

Review Article

The Limits of Forensic Faith: Understanding Potential Failures in DNA Evidence

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Abstract

DNA evidence has become a cornerstone of modern forensic science, widely regarded for its unparalleled accuracy in identifying suspects and exonerating the innocent. However, the growing reliance on DNA analysis in legal proceedings often overlooks its inherent limitations and vulnerabilities. This review critically examines the potential sources of error and failure in forensic DNA analysis, including contamination, degradation, low-template samples, interpretive bias, statistical misrepresentation, and human error. It also addresses the legal and ethical challenges associated with DNA databases, proprietary software, and public misconceptions driven by media influence - the so-called "CSI Effect." Through the lens of real-world case studies and emerging technologies such as massively parallel sequencing and DNA phenotyping, the article underscores the urgent need for robust quality assurance, transparent reporting, continuous training, and judicial literacy. By highlighting both the promise and pitfalls of DNA evidence, this review calls for a cautious, scientifically grounded, and ethically informed approach to ensure its effective and just application in forensic practice.

Key words

DNA evidence, forensic medicine, contamination, interpretive bias, probabilistic genotyping, CSI effect, chain of custody, legal admissibility, ethical governance, wrongful conviction.

Introduction

Since its forensic application began in the mid-1980s, DNA evidence has revolutionized criminal investigations by enabling precise identification of individuals, excluding all but identical twins, and helping to both implicate and exonerate suspects with remarkable accuracy [1, 2]. Techniques such as short tandem repeat (STR) profiling and mitochondrial DNA (mtDNA) analysis have earned DNA evidence the title of forensic science's "gold standard," due to their powerful statistical discriminability [1].

Despite this status, DNA evidence is not inherently infallible. Its reliability is entirely dependent on strict adherence to protocols governing collection, preservation, amplification, analysis, and interpretation. Any compromise in these stages can introduce significant risks, including false inclusions, erroneous exclusions, or complete investigative failure [3, 4]. Moreover, degradation of biological samples, contamination, procedural lapses, misinterpretation, and biased statistical communication can all erode the evidentiary value of DNA [5–7].

Real-world case failures - ranging from laboratory errors to contamination and interpretive bias - demonstrate that DNA evidence is vulnerable to error at every stage of the forensic pipeline [6, 8]. Further complicating its use is the "CSI Effect," wherein media portrayals create unrealistic expectations among jurors and legal practitioners, sometimes elevating flawed DNA findings above other forms of evidence [9].

This review explores the potential sources of failure within forensic DNA analysis, drawing from high-profile miscarriages of justice and scientific literature to emphasize the need for rigorous quality assurance, continuous analyst training, transparent statistical reporting, and enhanced legal literacy. Only through such vigilance can DNA evidence maintain its role as

a reliable ally in the fair administration of justice [10, 11].

The Promise and Perils of DNA Analysis

DNA, the fundamental molecule of inheritance, harbors the unique genetic blueprint of every individual. Forensic DNA analysis exploits the variability in specific loci - most commonly short tandem repeats (STRs) - to generate individual genetic profiles. By comparing DNA recovered from crime scenes with known samples, forensic scientists can either implicate or exclude individuals with high confidence [2].

The probative value of DNA evidence lies in its immense statistical power. Properly conducted STR analysis can yield random match probabilities as low as one in several billion, depending on the number and variability of loci examined [1, 12]. This statistical weight has led to broad judicial acceptance, and in many jurisdictions, DNA evidence carries decisive influence on judicial outcomes [5].

Nevertheless, the interpretation of DNA evidence is fraught with practical and scientific challenges. The reliability of a DNA match is not intrinsic but conditional - dependent on stringent adherence to protocols from sample collection through to analysis. Factors such as environmental degradation, sample contamination, low DNA quantity, and interpretive complexity in mixed samples can introduce ambiguity or error [3, 4].

Compounding these technical issues is the risk of overinterpretation. Jurors, influenced by the perceived objectivity of DNA, may overlook its limitations, while forensic analysts may face pressures to draw conclusions from borderline or incomplete profiles [6]. As such, while DNA remains a powerful investigative tool, its utility is maximized only when applied with scientific rigor, methodological transparency, and contextual restraint.

Sources of Failure in DNA Evidence

Despite its scientific precision, DNA evidence is highly susceptible to failure due to various factors that compromise its integrity throughout the forensic pipeline. One of the most critical and frequent vulnerabilities is contamination, which can occur at multiple stages - from crime scene collection to laboratory analysis - undermining the evidentiary value of DNA and potentially leading to miscarriages of justice [2, 3].

Sample Contamination

DNA contamination involves the inadvertent introduction of extraneous DNA into evidentiary samples. Even trace amounts from investigators, crime scene personnel, medical responders, or equipment can compromise the accuracy of profiling. Given the sensitivity of modern amplification techniques, such low-level DNA can distort the original signal, especially in low-template samples [4, 6].

Mechanisms of Contamination

- **Crime Scene Contamination:** Uncontrolled environments increase the risk of foreign DNA deposition from individuals present at the scene, including first responders, onlookers, or even the victim [2].
- **Cross-Contamination:** Concurrent processing of multiple items in forensic labs without strict sterilization protocols can lead to DNA transfer between unrelated samples [3].
- **Touch DNA and Primary Transfer:** Actions such as coughing, sneezing, or handling surfaces without proper protection can deposit microscopic amounts of DNA, leading to misleading associations [4].
- **Secondary and Tertiary Transfer:** DNA may transfer from one object to another via indirect contact - such as through shared surfaces or personnel - complicating attribution and potentially resulting in false matches [6, 12].

Consequences of Contamination

- **Interpretive Complexity:** Contaminated samples often yield complex or mixed

DNA profiles, complicating deconvolution and increasing the likelihood of misinterpretation [1].

- **False Inclusions:** Innocent individuals may be falsely implicated when contaminant DNA aligns with their genetic profile [8].
- **Masking True Contributors:** Excess or dominant foreign DNA can obscure the actual perpetrator's profile, impeding detection and compromising evidentiary value [1].
- **Uninterpretable Results:** In some cases, DNA mixtures may become too ambiguous to interpret reliably, stalling or misleading investigations [3, 5].

To uphold the integrity of DNA evidence, stringent contamination control protocols must be enforced at every stage - crime scene collection, transport, laboratory handling, and analysis. This includes using personal protective equipment, segregating samples, validating sterilization methods, and documenting chain-of-custody procedures rigorously [11].

Sample Degradation or Insufficient Samples

The reliability of forensic DNA analysis depends heavily on the quality and quantity of the biological material collected. Environmental exposure to heat, ultraviolet radiation, moisture, and microbial activity can lead to progressive DNA degradation, fragmenting the molecule and reducing its amplifiable content [2, 3]. This degradation compromises the generation of complete profiles and weakens the statistical confidence in DNA matches.

Degraded DNA often results in partial or low-quality profiles, which may omit crucial alleles or introduce artifacts during polymerase chain reaction (PCR) amplification. Additionally, degradation byproducts can inhibit enzymatic reactions, leading to allelic dropout, preferential amplification, or complete PCR failure [1, 7].

Similarly, samples containing minute amounts of starting material - such as trace biological fluids or "touch DNA" - may fall below the threshold necessary for reliable analysis. These insufficient samples are particularly vulnerable to stochastic effects during amplification and pose a heightened risk of contamination or interpretive error [4].

Such limitations not only reduce the evidentiary value of DNA but also complicate the probabilistic frameworks used to assess match strength, thereby increasing the potential for ambiguous or misleading results in judicial settings [3, 10].

Low Template DNA (ltDNA)

Low template DNA (ltDNA) analysis refers to profiling extremely small quantities of DNA - typically below 100 picograms - often obtained from minimal biological material such as skin cells on touched objects [2]. Despite advances in amplification sensitivity, ltDNA analysis remains fraught with interpretive complexity due to stochastic variation in polymerase chain reaction (PCR) outcomes [3].

A major concern is allelic dropout, where one allele in a heterozygous pair fails to amplify, and allelic drop-in, where extraneous alleles appear in the profile due to random amplification artifacts [1]. These effects challenge the reliability of conclusions drawn from ltDNA, particularly in mixed samples.

The risk of contamination is also magnified. When working with minuscule DNA quantities, even trace contamination from laboratory environments or handlers can produce misleading results or obscure the original genetic profile [4]. Moreover, partial profiles generated under these conditions can increase subjectivity in interpretation, amplifying the role of analyst discretion and potentially introducing bias [6].

As such, while ltDNA technology broadens forensic capabilities, its interpretive limitations

demand caution. Enhanced guidelines, conservative thresholds for interpretation, and thorough documentation are essential to mitigate the risks of misattribution or wrongful implication [12].

Laboratory Errors

Even in highly accredited forensic laboratories, DNA analysis is susceptible to human and technical errors, which can jeopardize the evidentiary integrity and lead to flawed outcomes [7]. Sample mix-ups during labeling or transfer can incorrectly associate DNA profiles with individuals, especially when chain-of-custody protocols are inadequately enforced [11].

Reagent contamination - the introduction of extraneous DNA through improperly sterilized consumables - can produce false positives or lead to misinterpretation of mixed profiles [8]. Additionally, instrumental failures, including software glitches or calibration issues in thermocyclers or capillary electrophoresis systems, can distort electropherogram readings and compromise data reliability [9].

PCR itself introduces vulnerability. Common issues include:

- **Primer-dimer formation**, where primers bind to each other instead of target sequences;
- **Non-specific amplification**, where unintended sequences are amplified;
- **Preferential amplification**, where one allele is overrepresented, skewing heterozygous loci [13].

Even more concerning are systemic failures stemming from malpractice or misconduct. Notable cases - such as those involving Annie Dookhan and Joyce Gilchrist - highlight how unethical practices like evidence fabrication or data misrepresentation can undermine justice and erode public trust in forensic science [5, 14].

Inadequate standardization, poor oversight, and pressure to produce favorable outcomes can

distort objectivity. Therefore, robust quality assurance measures, blind proficiency testing, and an unwavering commitment to scientific impartiality are essential to maintain the credibility of DNA laboratories [3, 10].

Interpretation Bias

DNA evidence is often regarded as scientifically objective; however, its interpretation - particularly in cases involving low template or mixed DNA samples - can be highly subjective and susceptible to cognitive biases. Forensic analysts, while trained to be impartial, do not operate in a vacuum. Exposure to extraneous case information, such as a suspect's identity, criminal history, or law enforcement expectations, may unconsciously influence their interpretations [6, 3].

Two dominant forms of cognitive bias are particularly concerning in forensic DNA analysis:

- **Contextual Bias** arises when irrelevant external information skews the analyst's perception. For example, knowing that a suspect has a prior conviction may subtly shape how an ambiguous or partial DNA mixture is evaluated, potentially favoring inclusion [15]. Studies have shown that analysts exposed to such information are more likely to interpret data in a direction consistent with the provided context [16].
- **Confirmation Bias** involves the tendency to favor interpretations that align with pre-existing expectations or hypotheses. In practice, analysts may unconsciously seek out data that supports the prosecution's theory or dismiss conflicting evidence that might suggest an alternative explanation [17].

Such biases are particularly dangerous when interpreting complex DNA mixtures or borderline profiles where discretion plays a central role. Given the potential for subjectivity, safeguards such as blind interpretation, peer

review, and rigorous training in cognitive bias awareness are essential to preserve scientific objectivity and protect the integrity of DNA evidence in judicial proceedings [1, 3].

Statistical Interpretation

The probative value of DNA evidence in legal contexts is largely derived from statistical analyses, particularly the random match probability (RMP) - a measure estimating the likelihood that a randomly selected individual from a reference population would share the same DNA profile as that found at a crime scene [1]. When calculated appropriately, RMP figures can reach one in billions, creating a perception of near certainty in identification.

However, misinterpretation or misuse of these statistics poses significant risks. Jurors, attorneys, and even judges may misunderstand what the RMP represents, often confusing the probability of a coincidental match with the probability of a defendant's innocence or guilt - a cognitive error commonly referred to as the "prosecutor's fallacy" [10, 12].

This fallacy conflates conditional probabilities: it assumes that a low probability of a random match implies a high probability of guilt, disregarding other contextual or exculpatory evidence [18]. Moreover, RMPs are often based on assumptions of population independence and completeness of reference databases. When a match is discovered through a database search rather than a targeted comparison, the actual statistical weight of the evidence can be significantly lower than reported - a phenomenon known as the "database search problem" [6].

Another challenge lies in effectively communicating these statistical nuances to lay audiences. DNA analysts must clearly differentiate between the rarity of a profile and the likelihood of a suspect's involvement. Failure to do so can inflate the perceived reliability of DNA evidence, especially in cases where profiles

are partial, degraded, or derived from mixtures [8, 3].

To mitigate these risks, courts and forensic practitioners must ensure that expert testimony accurately conveys the limitations of probabilistic assessments. This includes the use of visual aids, plain-language analogies, and transparent disclosures about database origin, population assumptions, and potential sources of error [3, 10].

Human Error

Despite technological advancements and standardized protocols, human error remains a persistent and serious threat to the reliability of forensic DNA analysis. Errors can occur at multiple stages of the forensic process - from evidence collection and handling to data entry and result interpretation - each with the potential to undermine scientific accuracy and legal integrity [3, 7].

Common operational errors include sample mislabeling, mishandling, or storage failures, which can result in cross-contamination, sample degradation, or the wrongful association of DNA profiles with individuals not connected to the crime [1]. Data entry mistakes in forensic databases such as CODIS may also lead to false matches or exclusions, particularly when oversight mechanisms are weak or absent [5].

In addition to these technical lapses, subjective interpretation of complex DNA mixtures further increases the risk of human influence on results. Analysts working under time pressure or influenced by case-specific information may unconsciously favor outcomes aligned with investigative expectations, particularly when profiles are partial, degraded, or include multiple contributors [19].

These errors are not always due to negligence - they may result from cognitive limitations or institutional pressures. Nonetheless, they can have grave consequences, including wrongful

convictions, delayed justice, and diminished public trust in forensic science [6].

To mitigate human error, forensic laboratories must adopt rigorous quality assurance systems, implement double-blind procedures, encourage peer review, and promote continuous training in cognitive bias and human factors awareness [15].

Overreliance and the “CSI Effect”

The cultural portrayal of forensic science in popular media, particularly through crime dramas like *CSI*, has given rise to the so-called “CSI Effect”, a phenomenon that fosters unrealistic expectations about the infallibility and availability of DNA evidence in real-world legal settings [6, 20]. This effect can significantly distort courtroom dynamics, shaping juror perceptions and influencing prosecutorial and defense strategies.

Jurors heavily influenced by televised portrayals may anticipate high-tech forensic evidence in every case, often assuming that the absence of DNA testing undermines the prosecution’s case. As a result, circumstantial or eyewitness testimony may be unjustly undervalued, leading to acquittals despite strong non-DNA evidence [21, 22].

Conversely, the presence of DNA evidence - regardless of quality, context, or interpretive limitations - may be perceived as conclusive, overshadowing its probabilistic nature and susceptibility to error. This misplaced confidence can skew verdicts and create challenges for defense counsel, especially in cases involving complex or mixed DNA profiles [19].

The “CSI Effect” also pressures prosecutors to introduce forensic evidence even when it is unnecessary, straining laboratory resources and extending trial timelines. In some jurisdictions, prosecutors have responded proactively by addressing jurors’ forensic expectations during voir dire or trial, explaining the distinctions

between entertainment and actual forensic practice [3].

This phenomenon underscores a critical concern in forensic communication: the gap between public perception and scientific reality. If left unaddressed, the overreliance on DNA evidence as a gold standard can erode legal fairness, reinforcing the myth of its infallibility rather than promoting an informed, critical evaluation of its strengths and limitations [5, 6].

Interpretative Challenges of Complex DNA Mixtures

Interpreting DNA profiles derived from mixed samples, such as those encountered in sexual assault cases or on shared surfaces, remains one of the most technically demanding aspects of forensic science. These samples may contain DNA from two or more individuals in varying quantities, complicating the identification of contributors and requiring probabilistic genotyping and sophisticated statistical modeling [1].

Advanced software tools like STRmix and TrueAllele have been developed to assist analysts in deconvoluting these complex mixtures. While these systems enhance objectivity and reproducibility, they also raise concerns about transparency, as their proprietary algorithms are often not fully accessible for independent verification [3, 23]. This lack of transparency has led to legal disputes over admissibility and has fueled criticism about overreliance on black-box tools in contexts where liberty is at stake [24].

Additionally, the statistical outputs of these systems - often expressed in terms of likelihood ratios - are not easily interpretable by laypersons. Judges and juries may struggle to grasp the evidentiary weight, especially in cases involving partial, degraded, or low-template profiles [25]. Without careful explanation, there is a risk of misinterpretation or undue confidence in results that are inherently probabilistic.

When DNA Evidence Fails: Real-World Case Studies

Several high-profile cases have exposed the fallibility of DNA evidence when protocols are not rigorously followed or interpretations are flawed. These examples underscore the need for transparency, robust validation, and critical oversight.

- **Amanda Knox Case (Italy):** Knox was convicted partly on low-template DNA recovered from a knife, but a later review found major flaws in collection and interpretation, leading to her acquittal. This case highlights the dangers of contamination and analyst overreach in interpretation [5].
- **Phantom of Heilbronn (Germany):** A mysterious female DNA profile was found at over 40 crime scenes across Europe, only to be traced to contaminated cotton swabs used in evidence collection. This case exemplifies how contamination at the manufacturing level can generate massive investigative errors [2].
- **Sean Hodgson (UK):** Wrongly convicted based on outdated serological evidence, Hodgson was later exonerated through DNA testing, illustrating how outdated forensic methods can lead to grave miscarriages of justice [26].
- **Adam Scott (UK):** Scott was falsely accused when his DNA was detected on a rape victim. Investigation revealed that the DNA had been transferred during test kit production. This emphasizes the importance of considering non-crime-related transfer mechanisms [27].
- **Lukis Anderson (USA):** Anderson's DNA was found on a murder victim, but he was in the hospital at the time. The transfer occurred via a paramedic's contaminated equipment, showing that presence of DNA does not equate to culpability [28].
- **Josiah Sutton (USA):** Convicted of rape based on misinterpreted mixed DNA profiles, Sutton served four years before

re-analysis cleared him. This case illustrates the consequences of poor mixture interpretation and lack of transparency in expert testimony [6].

These cases collectively demonstrate that while DNA evidence is powerful, its misuse or misinterpretation can lead to wrongful convictions. Ongoing validation, stringent contamination controls, and judicial caution are critical to safeguarding its role in forensic justice [3, 19].

Safeguarding the Integrity of DNA Evidence

To preserve the scientific credibility and legal reliability of DNA evidence, a comprehensive framework of procedural, technical, and ethical safeguards must be enforced throughout the forensic pipeline. These measures address not only contamination and analytical errors, but also mitigate interpretive bias, promote transparency, and ensure just application in legal contexts.

- **Rigorous Crime Scene Management** is essential to prevent contamination. This includes using personal protective equipment (PPE), controlled evidence collection procedures, detailed scene documentation, and contamination logs [11].
- An **Unbroken Chain of Custody** ensures that every transfer of DNA evidence - from collection to courtroom - is documented, maintaining the sample's traceability and admissibility. Any lapses may compromise evidentiary integrity or raise doubts about tampering or substitution [3].
- **Accredited Forensic Laboratories** should follow internationally recognized standards (e.g., ISO/IEC 17025), undergo regular audits, and participate in **external proficiency testing** to maintain quality assurance and public confidence [7].
- Employing **Standardized Analytical Protocols** - including validated methods,

appropriate controls, and objective interpretation thresholds - helps reduce variability and enhances reproducibility of results across laboratories [1].

- **Continuous Training and Proficiency Assessment** are vital. Analysts must be regularly evaluated for competence, especially in interpreting complex DNA mixtures or low-template profiles [12].
- **Blind Proficiency Testing**, in which analysts are unaware of the correct results, can reveal vulnerabilities in interpretation and help uncover unconscious bias, thereby enhancing objectivity in casework [29].
- An **Independent Review Process** for critical or high-stakes cases enables cross-verification of findings and safeguards against individual or systemic oversight errors. This is especially crucial when interpreting probabilistic genotyping results [23].
- **Legal Stakeholder Education** - targeted training for judges, attorneys, and jurors - is necessary to foster informed evaluation of DNA evidence, including understanding limitations, statistical relevance, and common misinterpretations like the prosecutor's fallacy [25].
- **Transparent Forensic Reporting** should clearly outline the methods used, the limitations of the findings, and any uncertainties or assumptions, especially when probabilistic conclusions are presented [6].
- Lastly, **Ethical Oversight** in the handling and storage of DNA is essential. Issues such as informed consent, database inclusion criteria, and potential misuse of genetic information must be carefully managed to protect individual privacy and prevent discriminatory practices [14].

These multi-layered safeguards collectively serve to ensure that DNA evidence fulfills its promise

as a robust tool for justice, rather than a source of uncritical overreliance or legal error.

Legal and Ethical Considerations

The reliability of DNA evidence in legal proceedings hinges not only on scientific integrity but also on adherence to robust legal and ethical frameworks. As DNA analysis becomes more technologically complex and influential in courtrooms, ensuring its admissibility, fairness, and ethical governance is vital to upholding justice and public trust.

Admissibility Thresholds

Courts serve as critical gatekeepers in determining whether DNA evidence is scientifically valid and legally permissible. In the United States, the Daubert Standard requires that expert testimony - such as DNA evidence - be grounded in scientifically validated methodology, subjected to peer review, and widely accepted within the scientific community [12]. This standard also mandates that the methods be reliably applied in the specific case context.

In India, the Bharatiya Sakshya Adhinyam, 2023, Section 39, outlines the evidentiary thresholds for forensic testimony. It emphasizes that DNA evidence must be presented by qualified experts and supported by established protocols. Indian courts have increasingly required strict adherence to chain of custody, accreditation of laboratories, and expert qualifications to prevent misuse or overreliance on flawed evidence [30].

Guaranteeing a Fair Trial

The use of DNA evidence must be balanced against constitutional protections, such as Article 21 of the Indian Constitution (right to life and personal liberty) and the Sixth Amendment in the U.S. (right to confront witnesses). These rights are compromised when defense counsel is denied access to the raw data, lab records, or source code of proprietary algorithms used in

probabilistic genotyping tools like STRmix or TrueAllele [23].

Transparent disclosure is essential to allow independent re-analysis and meaningful cross-examination. Without it, the defense cannot effectively contest the findings or investigate potential errors - undermining the adversarial process and increasing the risk of wrongful conviction [5].

Ethical Governance of DNA Databases

The expansion of national and transnational DNA databases has amplified privacy and ethical concerns. Issues include the scope of consent, inclusion of arrestees or non-convicted individuals, and retention of genetic profiles without periodic review [14]. These concerns are particularly acute in marginalized communities, which may be disproportionately represented in databases due to systemic biases in policing and arrest patterns [9].

To safeguard civil liberties, legislative frameworks must enforce strict access controls, purpose limitations, and independent oversight. Ethical governance should also address the potential for function creep - where DNA collected for one purpose (e.g., criminal investigation) is repurposed for surveillance or predictive policing, eroding public trust in forensic systems [3].

Strategies for Minimizing Errors in DNA Evidence Handling

To uphold the reliability and probative value of DNA evidence in forensic investigations, it is essential to implement multi-tiered strategies that address both technical and institutional vulnerabilities. These strategies must be grounded in scientific rigor, procedural integrity, and legal accountability.

- **Comprehensive Training and Quality Control:** Crime scene investigators and laboratory analysts must undergo regular, robust training in contamination prevention, evidence handling, and

cognitive bias mitigation. Independent audits and international accreditation (e.g., ISO/IEC 17025) help ensure sustained compliance with best practices [1, 3].

- **Transparent and Verifiable Analytical Tools:** The adoption of open-source or independently validated DNA analysis software can enhance scientific transparency and facilitate peer scrutiny, particularly for probabilistic genotyping. Independent expert review of findings - especially in complex or high-stakes cases - can serve as a critical safeguard against error or bias [23, 29].
- **Judicial Education and Oversight:** Given the interpretive complexity of DNA evidence, it is essential that judges and attorneys receive targeted education on forensic limitations. In India, Section 168 of the Bharatiya Sakshya Adhinyam, 2023, empowers courts to seek independent forensic expertise, thereby reinforcing impartiality and scientific accuracy in legal proceedings [31].
- **Chain of Custody Integrity:** Maintaining a secure and traceable chain of custody is foundational to preserving evidentiary reliability. Every transfer of biological material must be logged and monitored to prevent tampering, misidentification, or degradation [11].
- **Ethically Sound Legislation:** National legal frameworks, such as India's DNA Technology (Use and Application) Regulation Bill, 2019, aim to regulate the use of DNA in a manner that balances forensic utility with privacy rights. Such legislation should include provisions for consent, data security, and oversight to prevent misuse or unauthorized profiling - particularly of vulnerable populations [32].

By integrating these practices into forensic and judicial systems, stakeholders can reduce the risk of error, strengthen public trust, and ensure that

DNA evidence serves justice without compromising scientific integrity or civil liberties.

The Future of DNA Evidence

Rapid technological innovation continues to expand the capabilities of forensic DNA analysis, offering unprecedented sensitivity, resolution, and interpretive depth. Among the most transformative advancements is Massively Parallel Sequencing (MPS) - also known as Next-Generation Sequencing (NGS) - which allows for the simultaneous interrogation of hundreds of genetic markers. This enhances the power of discrimination, enables better resolution of complex DNA mixtures, and facilitates the analysis of degraded or low-template samples [1, 33].

Beyond STRs, emerging tools such as messenger RNA (mRNA) profiling and DNA phenotyping are being explored to provide additional layers of forensic intelligence. mRNA analysis can identify tissue types and body fluids, improving contextual interpretation of biological traces, while DNA phenotyping attempts to predict physical traits, biogeographic ancestry, or even age based on genetic markers [34, 35].

Despite these advances, heightened analytical sensitivity introduces new challenges, notably an increased vulnerability to trace contamination and incidental transfer. In such hyper-sensitive systems, even minute amounts of extraneous DNA can produce profiles that complicate or confound interpretation, especially when mixtures or indirect transfers are involved [4].

To responsibly harness these technologies, the forensic community must commit to rigorous validation, the development of standardized protocols, and ongoing training to ensure their appropriate implementation. Additionally, ethical and legal frameworks must evolve in parallel, particularly concerning privacy, consent, and the interpretation of probabilistic results [3, 14].

Thus, while the future of forensic DNA analysis promises greater accuracy and versatility, its success hinges on scientific caution, procedural integrity, and ethical foresight to ensure these tools advance justice without introducing new sources of error or inequity.

Discussion

While DNA evidence has revolutionized forensic science with its unparalleled power to identify or exclude suspects, its perceived infallibility often overshadows the complex realities of forensic application. This review demonstrates that the reliability of DNA evidence is conditional, not absolute - hinging on adherence to rigorous protocols across collection, analysis, interpretation, and courtroom presentation. Despite methodological advances, the potential for error remains substantial and multifaceted.

One of the most pressing concerns is contamination, which can occur at virtually any point in the forensic pipeline - from crime scene to laboratory analysis - and has been repeatedly implicated in wrongful convictions [2, 3, 6]. The infamous "Phantom of Heilbronn" case, wherein contaminated swabs led investigators astray for years, exemplifies the devastating consequences of overlooked contamination controls [2]. Equally concerning are the interpretive challenges posed by low-template and degraded samples. As DNA quantity diminishes, stochastic effects such as allelic dropout and drop-in increase, reducing reliability and inflating subjectivity [1, 4].

This subjectivity is further compounded by cognitive biases among analysts. Research has established that exposure to irrelevant contextual information - such as a suspect's identity or criminal history - can skew forensic interpretation, particularly in complex or ambiguous profiles [15, 16]. Cases like Josiah Sutton's wrongful conviction illustrate how flawed mixture interpretation, compounded by bias, can lead to egregious miscarriages of justice [6, 19].

Statistical miscommunication also undermines evidentiary integrity. Lay understanding of concepts such as random match probability (RMP) is limited, and when experts fail to adequately explain statistical nuances, jurors may fall prey to the "prosecutor's fallacy," equating rarity with guilt [10, 18]. Moreover, the increasing use of probabilistic genotyping software, while enhancing analytical power, raises legal and ethical concerns when proprietary algorithms prevent independent validation or meaningful cross-examination [23, 24].

Another significant distortion arises from the "CSI Effect," where media portrayals foster unrealistic expectations about the conclusiveness of DNA evidence. Jurors may demand DNA in every case or assign undue weight to inconclusive or low-quality profiles, influencing verdicts irrespective of the actual evidentiary context [20-22].

Despite its scientific rigor, DNA evidence is ultimately interpreted and presented by human actors within legal and institutional structures prone to error, bias, and external pressures. The cases of Amanda Knox, Adam Scott, and Lukis Anderson collectively underscore that DNA presence does not equate to culpability; transfer, contamination, or misinterpretation can easily confound justice [5, 27, 28].

Therefore, robust safeguards must be institutionalized to preserve the integrity of DNA evidence. These include blind proficiency testing, open-source analytical tools, judicial education, and strict chain-of-custody enforcement [3, 11, 23]. Legal systems must also recognize the need for transparency in probabilistic methodologies and ensure defendants' access to underlying data to uphold the right to a fair trial [12, 30].

Finally, as forensic DNA technology enters a new frontier with massively parallel sequencing and phenotyping, caution must guide adoption. Enhanced sensitivity increases susceptibility to

trace contamination and interpretive ambiguity, necessitating concurrent evolution in ethical oversight and methodological validation [3, 14, 33].

In sum, while DNA evidence remains a cornerstone of modern forensic science, it must be employed with humility, vigilance, and an unwavering commitment to scientific and legal integrity. Only then can it serve its true purpose - not as a symbol of certainty, but as a tool of justice grounded in transparency and accountability.

Conclusion

DNA evidence has undeniably revolutionized forensic science, providing a powerful tool for identifying perpetrators and exonerating the innocent with a level of precision previously unattainable. However, this transformative capability has also cultivated a perception of infallibility that often masks its vulnerabilities. As this review has outlined, errors in DNA analysis can arise from numerous sources - ranging from contamination and degradation to human bias, interpretive uncertainty, and flawed statistical communication. These risks, though mitigable through rigorous protocols, are not theoretical; they have manifested in real-world miscarriages of justice.

As forensic technologies grow more sophisticated - ushering in advanced methods like massively parallel sequencing and DNA phenotyping - so too does the potential for error, misapplication, and ethical controversy. The forensic and legal communities must therefore proceed not with blind faith, but with a critical, evidence-informed approach that emphasizes methodological transparency, continuous education, and procedural accountability.

Ultimately, DNA evidence is not a substitute for thorough investigation or judicial discernment. Its value lies in its responsible use - anchored in scientific integrity and ethical vigilance. Only through sustained commitment to these

principles can DNA maintain its status as a cornerstone of modern forensic science while safeguarding the rights and liberties of those it seeks to serve.

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