer microorganisms exhibit optimal growth within moderate to warm temperature ranges, elevated environmental

temperatures frequently correspond to increased rates of DNA loss in forensic samples.[6,8]

Temperature-dependent degradation is particularly relevant in post-mortem forensic investigations. Soft tissues such as liver, spleen, brain, and muscle contain abundant DNA but are also highly susceptible to decomposition. Warm environmental conditions accelerate autolysis and putrefaction, resulting in rapid fragmentation of DNA and reduced success of downstream forensic analyses. In contrast, cooler temperatures slow these biological processes, delaying decomposition and preserving genetic material for longer periods. [3,6]

The effects of temperature on forensic DNA analysis are evident during STR profiling. Progressive thermal degradation reduces average DNA fragment length, producing a characteristic pattern in which larger genetic targets fail to amplify while shorter fragments remain detectable. This phenomenon is commonly observed in degraded forensic samples and contributes to peak imbalance, partial profiles, and allelic dropout. [3,13] Because larger STR loci are more susceptible to fragmentation, degraded samples frequently yield incomplete genetic profiles that contain only shorter amplifiable regions. These observations have led to the development of mini-STR and short-amplicon approaches specifically designed for degraded DNA. [13]

The impact of temperature varies among biological substrates. Soft tissues generally exhibit rapid degradation because they contain high moisture content, abundant endogenous enzymes, and extensive microbial activity. By contrast, hard tissues such as bone and teeth often provide a degree of protection against environmental effects. DNA preserved within mineralised structures may remain recoverable even after prolonged exposure to adverse conditions because the surrounding hydroxyapatite matrix restricts microbial penetration and slows environmental damage. [4,9,10] Consequently, bone and teeth frequently serve as preferred sources of DNA in highly decomposed, skeletonised, or environmentally exposed remains.

Low temperatures exert the opposite effect and are generally associated with enhanced DNA preservation. Cooling reduces molecular motion, slows hydrolytic and oxidative reactions, and suppresses microbial metabolism. These protective effects explain why refrigeration and freezing are routinely employed during forensic evidence storage and transportation. Biological samples maintained under low-temperature conditions exhibit reduced degradation rates and greater long-term DNA stability compared with samples exposed to ambient or elevated temperatures. [3,6] The preservation of DNA in archaeological, frozen, and cold-environment specimens further illustrates the substantial influence of temperature on long-term genetic survival. [4]

The interaction between temperature and other environmental variables is also important. Elevated temperatures often act synergistically with moisture and pH to accelerate degradation processes. Warm and humid conditions facilitate microbial growth and hydrolysis altogether, while temperature-related increases in reaction rates can amplify the damaging effects of acidic or alkaline environments. Consequently, temperature should not be viewed as an isolated factor but rather as a component of a broader environmental system influencing DNA preservation. [5,6]

The available evidence demonstrates that temperature is a critical determinant of DNA stability in forensic samples. Elevated temperatures accelerate chemical, enzymatic, and microbial degradation pathways, resulting in increased DNA fragmentation and reduced profiling success. On the other hand, low temperatures inhibit these processes and promote long-term preservation of genetic material. Understanding the effects of temperature on DNA degradation is therefore essential for evidence collection, storage, interpretation, and the successful recovery of forensic genetic information.

pH Effects on DNA Preservation

The hydrogen ion concentration (pH) of the surrounding environment is a critical determinant of DNA stability and preservation. DNA exhibits its greatest stability under near-neutral conditions, whereas strongly acidic or strongly alkaline environments accelerate chemical degradation and contribute to the loss of amplifiable genetic material. The influence of pH is particularly important in forensic contexts because biological evidence may be exposed to diverse environmental conditions, including acidic soils, alkaline cleaning agents, industrial waste products, and decomposition-associated changes in microenvironmental chemistry. [5,6]

The effects of pH on DNA preservation are primarily mediated through chemical alterations of the nucleic acid molecule. Under acidic conditions, protonation of nucleotide bases destabilises the N-glycosidic bond linking purine bases to the deoxyribose sugar. This process accelerates depurination, resulting in the formation of apurinic sites that are highly susceptible to

strand breakage.[1,5] Experimental investigations have demonstrated that depurination rates increase markedly as pH decreases, confirming that acidic environments promote rapid DNA degradation.[5,17] Once abasic sites are formed, subsequent hydrolytic reactions may cleave the phosphodiester backbone, producing fragmented DNA molecules that are increasingly difficult to amplify during forensic analysis.

Acid-mediated DNA degradation has been recognised for decades. Early investigations into the behaviour of nucleic acids under acidic conditions demonstrated substantial degradation of DNA structure following exposure to mild acid environments. [17] These observations provided some of the earliest experimental evidence that acidic conditions can compromise DNA integrity through chemical mechanisms independent of enzymatic activity. More recent studies examining depurination kinetics have further confirmed that decreasing pH substantially increases the rate of purine loss and subsequent DNA fragmentation. [5]

Strongly alkaline environments also adversely affect DNA stability, although the underlying mechanisms differ from those operating under acidic conditions. Higher pH promotes disruption of hydrogen bonding between complementary strands, resulting in denaturation of the DNA double helix. As strand separation occurs, single-stranded DNA becomes more vulnerable to hydrolytic damage, oxidation, and nuclease attack. Under sufficiently alkaline conditions, cleavage of phosphodiester bonds may also occur, contributing directly to strand fragmentation. The combined effects of denaturation and strand scission can significantly reduce the quantity of intact DNA available for forensic profiling. [5]

The influence of pH extends beyond direct chemical damage to DNA. Environmental pH affects microbial communities and enzymatic activity, both of which play important roles in decomposition and DNA preservation. Highly acidic or alkaline environments may alter microbial composition and influence the production of extracellular nucleases capable of degrading genetic material. In soil environments, pH also affects mineral composition, DNA adsorption, and the persistence of extracellular DNA molecules. [6,7]

Forensic observations support the importance of pH in DNA preservation. Burial environments characterised by strongly acidic soils are frequently associated with reduced DNA recovery and increased degradation. Acidic conditions accelerate chemical breakdown and may contribute to more rapid decomposition of biological tissues. In contrast, neutral or mildly alkaline environments are generally considered more favourable for DNA preservation because they reduce depurination rates and may suppress some degradative enzymatic processes. [6]

The practical implications of pH are particularly evident in forensic casework involving environmental exposure. Biological evidence recovered from peat bogs, acidic forest soils, industrial sites, or chemically contaminated locations may exhibit substantial DNA degradation despite apparent preservation of physical tissue structures. Similarly, exposure to strongly alkaline substances such as bleach and certain industrial cleaning agents can severely compromise DNA recovery by inducing denaturation and strand damage. Therefore, environmental pH should always be considered when evaluating the likelihood of successful DNA profiling from compromised samples.

The impact of pH on forensic DNA analysis is reflected in the quality of genetic profiles obtained from degraded evidence. Progressive acid- or alkali-mediated degradation results in shorter DNA fragments, increased template damage, and reduced amplification efficiency. Larger STR loci are particularly susceptible to failure because fragmentation limits the availability of intact template molecules spanning the entire target region. As degradation advances, partial profiles, peak imbalance, and allelic dropout become increasingly common. [3,13] pH rarely acts as an isolated variable. Environmental pH interacts closely with temperature and moisture, creating complex conditions that influence DNA preservation. Warm and humid acidic environments promote hydrolysis, microbial growth, and enzymatic activity altogether, producing substantially greater degradation than any single factor alone. Likewise, alkaline conditions combined with Elevated temperature may accelerate denaturation and strand fragmentation. These synergistic interactions highlight the importance of considering pH within the broader environmental context of forensic evidence recovery. [6]

To minimise pH-related degradation, forensic laboratories routinely employ buffered storage systems during DNA extraction and preservation. Solutions containing buffering agents and chelating compounds, such as EDTA, help maintain near-neutral pH conditions while inhibiting metal-catalysed degradation reactions. Such approaches contribute significantly to the long-term stability of forensic DNA samples and maximise the probability of successful genetic analysis.

Available evidence demonstrates that DNA preservation is strongly influenced by environmental pH. Acidic conditions accelerate depurination and hydrolysis, while alkaline environments promote denaturation and strand fragmentation. Neutral to mildly alkaline conditions generally provide the most favourable environment for DNA stability. Understanding the role of pH in DNA degradation is therefore essential for forensic evidence collection, storage, interpretation, and the development of effective preservation strategies.

Tissue-Specific Preservation Patterns

The preservation of forensic DNA is influenced not only by environmental conditions but also by the intrinsic biological characteristics of the tissue from which the DNA is recovered. Different tissues vary considerably in cellular composition, DNA concentration, water content, enzymatic activity, structural protection, and susceptibility to decomposition. Therefore , substantial differences exist in both the quantity of recoverable DNA and the duration for which DNA remains suitable for forensic analysis. Understanding these tissue-specific preservation patterns is essential for evidence collection, post-mortem identification, disaster victim identification, and the interpretation of degraded biological samples.[3,15]

Blood

Blood is among the most frequently encountered biological materials in forensic investigations. Since mature human erythrocytes lack nuclei, forensic DNA recovered from blood originates primarily from leukocytes.[15] Despite its relatively limited nuclear cell population, blood remains an important forensic substrate because it is commonly deposited at crime scenes and can often yield reliable genetic profiles when appropriately preserved.

Dried bloodstains generally demonstrate good stability because desiccation reduces microbial growth and limits hydrolytic damage. However, prolonged exposure to moisture, elevated temperatures, ultraviolet radiation, and environmental contaminants can progressively reduce DNA quality.[3,6] As degradation proceeds, DNA fragmentation increases, leading to reduced amplification efficiency, peak imbalance, and allelic dropout during STR analysis.[13]

Saliva and Buccal Cells

Saliva is frequently encountered on cigarette butts, drinking vessels, envelopes, bite marks, and touched objects. DNA within saliva originates primarily from exfoliated buccal epithelial cells suspended within oral secretions.[15]

Under favourable conditions, dried saliva stains can remain suitable for forensic analysis for extended periods. However, saliva contains a complex microbial community that may contribute to DNA degradation when moisture is present. Raised humidity promotes bacterial proliferation and enzymatic activity, accelerating DNA fragmentation. Therefore , DNA preservation in saliva is strongly influenced by environmental conditions and storage practices.[3,6]

Skeletal Muscle

Skeletal muscle is an important source of DNA in post-mortem investigations because it contains abundant nucleated cells and relatively high concentrations of nuclear DNA. During the early post-mortem interval, muscle tissue often yields high-quality DNA suitable for STR profiling and individual identification.[3]

However, muscle tissue undergoes rapid autolysis following death. The release of intracellular enzymes, combined with microbial colonisation, progressively degrades cellular structures and fragments DNA molecules. Environmental factors such as elevated temperature and moisture further accelerate these processes. As a result, muscle is generally considered a useful source of DNA during early decomposition but becomes less reliable during advanced post-mortem intervals.

Liver

The liver contains large numbers of nucleated cells and initially provides abundant DNA. Despite this advantage, it is often considered one of the less favourable tissues for long-term forensic preservation. The organ possesses high metabolic activity and contains numerous endogenous enzymes that contribute to rapid autolytic degradation following death.[3]

The liver is anatomically close to the gastrointestinal tract, making it particularly vulnerable to microbial invasion during decomposition. Consequently, liver DNA frequently exhibits significant degradation unless samples are collected soon after death or preserved under controlled conditions.

Bone

Bone is widely recognised as one of the most valuable long-term reservoirs of forensic DNA. DNA within skeletal tissue is protected by a mineralised

hydroxyapatite matrix that limits environmental exposure and reduces microbial penetration.[4,9]

Because of this protective architecture, bone frequently remains a viable source of DNA when soft tissues have completely decomposed. Forensic investigations involving skeletonised remains routinely rely on cortical bone as a primary source of genetic material. DNA recovery from skeletal remains may be successful years or even decades after death when environmental conditions are favourable.[4,9,18]

However, DNA preservation in bone is influenced by burial conditions, soil chemistry, moisture levels, and microbial activity. Acidic soils may accelerate mineral dissolution, while porous trabecular regions are generally more susceptible to microbial invasion than dense cortical bone.[6] Despite these limitations, bone remains one of the most reliable tissues for forensic identification in advanced decomposition.

Teeth

Teeth are often regarded as the most durable biological source of forensic DNA. Their highly mineralised structure provides exceptional protection against physical, chemical, and biological degradation.[10] Enamel, dentine, and cementum surround and protect the dental pulp, creating an enclosed environment that can preserve DNA long after surrounding soft tissues have disappeared.

The forensic importance of teeth is particularly evident in cases involving fire, mass disasters, prolonged burial, and advanced decomposition. Numerous investigations have demonstrated successful recovery of DNA from dental tissues under conditions where other biological materials fail to yield usable genetic information.[10] Because of their durability and resistance to environmental stress, teeth are frequently considered the preferred source of DNA in highly compromised human remains.

Hair

Hair presents unique challenges and opportunities for forensic DNA analysis. The evidential value of hair depends largely on whether the root is present. Hair roots contain nucleated follicular cells capable of providing nuclear DNA suitable for STR profiling.[11]

On the other hand, the keratinised hair shaft contains little or no nuclear DNA and is therefore less useful for conventional STR analysis. However, mitochondrial DNA may persist within the shaft and can be used for maternal lineage investigations when nuclear DNA is unavailable.[12]

Hair roots often yield useful forensic DNA when recovered shortly after shedding or removal. Environmental exposure, ultraviolet radiation, moisture, and prolonged weathering may damage follicular cells and reduce DNA recovery. Still, because hair is relatively resistant to decomposition compared with many soft tissues, it may remain available as forensic evidence after other biological materials have deteriorated.[11,12]

Nails

Fingernails and toenails are composed primarily of keratinised tissue and generally contain limited amounts of intrinsic nuclear DNA. However, biological material trapped beneath the nail plate may provide valuable forensic evidence, particularly in cases involving assault, defensive injuries, or physical struggle. [15]

The dense keratin structure of nails provides some resistance to environmental degradation and moisture penetration. Although DNA yield is often lower than that obtained from blood, saliva, or soft tissues, useful genetic profiles may occasionally be recovered when sufficient biological material is present. Consequently, nails are considered supplementary forensic substrates that may provide important evidential information in specific investigative contexts.

Comparative Preservation Potential

When preservation potential is compared across biological substrates, a general hierarchy emerges. Teeth and dense cortical bone demonstrate the greatest long-term DNA stability because of extensive mineral protection. Hair roots may provide excellent-quality nuclear DNA when available, while blood and saliva serve as reliable sources during early forensic investigations. Soft tissues such as skeletal muscle and liver initially contain abundant DNA but undergo rapid degradation during decomposition. Nails generally provide lower DNA yields but may retain evidential value when associated biological material is present.

These differences illustrate that no single tissue is universally optimal for all forensic situations. Rather, successful DNA recovery depends on selecting the most appropriate biological substrate according to environmental conditions, post-mortem interval, and the degree of decomposition. Understanding tissue-specific preservation patterns, therefore, remains essential for maximising forensic DNA recovery and ensuring accurate interpretation of genetic evidence.

Table 1: **Comparative Analysis of Forensic Tissue Types and DNA Preservation Potential**

Tissue/ Source	Relative DNA Yield*	Long-Term Preservation Potential	Principal Advantages	Major Limitations	Key References
Hair Root	High	Moderate to High	Contains nucleated follicular cells suitable for STR profiling	Requires an intact root; environmental exposure may damage follicular DNA	[11], [12]
Hair Shaft	Very Low Nuclear DNA	High Structural Stability	Useful source of mitochondrial DNA	Limited nuclear DNA for STR analysis	[12]
Blood	Moderate	Moderate	Commonly encountered forensic sample; reliable STR profiling when properly preserved	DNA originates only from leukocytes; susceptible to moisture and environmental degradation	[3], [15]
Saliva	Moderate	Moderate	Easily deposited on objects; rich source of epithelial cells	Contains microbial flora and enzymes that may accelerate degradation	[3], [15]
Skeletal Muscle	High	Moderate	Abundant nucleated cells; useful in early post-mortem intervals	Rapid autolysis and enzymatic degradation after death	[3]
Liver	High	Low	Initially, high cellularity and DNA content	High endogenous nuclease activity and rapid decomposition	[3]
Bone	Moderate	Very High	Mineral matrix protects DNA; useful in skeletonised remains	Requires specialised extraction and demineralisation procedures	[4], [9], [18]
Teeth	Moderate	Very High	Excellent protection from environmental stress; valuable in burned and decomposed remains	Invasive sampling; limited availability	[10]
Nails	Low	Moderate	Resistant keratin structure; may retain foreign biological material	Low intrinsic nuclear DNA yield	[15]
Adipose Tissue	Low	Low	Occasionally available in fresh remains	Low cellular density and limited forensic utility	[3]

In general, evidence suggests substantial variation in DNA yield among tissue types. Hair roots, skeletal muscle, and highly cellular soft tissues frequently provide abundant nuclear DNA, whereas blood and saliva generally provide moderate yields dependent on cellular content and environmental preservation. Bone and teeth often yield lower quantities of DNA than fresh soft tissues but exhibit superior long-term preservation because of their mineralised structure. Adipose tissue generally contributes comparatively little recoverable DNA because of its low cellular density.[3,4,9,10,11,18]

Tissue-Synergistic Interactions of Environmental Factors

DNA degradation in forensic evidence rarely results from the action of a single environmental variable. Instead, temperature, moisture, pH, microbial activity, ultraviolet radiation, and tissue characteristics interact simultaneously to determine the rate and extent of genetic deterioration. These interactions frequently produce effects that are greater than the sum of individual factors, resulting in accelerated DNA fragmentation and reduced forensic recovery. Understanding such synergistic relationships is essential for accurately interpreting DNA evidence recovered from complex environmental settings. [3,6]

The combined effects of temperature and moisture represent one of the most important examples of environmental synergy. Elevated temperatures accelerate chemical reactions such as hydrolysis and oxidation, while moisture supplies the water necessary for hydrolytic damage and promotes microbial proliferation. [1,5,6] When both factors occur together, DNA degradation

often proceeds substantially faster than under either condition alone. Warm, humid environments facilitate simultaneous chemical breakdown, enzymatic activity, and microbial colonisation, producing conditions highly detrimental to DNA preservation. [6,8]

Microbial activity serves as a key mediator of these synergistic effects. Moisture enables bacterial and fungal growth, while favourable temperatures enhance microbial metabolism and reproduction. Once established, microbial communities produce extracellular nucleases capable of degrading both intracellular and extracellular DNA. [7,8] Therefore , biological evidence exposed to warm and humid conditions often experiences rapid losses in DNA quantity and quality. Such environments are particularly common in tropical climates, shallow burials, decomposing remains, and water-associated forensic scenarios.

Interactions between pH and temperature also significantly influence DNA stability. Acidic environments accelerate depurination reactions, while elevated temperatures increase reaction kinetics and enhance the rate of chemical degradation. [1,5,17] As a result, DNA exposed to both elevated temperatures and acidic conditions undergo accelerated strand breakage and fragmentation. Similarly, alkaline environments promote denaturation of the DNA double helix, exposing single strands to hydrolytic damage and enzymatic attack. When alkaline conditions occur simultaneously with elevated temperatures, degradation may proceed more rapidly than under either stressor independently. [5]

The effects of environmental factors are further modified by tissue-specific characteristics. Different tissues possess distinct structural, biochemical, and anatomical properties that influence their response to environmental stress. Soft tissues such as liver, brain, and skeletal muscle contain high water content and abundant endogenous enzymes, making them particularly vulnerable to synergistic degradation. Elevated temperature and humidity accelerate autolysis in these tissues, while microbial invasion further contributes to DNA loss. [3,8] Therefore, soft tissues frequently exhibit substantial DNA degradation during relatively short post-mortem intervals under adverse environmental conditions.

On the other hand, mineralised tissues such as bone and teeth demonstrate considerable resistance to environmental stressors. The hydroxyapatite matrix of bone and the highly mineralised structure of teeth provide physical protection against moisture, microbial penetration, and environmental fluctuations. [4,9,10] Although environmental factors still influence long-term preservation, the protective architecture of these tissues substantially reduces the rate of degradation compared with exposed soft tissues. As a result, bone and teeth often remain viable sources of DNA long after other tissues have deteriorated beyond forensic utility.

Hair and nails exhibit intermediate behaviour within this continuum. Keratinised structures are relatively resistant to microbial decomposition and environmental moisture, yet the availability of recoverable DNA depends heavily on the presence of nucleated tissue components such as hair roots or attached biological material. [11,15] Environmental stressors may damage these cellular components, reducing DNA recovery despite the apparent physical preservation of the keratin matrix.

Ultraviolet radiation introduces another important synergistic interaction. UV exposure causes base modifications, pyrimidine dimer formation, and strand breaks that directly damage DNA molecules. [3] When UV-induced lesions occur in conjunction with elevated temperature and moisture, already weakened DNA fragments become more susceptible to hydrolysis and microbial degradation. Therefore, biological evidence exposed to sunlight often experiences substantially greater deterioration than samples protected from radiation, even when other environmental conditions are similar.

The forensic consequences of these synergistic interactions are reflected in DNA profiling outcomes. Progressive fragmentation reduces the availability of intact template molecules required for amplification, particularly for larger STR loci. As degradation intensifies, forensic analysts may observe reduced peak heights, partial genetic profiles, stochastic effects, and allelic dropout. [3,13] Because environmental variables frequently act simultaneously, interpretation of degraded DNA evidence requires consideration of the cumulative effects of multiple stressors rather than assessment of individual factors in isolation.

Tissue-specific responses to environmental stress are particularly relevant in post-mortem investigations. For example, skeletal muscle may provide excellent DNA during early decomposition but rapidly deteriorates when exposed to warm and humid conditions. On the other hand, teeth and cortical bone may continue to yield usable DNA despite prolonged exposure to adverse environments. These differences demonstrate that tissue

characteristics can either amplify or mitigate the effects of environmental stressors and must therefore be incorporated into forensic sampling strategies.

Available evidence indicates that DNA degradation is governed by a complex interaction between environmental variables and tissue-specific characteristics. Temperature, moisture, pH, microbial activity, and ultraviolet radiation frequently operate altogether, producing synergistic effects that accelerate DNA deterioration beyond what would be expected from individual factors alone. The degree of degradation ultimately depends on both the environmental conditions encountered and the biological properties of the tissue involved. Recognition of these interactions is essential for forensic evidence preservation, interpretation of degraded DNA profiles, and optimisation of sampling strategies in challenging forensic contexts.

Forensic Implications

The forensic value of DNA evidence depends not only on the presence of genetic material but also on its integrity and suitability for downstream analysis. Environmental degradation and tissue-specific preservation patterns directly influence DNA quantity, fragment length, amplification efficiency, and ultimately the reliability of forensic genetic profiles. Consequently, understanding the mechanisms and consequences of DNA degradation is essential for evidence collection, laboratory processing, interpretation, and judicial evaluation. [3,13,20]

STR Fragmentation and Allelic Dropout

One of the most significant consequences of DNA degradation is progressive fragmentation of the genetic template. Modern forensic STR profiling systems typically amplify loci ranging from approximately 100 to 400 base pairs. As DNA molecules become fragmented, larger STR targets are disproportionately affected because intact template molecules spanning the complete amplicon become increasingly less. [3,13]

This phenomenon results in allelic dropout, where one or both alleles at a locus fail to amplify despite being present in the original sample. Allelic dropout occurs more frequently in highly degraded DNA and is particularly common among larger STR loci. The resulting genetic profiles may therefore be incomplete, containing only shorter amplifiable targets. [3,21,22]

Such degradation-induced profile loss has important forensic implications because incomplete profiles reduce discrimination power and may complicate statistical interpretation. In severe cases, DNA damage can result in substantial loss of genetic information, limiting the evidential value of the sample.

Profile Completeness and Evidential Strength

The completeness of a DNA profile is one of the primary determinants of its forensic usefulness. High-quality DNA samples generally produce full STR profiles containing all targeted loci, whereas degraded samples often yield partial profiles with missing alleles or loci. [3,13]

Partial profiles remain valuable investigative tools but generally provide lower statistical power than complete profiles. Reduced profile completeness may increase uncertainty during interpretation and can limit the strength of conclusions regarding identity or exclusion. Therefore, forensic scientists must evaluate DNA quality alongside profile content when assessing evidential significance.

Environmental context is particularly important in such evaluations. Samples recovered from warm, humid, acidic, submerged, burned, or heavily decomposed environments are inherently more susceptible to degradation and therefore more likely to produce incomplete genetic profiles. [3,6]

DNA Quantity Versus DNA Quality

DNA quantity alone does not guarantee successful forensic analysis. While forensic laboratories routinely quantify extracted DNA before amplification, the amount of DNA recovered may not accurately reflect its suitability for STR profiling. [3]

A sample may contain relatively large quantities of highly fragmented DNA that perform poorly during amplification, whereas a smaller quantity of well-preserved DNA may generate a complete profile. Therefore, DNA quality metrics have become increasingly important in forensic workflows. Modern quantification systems frequently incorporate degradation indices that compare amplification of short and long targets, providing an estimate of template integrity before STR analysis. [13,20]

MiniSTRs and Alternative Genetic Markers

Recognition of degradation related limitations has driven the development of specialised analytical approaches for compromised forensic samples. MiniSTR assays were specifically designed to target shorter DNA fragments than conventional STR systems, thereby increasing the

probability of successful amplification from degraded templates. [21,22]

These approaches have improved the analysis of highly degraded forensic evidence, including skeletal remains, disaster victim samples, and historical specimens. Concurrently, single-nucleotide polymorphism (SNP) panels and microhaplotype markers have emerged as promising alternatives because they require even shorter amplification targets and may provide useful genetic information when conventional STR analysis fails. [23]

Although STR profiling remains the global standard for forensic human identification, emerging marker systems are expected to play an increasingly important role in the analysis of degraded DNA.

Post-Mortem Interval Estimation

DNA degradation has also attracted attention as a potential indicator of post-mortem interval (PMI). Progressive fragmentation of DNA occurs following death as a result of autolysis, microbial activity, and environmental exposure. Because these processes generally increase with time, several investigators have explored whether DNA degradation measurements could assist in estimating the interval since death. [3]

But the practical application of DNA degradation for PMI estimation remains challenging. Temperature, humidity, pH, microbial colonisation, body condition, burial environment, and tissue type all influence degradation rates. Together, similar levels of DNA fragmentation may correspond to substantially different post-mortem intervals under different environmental conditions. While DNA degradation may contribute useful supplementary information, it is unlikely to serve as a standalone PMI indicator without consideration of environmental variables.

Interpretation of Degraded DNA Evidence

The interpretation of degraded DNA evidence requires careful consideration of environmental and biological context. Allelic dropout, peak imbalance, locus failure, and reduced template quantity may arise from degradation rather than from mixed DNA profiles, contamination, or analytical artefacts. [3,13]

Forensic practitioners must therefore integrate laboratory findings with information concerning sample type, storage history, environmental exposure, and post-mortem condition. Such contextual interpretation is essential for avoiding misclassification of degraded samples and ensuring accurate evidential conclusions.

Professional forensic guidelines increasingly emphasise the importance of documenting degradation indicators, evaluating DNA quality metrics, and considering environmental factors during profile interpretation. [20] These practices enhance the reliability and transparency of forensic DNA analysis and support robust judicial decision-making.

Implications for Evidence Collection and Preservation

The findings reviewed throughout this study have direct practical implications for forensic evidence management. Rapid collection, appropriate drying of biological stains, refrigeration of tissues, avoiding the excessive moisture, and protection from extreme pH and temperature conditions can substantially improve the preservation of DNA. [3,6]

When advanced decomposition is present, investigators should prioritise tissues with greater preservation potential, particularly teeth and dense cortical bone. [4,9,10] on the other hand, soft tissues such as liver and muscle should ideally be collected as early as possible before extensive autolysis and microbial degradation occur.

At last the successful forensic DNA analysis depends upon recognising that environmental conditions and tissue characteristics jointly determine DNA survival. Understanding these factors enables investigators and laboratory personnel to maximise DNA recovery, improve profile quality, and strengthen the evidential value of forensic genetic analyses.

LIMITATIONS

1. Methodological heterogeneity among studies: The reviewed literature exhibited substantial variation in experimental design, sample preparation methods, DNA extraction protocols, quantification techniques, environmental exposure conditions, analytical platforms, and outcome measures. This heterogeneity limited direct comparison between studies and restricted the ability to perform quantitative synthesis across datasets.
2. Limited multi-factor experimental studies: Most published investigations examined individual variables such as temperature, humidity, pH, ultraviolet radiation, or microbial activity independently. Relatively few studies systematically evaluated the combined effects of multiple environmental stressors, limiting

current understanding of synergistic degradation mechanisms.

3. Reliance on observational and case-based evidence: A significant proportion of forensic DNA degradation research is based on field observations, forensic case reports, or retrospective analyses rather than controlled laboratory experiments. Such studies provide valuable real-world evidence but often lack adequate environmental effect.
4. Difficulty standardising environmental conditions: Factors such as seasonal variation, fluctuating temperatures, soil chemistry, burial depth, microbial ecology, scavenger activity, water exposure, and local climate conditions can substantially influence DNA preservation. These variables are difficult to standardise and may contribute to inconsistencies between studies.
5. Use of accelerated degradation models: Many investigations simulate long-term degradation through exposure to elevated temperatures, extreme humidity, or chemically aggressive environments over short periods. While useful for understanding degradation pathways, these models may not fully replicate natural decomposition processes encountered in forensic settings.
6. Sampling bias toward commonly encountered forensic materials: The majority of available studies focus on blood, saliva, buccal swabs, touch DNA, bone, and teeth. Comparatively fewer studies investigate degradation patterns in tissues such as liver, brain, spleen, kidney, lung, adipose tissue, skin, fingernails, and toenails, limiting comprehensive tissue-specific comparisons.
7. Challenges in post-mortem interval estimation: Although DNA degradation has been proposed as a potential marker for estimating post-mortem interval, degradation rates are influenced by numerous confusing variables, including environmental conditions, tissue characteristics, microbial activity, and individual biological variation. These factors currently restrict its reliability as a standalone PMI indicator.
8. Dependence on qualitative evidence in some sources: Authoritative forensic textbooks and review resources provided important mechanistic and forensic context; however, some sources contained qualitative descriptions rather than detailed quantitative measurements. Therefore, certain conclusions relied on consensus interpretation rather than direct numerical comparison.
9. Potential publication bias: Studies reporting statistically significant or positive findings are generally more likely to be published than studies reporting negative, inconclusive, or null results. As a result, the available literature may not fully represent the complete body of evidence regarding DNA degradation.
10. Possible omission of grey literature: Conference proceedings, institutional reports, technical documents, government publications, dissertations, and unpublished forensic case studies were not included and may contain relevant information not captured in the present review.
11. Language-related limitations: The review primarily included English-language publications. Relevant studies published in other languages, particularly region-specific forensic and decomposition research, may therefore have been overlooked.
12. Rapidly evolving nature of forensic genetics: Advances in next-generation sequencing, microhaplotypes, SNP-based identification systems, forensic epigenetics, forensic microbiomics, and artificial intelligence-assisted degradation modelling continue to emerge. Future discoveries may refine, expand, or modify some conclusions presented in this review.

Collectively, these limitations highlight the need for standardised methodologies, long-term environmental studies, comprehensive multi-factor experimental designs, broader tissue comparisons, and improved reporting practices to strengthen future research on forensic DNA degradation and preservation.

Future Directions

Although significant advancements have been made in understanding forensic DNA degradation, important

research gaps still remain that justify further investigation. Future studies should prioritise controlled multi-factor experimental designs that simultaneously evaluate temperature, humidity, pH, ultraviolet radiation, microbial activity, and tissue type under standardised conditions. Most existing studies examine these variables independently, limiting our understanding of their combined effects on DNA persistence. Long-term environmental studies conducted under realistic outdoor conditions are also needed to complement accelerated laboratory degradation experiments and better reflect natural forensic scenarios. The attention should be given to geographically diverse climates, seasonal variation, burial environments, aquatic settings, and fluctuating environmental exposures that more accurately represent real-world casework. [3,6] Also, comparative investigations involving a broader range of biological substrates are required. Current forensic knowledge is largely based on blood, saliva, touch DNA, bone, and teeth, whereas tissues such as spleen, lung, kidney, brain, adipose tissue, skin swabs, fingernails, and toenails remain insufficiently studied. Comprehensive tissue-specific degradation studies would improve evidence recovery strategies and assist forensic practitioners in selecting optimal sampling sites across different stages of decomposition. [3,4,9,10] Furthermore, greater emphasis should be placed on understanding microbial influences on DNA degradation. Environmental microorganisms and post-mortem microbial succession play critical roles in decomposition processes, yet their interactions with environmental variables and tissue characteristics remain incompletely understood. Future forensic microbiome research may help establish more accurate models of DNA persistence and decomposition dynamics. [7,8]

Advancement in quantitative modelling and analytical technologies also represent promising directions for future research. The development of predictive degradation models based on chemical kinetics, including hydrolysis, depurination, oxidation, and Arrhenius-based reaction principles, may improve estimation of DNA survival under varying environmental conditions. [1,5] Integration of machine learning and artificial intelligence approaches with large forensic datasets could further enhance predictions of DNA preservation and potentially contribute to post-mortem interval estimation. On the analytical side, continued development of degradation-resistant genetic typing systems is essential. MiniSTR assays have already demonstrated improved performance with fragmented DNA, and future marker systems should continue to target shorter amplicons and incorporate more robust amplification chemistries.[13] Also, the emerging technologies such as next-generation sequencing, SNP panels, microhaplotypes, and mitochondrial genome sequencing offer considerable potential for analysing highly degraded forensic samples that fail conventional STR analysis.[12] Future studies should also focus on standardising experimental methodologies, DNA quantification approaches, degradation indices, and reporting practices to improve reproducibility and facilitate comparison between studies. Increased incorporation of degradation science into forensic training programmes, laboratory protocols, evidence-handling procedures, and interpretation guidelines will help ensure that environmental effects are appropriately considered throughout forensic investigations. and these advances will strengthen the scientific understanding of DNA degradation, improve evidence recovery from challenging samples, and enhance the reliability of forensic genetic identification. [1,3,6]

CONCLUSION

DNA degradation represents one of the most significant challenges in forensic genetics because the successful recovery and interpretation of genetic evidence depend fundamentally on the preservation of DNA integrity. The findings synthesized in this review demonstrate that DNA persistence is not governed by a single factor but rather by a complex interplay between environmental conditions and tissue-specific biological characteristics. Temperature, moisture, pH, microbial activity, ultraviolet radiation, and intrinsic tissue properties collectively determine the extent to which DNA remains suitable for forensic analysis. Understanding these interactions is therefore essential for evidence collection, preservation, laboratory processing, and the interpretation of forensic genetic profiles. [1,3,6]

Among the papers examined, temperature emerged as one of the most influential determinants of DNA stability. Elevated temperatures accelerate hydrolysis, oxidation, depurination, and enzymatic degradation, leading to progressive fragmentation of DNA molecules and reduced amplifiability. [1,5] The literature constantly demonstrates that warm environments promote both chemical decay and microbial activity, thereby accelerating DNA deterioration. Conversely, refrigeration and freezing substantially retard degradation processes, preserving DNA integrity over extended periods. These observations reinforce the long-established forensic principle that prompt cooling of biological evidence is one of the most effective methods of maintaining DNA quality. [1,3,6]

Moisture similarly plays a critical role in DNA preservation. Water acts as a reactant in hydrolytic degradation pathways and simultaneously supports microbial proliferation. [6,7,8] as a result, humid environments frequently produce more rapid DNA degradation than dry environments. The combination of moisture and elevated temperature is particularly destructive because it promotes both chemical and biological mechanisms of decay. Evidence exposed to humid conditions therefore experiences accelerated fragmentation, reduced DNA yield, and diminished forensic utility. These findings emphasise the importance of drying biological evidence prior to storage and preventing prolonged exposure to moisture throughout the chain of custody. [3,6]

Environmental pH was also identified as a major contributor to DNA degradation. Acidic conditions enhance depurination and hydrolytic cleavage, while alkaline environments promote denaturation and strand instability. [1,5,17] Although most forensic samples are encountered under near-neutral conditions, exposure to acidic soils, industrial chemicals, cleaning agents, or alkaline substances can significantly compromise DNA preservation. The literature indicates that maintaining neutral or slightly alkaline storage conditions remains one of the most effective strategies for protecting extracted DNA and biological evidence from chemically induced degradation. [5]

A major contribution of this review is the integration of environmental factors with tissue-specific preservation patterns. Different biological substrates exhibit substantial variation in DNA content, structural protection, enzymatic activity, and susceptibility to decomposition. Soft tissues such as liver and skeletal muscle initially provide abundant DNA but are highly vulnerable to autolysis and microbial degradation after death.[3] on the other hand, mineralised tissues such as bone and teeth offer exceptional long-term preservation because their protective matrices shield DNA from environmental insults and microbial invasion.[4,9,10] Hair roots can provide substantial amounts of nuclear DNA when intact, whereas hair shafts are generally limited to mitochondrial DNA analysis.[11,12] Nails occupy an intermediate position, providing limited but occasionally valuable forensic genetic material. Collectively, these findings demonstrate that the choice of biological substrate is often as important as the environmental conditions under which evidence is recovered.

The review further highlights the importance of considering synergistic interactions among environmental variables. Temperature, moisture, pH, microbial activity, and ultraviolet radiation rarely operate independently in real forensic situations. Rather, they interact to produce degradation rates that frequently exceed the effects predicted from individual factors alone.[6,8] Warm and humid environments, for example, simultaneously enhance hydrolysis, oxidation, microbial growth, and enzymatic activity, creating conditions that are particularly destructive to DNA preservation. Such synergistic effects explain why biological evidence recovered from tropical climates, submerged remains, shallow burials, or poorly preserved crime scenes often exhibits extensive degradation. Recognition of these interactions is critical for accurate forensic interpretation and evidence management.

The forensic implications of DNA degradation extend beyond simple reductions in DNA quantity. Progressive fragmentation directly affects STR profiling by increasing the likelihood of locus failure, peak imbalance, and allelic dropout.[3,13,21,22] Larger STR loci are disproportionately affected because intact template molecules become increasingly rare as degradation progresses. Together, degraded samples frequently produce partial profiles with reduced discriminatory power and increased interpretative uncertainty. Advances such as miniSTRs, SNP-based systems, microhaplotypes, and next-generation sequencing technologies offer promising solutions for analysing compromised DNA, but DNA integrity remains a central determinant of forensic success.[21,22,23]

Despite considerable advances in forensic DNA research, significant knowledge gaps remain. The literature continues to be dominated by single-factor studies, accelerated degradation experiments, and investigations focused primarily on blood, saliva, and touch DNA. Comprehensive multi-factor experiments, long-term environmental studies, and broader investigations of diverse tissue types are still needed to improve predictive models of DNA persistence. Emerging approaches involving machine learning, forensic microbiomics, and quantitative degradation modelling may substantially enhance future understanding of DNA preservation and its forensic applications.[6,7,8]

Together, the evidence reviewed herein demonstrates that DNA degradation is a dynamic and multifactorial process shaped by both environmental exposure and tissue-specific characteristics. High temperature, high moisture, and extreme pH conditions accelerate DNA deterioration through interconnected chemical,

enzymatic, and microbial pathways, whereas cold, dry, and chemically stable environments promote preservation. Hard tissues such as bone and teeth consistently provide the greatest long-term protection, while soft tissues exhibit more rapid post-mortem degradation. The interaction of these factors ultimately determines whether DNA remains suitable for forensic identification.

From a practical perspective, the findings of this review reinforce several fundamental forensic principles: biological evidence should be collected as rapidly as possible, protected from heat and moisture, stored under appropriate environmental conditions, and sampled strategically according to tissue type and preservation status. In cases involving advanced decomposition, environmental exposure, or challenging recovery conditions, prioritising resilient substrates such as teeth and dense cortical bone can substantially improve the likelihood of successful DNA analysis. [4,9,10]

A comprehensive understanding of environmental and tissue-specific influences on DNA degradation is essential for modern forensic science. By integrating current evidence on temperature, moisture, pH, tissue preservation, synergistic degradation mechanisms, and forensic implications, this review provides a consolidated framework for understanding DNA persistence in forensic contexts. Such knowledge not only improves evidence recovery and interpretation but also strengthens the scientific reliability of forensic genetic identification, ultimately supporting the pursuit of accurate and defensible justice.

REFERENCES

1. Lindahl T. Instability and decay of the primary structure of DNA. *Nature*. 1993;362(6422):709-715. Available at: **https://doi.org/10.1038/362709a0**
2. Butler, J.M.. (2012). Advanced Topics in Forensic DNA Typing: Methodology. https://doi.org/10.1016/C2011-0-04189-3
3. Alaeddini R, Walsh SJ, Abbas A. Forensic implications of genetic analyses from degraded DNA. *Forensic Science International: Genetics*. 2010;4(3):148-157. Available at: **https://doi.org/10.1016/j.fsigen.2009.09.007**
4. Campos PF, Craig OE, Turner-Walker G, Peacock E, Willerslev E, Gilbert MTP. DNA in ancient bone: where is it located and how should we extract it? *Annals of Anatomy*. 2012;194(1):7-16. Available at: **https://doi.org/10.1016/j.aanat.2011.07.003**
5. An R, Jia Y, Wan B, Zhang Y, Dong P, Li J, Liang X. Non-enzymatic depurination of nucleic acids: factors and mechanisms. *PLoS One*. 2014;9(12):e115950. Available at: **https://doi.org/10.1371/journal.pone.0115950**
6. Bruni M, Bini C, Chiaramonte F, et al. Environmental effects on DNA preservation in forensic samples. *Egyptian Journal of Forensic Sciences*. 2024;14:24. Available at: **https://doi.org/10.1186/s41935-024-00389-y**
7. Nielsen KM, Johnsen PJ, Bensasson D, Daffonchio D. Release and persistence of extracellular DNA in the environment. *Environmental Biosafety Research*. 2007;6(1-2):37-53. Available at: **https://doi.org/10.1051/ebr:2007031**
8. Hyde ER, Haarmann DP, Lynne AM, Bucheli SR, Petrosino JF. The living dead: bacterial community structure of a cadaver during decomposition. *PLoS One*. 2013;8(10):e77733. Available at: **https://doi.org/10.1371/journal.pone.0077733**
9. Loreille OM, Diegoli TM, Irwin JA, Coble MD, Parsons TJ. High efficiency DNA extraction from bone by total demineralization. *Forensic Science International: Genetics*. 2007;1(2):191-195. Available at: **https://doi.org/10.1016/j.fsigen.2007.02.006**
10. Higgins D, Austin JJ. Teeth as a source of DNA for forensic identification. *Australian Journal of Forensic Sciences*. 2013;45(4):421-431. Available at: **https://doi.org/10.1080/00450618.2013.784356**
11. Linch CA, Smith SL, Prahlow JA. Evaluation of the human hair root for DNA typing. *Journal of Forensic Sciences*. 1998;43(2):305-314. Available at: **https://doi.org/10.1520/JFS16126J**
12. Wilson MR, DiZinno JA, Polanskey D, Replogle J, Budowle B. Validation of mitochondrial DNA sequencing for forensic casework analysis. *International Journal of Legal Medicine*. 1995;108(2):68-74. Available at: https://doi.org/10.1007/BF01369907

13. Opel KL, Chung DT, Drábek J, McCord BR. The application of miniplex primer sets in DNA degradation analysis. *Journal of Forensic Sciences*. 2006;51(2):351-356. Available at: https://doi.org/10.1111/j.1556-4029.2006.00077.x
14. Jeffreys AJ, Wilson V, Thein SL. Individual-specific fingerprints of human DNA. *Nature*. 1985;316(6023):76-79. Available at: https://doi.org/10.1038/316076a0
15. Goodwin W, Linacre A, Hadi S. *An Introduction to Forensic Genetics*. 3rd ed. Chichester: Wiley-Blackwell; 2011.
16. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71. Available at: **https://doi.org/10.1136/bmj.n71**
17. Thomas CA Jr, Doty P. *The Mild Acidic Degradation of Deoxyribose Nucleic Acid*. Journal of the American Chemical Society. 1956;78(9):1854-1860. Available at: **https://doi.org/10.1021/ja01590a023**
18. Davoren J, Vanek D, Konjhodzić R, Crews J, Huffine E, Parsons TJ. Highly effective DNA extraction method for nuclear short tandem repeat testing of skeletal remains from mass graves. Croat Med J. 2007 Aug;48(4):478-85. PMID: 17696302; PMCID: PMC2080566.
19. Loreille OM, Parr RL, McGregor KA, Fitzpatrick CM, Lyon C, Yang DY, Speller CF, Grimm MR, Grimm MJ, Irwin JA, Robinson EM. Integrated DNA and fingerprint analyses in the identification of 60-year-old mummified human remains discovered in an Alaskan glacier. J Forensic Sci. 2010 May;55(3):813-8. doi: 10.1111/j.1556-4029.2010.01356.x. Epub 2010 Apr 2. PMID: 20384910.
20. Butler, J.M.. (2014). Advanced Topics in Forensic DNA Typing: Interpretation. Advanced Topics in Forensic DNA Typing: Interpretation. 1-585.
21. Butler JM, Shen Y, McCord BR. The development of reduced size STR amplicons as tools for analysis of degraded DNA. J Forensic Sci. 2003 Sep;48(5):1054-64. PMID: 14535668.
22. Coble MD, Butler JM. Characterization of new miniSTR loci to aid analysis of degraded DNA. J Forensic Sci. 2005 Jan;50(1):43-53. PMID: 15830996.
23. Phillips C, Gettings KB, King JL, Ballard D, Bodner M, Børsting C, et al. The devil's in the detail: Release of an expanded, enhanced and dynamically revised forensic STR Sequence Guide. *Forensic Science International: Genetics*. 2018;34:162-169.