

## A Comprehensive Analysis of Challenges in DNA Profiling: Technical, Ethical, and Legal Issues in Forensic Science

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### Abstract

This study investigates the multifaceted challenges and evolving role of DNA profiling in the Indian criminal justice system, focusing on Karnataka. The primary objective is to identify and analyze the technical, ethical, and legal obstacles surrounding using DNA evidence in forensic investigations. Employing a doctrinal and analytical research design, the study draws on case law, statutory interpretation, and comparative insights from the United States and the United Kingdom to evaluate the admissibility, reliability, and judicial impact of DNA profiling in India. Findings reveal a growing reliance on DNA evidence in courts, particularly in cases involving homicide and sexual assault, while also highlighting systemic issues such as laboratory backlogs, inconsistent forensic standards, procedural lapses, and lack of a comprehensive DNA-specific legal framework. Ethical concerns regarding consent, data privacy, and misuse of forensic databases further complicate the landscape. The study calls for urgent reforms, including enacting a dedicated DNA law, standardized protocols, forensic training for law enforcement, and strengthened safeguards against evidence tampering. While DNA profiling holds immense potential for delivering justice and reinforcing evidentiary integrity, its effective utilization demands robust legal infrastructure, technical capacity, and ethical oversight.

**Keywords:** DNA Profiling, Forensic Science, Criminal Justice System, Admissibility of Evidence, Ethical Concerns and Digital Forensics.

### Introduction

#### Background and Context

DNA profiling has emerged as a transformative tool in forensic science, revolutionizing how crimes are investigated, suspects are identified, and justice is delivered. As a technique that leverages the uniqueness of an individual's genetic code, DNA profiling, also known as DNA fingerprinting, has provided forensic experts with unprecedented accuracy in linking individuals to crime scenes or eliminating them as suspects. From criminal investigations and paternity disputes to mass disaster victim identification, the applications of DNA profiling have become increasingly central to modern forensic practice.

In India, the integration of DNA profiling into the criminal justice system began in the late 1990s, coinciding with the development of forensic infrastructure and the evolution of scientific capabilities. However, despite its technological sophistication, DNA profiling faces multiple layers of challenges that span technical, ethical, and legal domains. These concerns

have gained renewed attention with the introduction of legislative reforms such as the Bharatiya Nyaya Sanhita, 2023, the Bharatiya Nagarik Suraksha Sanhita, 2023, and the Bharatiya Sakshya Adhinyam, 2023, which aim to replace the Indian Penal Code, the Criminal Procedure Code, and the Indian Evidence Act respectively. These reforms, though progressive in codifying procedures for the use of forensic evidence, also raise critical questions about privacy, data protection, and due process in collecting, storing, and applying DNA data.

While DNA profiling has proven invaluable in solving crimes and exonerating the innocent, as evidenced by initiatives like the Innocence Project in the United States, its implementation is fraught with challenges. Technical issues such as sample contamination, degradation, and the interpretation of mixed DNA profiles pose significant risks to the accuracy and reliability of forensic conclusions. These problems are further compounded by inconsistent adherence to standard operating procedures and gaps in laboratory accreditation across jurisdictions.

Ethically, the storage and use of genetic data raise profound concerns about individual privacy, consent, and potential misuse. The growing trend toward building national DNA databases, although beneficial for crime detection, carries with it the risk of genetic surveillance and discrimination. These issues necessitate a cautious and well-regulated approach to ensure that the benefits of DNA technology do not come at the cost of civil liberties.

This study aims to comprehensively analyze these technical, ethical, and legal challenges in DNA profiling, focusing on their implications for forensic science and criminal justice in India. By exploring real-world limitations, recent legislative developments, and best practices in forensic methodology, the study offers a nuanced understanding of the complex landscape in which DNA profiling operates. The ultimate goal is to inform policy, improve forensic reliability, and safeguard the rights of individuals in an era increasingly defined by genetic evidence.

## Review of Literature

**Kambiz Ghazinour et al. (2017)<sup>1</sup>** Kambiz Ghazinour et al. (2017) highlight that the exponential growth in data storage and usage has increased the risk of misuse, making stored data vulnerable to cyber-attacks. Their article, "*A Study on Digital Forensics Tools*," provides a comprehensive overview of digital forensic tools used by corporations, government agencies, and individuals to gather, extract, and present digital evidence. It emphasizes the evolving nature of cyber threats and the adaptability of these tools in legal and investigative contexts. While the paper offers clear comparisons and practical insights, it could further explore the integration of emerging technologies in forensic workflows. Overall, it is a valuable resource for experts and beginners in digital forensics.

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<sup>1</sup> Kambiz Ghazinour, Deep M. Vakharia, Krishna Chaitanya Kannaji & Rohit Satyakumar, *A Study on Digital Forensic Tools*, IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), held on (September 2017).

The paper by **S.K. Shali (2018)**<sup>2</sup> examines the legislative framework governing the role of forensic science in India's criminal justice system, highlighting why its application remains limited despite significant technological advancements. The paper "*Applicability of Forensic Science in Criminal Justice System in India*" thoroughly analyzes crime scene investigation, legal provisions, the restricted use of forensic evidence, systemic constraints, and landmark judgments. It emphasizes the need to reform India's legal and investigative structures to ensure effective and timely justice. The author combines technical insights with ethical considerations, making the study informative and reflective of forensic science's critical role in reinforcing the rule of law.

**Barani Manikantan (2019)**<sup>3</sup> states that "Forensic Criminology" presents a comprehensive study of the intersection between forensic science and criminology. The author effectively blends theory with case studies to demonstrate the real-world application of forensic techniques in the criminal justice system. Topics covered include the distinctions between criminology and forensics, crime detection methods, trace and hair analysis, gunshot residue and distance determination, forensic toxicology, odontology, psychology, and integrating forensic science into legal frameworks. The work also addresses constitutional and judicial perspectives and the limitations of forensic evidence in Indian courts. Written clearly and engagingly, this article is a valuable resource for students, professionals, and anyone involved in law enforcement or forensic investigation.

**Ragib Hasan et al. (2020)**<sup>4</sup> emphasize that with society's increasing reliance on digital technologies, cybercrime is on the rise, necessitating robust digital forensics practices. Their article, "Digital Forensics Education Modules for Judicial Officials," addresses the critical need to train law enforcement and judicial officers in understanding digital evidence. The work introduces specialized education modules designed to help judicial officials grasp the complexities of digital forensics, particularly in evolving technologies like cloud computing, IoT, and mobile devices. Through practical examples and case studies, the article illustrates the importance of digital evidence in criminal proceedings and highlights the role of an informed judiciary in upholding justice. It also touches on ethical issues and data privacy, reinforcing the need for responsible forensic practices. Overall, the article offers an innovative and timely framework to bridge the gap between law and technology, supporting the development of a more technologically competent legal system.

**Delia Magherescu's (2021)**<sup>5</sup> article "Challenges of the Forensic Science Facing New Technologies" explores the complex interplay between technological advancements and forensic science. The author discusses key themes such as the implications of artificial

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<sup>2</sup> S.K. Shali, *Applicability of Forensic Science in Criminal Justice System in India With Special Emphasis on Crime Scene Investigation* (Medico-Legal Desire Media and Publications, 2018).

<sup>3</sup> Barani Manikantan, "Forensic Criminology" 15 *CMR Law School, Bengaluru* 582 (2019).

<sup>4</sup> Ragib Hasan, Yuliang Zheng & Jeff Walker, *Digital Forensics Education Modules for Judicial Officials*, University of Alabama at Birmingham, Birmingham, AL, USA, held on (September 2020).

<sup>5</sup> Delia Magherescu, "Challenges of the Forensic Science Facing New Technologies" 7 *Lawyer, Gorj Bar Association, Romania* 2444 (2021).

intelligence in justice, conceptual frameworks for conducting forensic investigations using new technologies, and the broader consequences these technologies pose. With a focus on innovations like DNA profiling, biometrics, and digital forensics, the article highlights the transformative potential and the challenges these tools bring to criminal investigations. It further emphasizes the growing expertise gap as forensic professionals struggle to keep pace with rapidly evolving methodologies. Magherescu underscores the necessity of comprehensive training and strategic planning to equip experts with the skills needed for this new technological landscape. This article is a valuable resource for practitioners, scholars, and policymakers aiming to understand the evolving dynamics of forensic science in the digital era.

**Prithvi Raj (2022)**<sup>6</sup> offers an insightful analysis of how scientific evidence shapes fair trials within India's legal framework. The article covers core aspects such as research methodology, literature review, and key stages of medical examinations related to accused individuals, rape victims, and unnatural death cases. It highlights the pivotal role of forensic tools like DNA profiling, forensic ballistics, and digital forensics in corroborating facts during investigations. Drawing from real-life case studies, the author illustrates how these scientific techniques enhance the credibility of First Information Reports (F.I.R.s) and support the judiciary in establishing guilt or innocence. The paper also addresses the operational and legal challenges of integrating forensic evidence into the Indian criminal justice system. Overall, this work bridges the divide between science and law. It offers a practical and scholarly perspective, making it a valuable resource for legal professionals, forensic experts, and policy enthusiasts.

**Thakare V et al. (2023)**<sup>7</sup> reported Forensic Science Laboratories deal with many cases under various acts, including murder, accidents, poisoning, cheating, rape, paternity, illicit liquor, ballistics, cybercrime, and many more. The authors describe the Environment Protection Act (E. P. Act), enacted in 1986 to protect and improve the environment. The primary role of forensic science laboratories is to assist the judiciary system with examining physical, chemical, and biological evidence. The examination reports generated by forensic experts help punish criminals involved in many criminal cases. Besides the social cases, criminal acts related to environmental issues are now considered. Hence, keeping this point in mind, the National Green Tribunal (NGT) has taken different actions to control activities that are harmful to the environment in India.

### Objectives of the Study

The following objectives are formulated to guide the study:

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<sup>6</sup> Prithvi Raj, "Evidentiary Value of Scientific Criminal Investigation Under Indian Criminal Justice System" 11 *International Journal of Multidisciplinary Educational Research* (April 2022), 2277-7881.

<sup>7</sup> Thakare V., Phadke R., Kapgate K., Kohpare J. & Pande A., *Forensic Science Analysis as an Emerging New Dimension of Environmental Issues*, Regional Forensic Science Laboratory, Dhantoli, Nagpur, India, held on (2 May 2023), available at <https://juniperpublishers.com/jfsci/pdf/JFSCI.MS.ID.555960.pdf> (last visited on 5 March 2025).

- To identify and analyze the challenges and obstacles associated with DNA profiling in forensic science, including technical, ethical, and legal issues.

## Research Methodology

This research adopted an interpretive and positivistic research paradigm, relying on observing and analyzing existing texts. The study took a critical approach to the existing law in India and its progenitors, such as the United Kingdom and the United States of America, as well as all available literature on forensic evidence and its relation to judicial decision-making. This thesis's most crucial theoretical principle was to study the courts' approach in the decision-making process of criminal cases in developed countries and examine their similarities and differences with India.

## Study Design

The research method was primarily analytical, and the methodology adopted was doctrinal. As the research title suggested, the study was only possible by chronologically analyzing select cases and observations from the Hon'ble Supreme Court and the High Court. The aim was to assess and explore the privileges and shortcomings in the criminal justice system concerning forensic evidence by stimulating insights incorporated into the analysis. Decisive cases that changed the law regarding accepting or rejecting forensic evidence in court were also studied. Although case law was distinguished from statute law, statute law was sometimes considered the primary source of law, especially when the Supreme Court gave judgments interpreting the statutes.

This was a crucial feature of the common law system, and researching case law formed an integral part of the legal research process. Case law was based on judges' reported decisions in cases before them. In their decisions, the judges laid out the relevant facts of the case and the legal reasoning that was applied while deciding the case. Under common law, there was a hierarchy of authority in judgments. Those made by superior courts formed precedents, and inferior courts were required to follow these precedents. Therefore, the reported decisions of judges in cases formed an essential part of the law.

The research combined historical, empirical, comparative, and critical methods. The study extensively used legal libraries, especially the I.L.I. Law Library and N.L.U. Delhi deserved special mention.

## Data Collection Procedure

The study was based on primary and secondary sources, such as statutes, reported judgments in journals, books, and articles on forensic science, including e-journals. The role of forensic evidence in criminal cases in India was analyzed by studying the decisions of the Superior Courts available in sources such as *Supreme Court Cases*, *Criminal Law Journal*, *S.C.C. Online*, *Manupatra*, etc., where evidence like DNA, fingerprints, ballistics, and toxicology had been used.

## Technical Challenges in DNA Replication: DNA Degradation and Sample Contamination

Forensic DNA analysis has become a powerful tool in criminal investigations, but its effectiveness hinges on the integrity of the DNA samples. Technical challenges in DNA replication, particularly DNA degradation and sample contamination, pose significant obstacles to obtaining reliable and admissible evidence<sup>8</sup>. These challenges are further compounded by specific environmental conditions and handling practices prevalent in regions like Karnataka, India, raising crucial legal concerns about DNA evidence's admissibility and probative value.

### DNA Degradation and Sample Contamination

DNA, while a relatively stable molecule, is susceptible to degradation from various environmental factors. Heat, moisture, sunlight, and exposure to chemicals can all contribute to the breakdown of DNA into smaller, less informative fragments. This degradation can significantly impact the success of PCR amplification, the cornerstone of modern DNA profiling. In Karnataka, forensic labs often face the challenge of analyzing DNA samples from crime scenes exposed to extreme climatic conditions<sup>9</sup>. The region experiences a wide range of temperatures, from intense heat in the summer to high humidity during the monsoon season. These fluctuations in temperature and humidity can accelerate DNA degradation, making it difficult to obtain a complete and reliable DNA profile.

Beyond climatic factors, improper handling of DNA samples by law enforcement officials can also contribute to degradation. Improper storage, such as leaving samples at room temperature or in direct sunlight, can accelerate the breakdown of DNA<sup>10</sup>. Contamination can occur if samples are not collected using sterile equipment or improperly packaged and transported. Delays in transporting samples to the forensic laboratory can also exacerbate degradation, especially if the samples are not stored appropriately during transit<sup>11</sup>. The chain of custody, a critical legal requirement for ensuring the integrity of evidence, can be compromised at any stage, from the initial collection at the crime scene to the analysis in the laboratory. Any lapse

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<sup>8</sup> Fonville, N. C., Ward, R. M., & Mittelman, D. (2011). Stress-induced modulators of repeat instability and genome evolution. *Journal of Molecular Microbiology and Biotechnology*, 21(1–2), 36–44. <https://doi.org/10.1159/000332748>

<sup>9</sup> Garm, C., Moreno-Villanueva, M., Bürkle, A., Larsen, L. A., Bohr, V. A., Christensen, K., & Stevnsner, T. (2013). Genetic and environmental influence on DNA strand break repair: A twin study. *Environmental and Molecular Mutagenesis*, 54(6), 414–420. <https://doi.org/10.1002/em.21791>

<sup>10</sup> Dash, H. R., & Das, S. (2018). Microbial degradation of forensic samples of biological origin: Potential threat to human DNA typing. In *Molecular Biotechnology* (pp. 141–153). Humana Press Inc.

<sup>11</sup> Curwen, G. B., Cadwell, K. K., Winther, J. F., Tawn, E. J., Rees, G. S., Olsen, J. H., Rechnitzer, C., Schroeder, H., Guldborg, P., Cordell, H. J., & Boice, J. D. Jr. (2010). The heritability of G2 chromosomal radiosensitivity and its association with cancer in Danish cancer survivors and their offspring. *International Journal of Radiation Biology*, 86(11), 986–995. <https://doi.org/10.3109/09553002.2010.496027>

in the chain of custody can raise reasonable doubt about the authenticity and reliability of the DNA evidence<sup>12</sup>.

Contamination is another major challenge. Crime scenes are often complex environments where DNA from multiple individuals may be present. Samples collected from these scenes can be contaminated with soil, water, other biological materials, or even DNA from individuals not connected to the crime. Contamination can lead to mixed DNA profiles, where the DNA from multiple individuals is present in the sample. Interpreting mixed profiles can be complex and require sophisticated analytical techniques<sup>13</sup>. Furthermore, contamination can interfere with the PCR process, leading to incomplete or inaccurate results. For instance, if a sample is contaminated with bacterial DNA, the PCR primers may amplify the bacterial DNA instead of the target human DNA, rendering the analysis useless for human identification<sup>14</sup>.

### Legal Concerns:

Under the Bharatiya Sakshya Adhiniyam, 2023, expert opinions are admissible when the court needs to form an opinion on matters requiring specialized knowledge or skills, like science, art, or handwriting. Sections 39 and 40 of the BSA specifically address the relevance and admissibility of expert opinions, allowing courts to rely on the expertise of individuals in various fields<sup>15</sup>. DNA evidence, while generally considered a robust form of evidence, falls under this category. The courts in India have recognized the scientific validity of DNA evidence, but they have also emphasized the importance of ensuring its integrity. DNA evidence's admissibility and probative value are contingent upon its reliability, which can be significantly impacted by degradation and contamination.

Section 39 of the Bharatiya Sakshya Adhiniyam, 2023 (BSA) deals with experts' opinions when relevant in court. It specifies that when the court needs to form an opinion on the point of foreign law, science, art, or any other specialized field or to identify handwriting or fingerprints, experts' opinions are relevant facts. These experts are considered "persons specially skilled" in the relevant field<sup>16</sup>. This section essentially allows courts to rely on the specialized knowledge of experts to understand and interpret evidence that falls outside the common understanding of the court.

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<sup>12</sup> Shahzad, M., De Maeyer, H., Salih, G. A., Nilsson, M., Haratourian, A., Shafique, M., Shahid, A. A., & Allen, M. (2024). Evaluation of storage conditions and the effect on DNA from forensic evidence objects retrieved from lake water. *Genes*, 15(3), 279. <https://doi.org/10.3390/genes15030279>

<sup>13</sup> Leek, J. T., Scharpf, R. B., Bravo, H. C., Simcha, D., Langmead, B., Johnson, W. E., Geman, D., Baggerly, K., & Irizarry, R. A. (2010). Tackling the widespread and critical impact of batch effects in high-throughput data. *Nature Reviews Genetics*, 11(10), 733–739. <https://doi.org/10.1038/nrg2825>

<sup>14</sup> Ludeman, M. J., Zhong, C., Mulero, J. J., Lagacé, R. E., Hennessy, L. K., Short, M. L., & Wang, D. Y. (2018). Developmental validation of GlobalFiler, PCR amplification kit: A 6-dye multiplex assay designed for amplification of casework samples. *International Journal of Legal Medicine*, 132, 1555–1573. <https://doi.org/10.1007/s00414-018-1817-5>

<sup>15</sup> *The Bharatiya Sakshya Adhiniyam, 2023*, s 39 and s 40

<sup>16</sup> *The Bharatiya Sakshya Adhiniyam, 2023*, s 39

Forensic reports, including those related to DNA analysis, fall under the ambit of "science," as mentioned in Section 39. Therefore, the opinions of forensic experts, as documented in their reports, are admissible in court as expert opinions. However, the admissibility is not automatic. The court must be satisfied that the expert is "specially skilled" in the relevant field. This means the expert must possess the qualifications, training, and experience to render a reliable opinion<sup>17</sup>. The court may inquire into the expert's credentials, methodology, and the underlying data used to form the opinion. Section 39(2) introduces a specific provision related to electronic evidence. It states that in cases involving information stored or transmitted in electronic or digital form, the opinion of an Examiner of Electronic Evidence, as defined by the Information Technology Act, 2000, is a relevant fact.

While Section 39 makes expert opinions relevant, it's crucial to understand that these opinions are not conclusive. The court is not bound to accept the expert's opinion unquestioningly. The court's prerogative evaluates the expert's testimony, considers other evidence on record, and arrives at its conclusions. The court may also seek a second opinion from another expert if it deems necessary. Expert opinions are meant to assist the court, not dictate its decision. The weight given to the expert opinion depends on various factors, including the expert's credibility, the soundness of the methodology, and the consistency of the opinion with other evidence.

Section 40 of the Bharatiya Sakshya Adhinyam, 2023, addresses relevant facts because they support or contradict expert opinions, even if those facts are not otherwise directly relevant to the case. This section ensures that the court considers all relevant evidence, including facts that may seem peripheral but are crucial to understanding the basis of an expert's opinion<sup>18</sup>. Section 40 states that facts, even if not directly relevant, are relevant if they support or contradict experts' opinions. This means that the court can consider facts that, on their own, might not be directly related to the case but become relevant when they bear upon the expertise being presented. The relevance of the facts hinges on whether they reinforce the expert's opinion or provide evidence that contradicts it. This allows the court to assess the strength and credibility of the expert testimony. By allowing the consideration of these facts, Section 40 enables a more nuanced and comprehensive evaluation of evidence, ensuring that the court can make a more informed decision.

Courts have consistently stressed the need for strict adherence to established protocols for collecting, handling, and analyzing DNA evidence. Any deviation from these protocols can raise doubts about the reliability of the evidence. Defense attorneys often challenge the admissibility of DNA evidence by arguing that the sample was degraded, contaminated, or improperly handled<sup>19</sup>. They may question the chain of custody, the storage conditions of the sample, or the laboratory procedures used for analysis. The burden of proof lies with the

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<sup>17</sup> *Ibid*

<sup>18</sup> *The Bharatiya Sakshya Adhinyam, 2023, s 40*

<sup>19</sup> The Hammer Law Firm. (2023). The role of DNA evidence in criminal defense cases. *The Hammer Law Firm Blog*. Retrieved from <https://www.thehammerlawfirm.com/criminal-defense-blog/2023/november/the-role-of-dna-evidence-in-criminal-defense-cas/>

prosecution to establish beyond a reasonable doubt that the DNA evidence is reliable and has not been compromised.

Judicial scrutiny of DNA evidence has increased in recent years, with courts becoming more aware of the potential for errors and contamination. Courts have emphasized the need for clear and comprehensive forensic reports that explain the methods used for DNA analysis, the limitations of those methods, and the potential impact of degradation or contamination on the results. Forensic experts must be prepared to address challenges to their expertise and the reliability of their findings. They must explain complex scientific concepts clearly and understandably to the court<sup>20</sup>.

The courts have also highlighted the importance of proper training and quality control in forensic laboratories. Laboratories must ensure their personnel are adequately trained and qualified to perform DNA analysis. They must also implement rigorous quality control measures to minimize the risk of errors and contamination<sup>21</sup>. Regular audits and proficiency testing are essential to maintain the highest standards of quality and reliability in DNA testing.

In cases where DNA degradation or contamination is significant, the court may give less weight to the DNA evidence or even disregard it altogether. The ultimate decision of how much weight to give to DNA evidence rests with the court. Therefore, forensic labs in Karnataka must implement stringent quality control measures to minimize the risk of DNA degradation and contamination. This includes using appropriate collection and storage methods, ensuring proper chain of custody documentation, and adhering to strict laboratory protocols. Addressing these challenges is essential for ensuring the reliability and admissibility of DNA evidence in legal proceedings protecting the justice system's integrity. The legal implications of compromised DNA evidence are substantial, potentially leading to wrongful convictions or acquittals. Therefore, continuous improvement in forensic techniques and adherence to stringent quality control measures are crucial for effectively using DNA evidence in the Indian legal system.

### **Errors in PCR Amplification and Their Impact on DNA Evidence Admissibility in India**

Polymerase Chain Reaction (PCR) is a cornerstone of modern forensic DNA analysis, amplifying minute quantities of DNA into quantities sufficient for profiling. While PCR is a powerful and sensitive technique, it has limitations. Certain inherent characteristics of the PCR process can introduce errors, potentially compromising the accuracy and reliability of DNA profiles and raising significant legal concerns, particularly within the Indian legal context<sup>22</sup>. If

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<sup>20</sup> Nimbkar, P. H., & Bhatt, V. D. (2022). A review on touch DNA collection, extraction, amplification, analysis, and determination of phenotype. *Forensic Science International*, 336, 111352. <https://doi.org/10.1016/j.forsciint.2022.111352>

<sup>21</sup> Alketbi, S. K. (2024). Emerging technologies in forensic DNA analysis. *Perspectives in Legal and Forensic Sciences*, 1(1), 10007. <https://doi.org/10.70322/plfs.2024.10007>

<sup>22</sup> Srivastava, A., et al. (2022). Impact of DNA evidence in the criminal justice system: Indian legislative perspectives. *Egyptian Journal of Forensic Sciences*, 12(1), 51.

not properly accounted for, these errors can create reasonable doubt in criminal trials, impacting DNA evidence's admissibility and probative value and potentially affecting conviction rates.

Three primary errors associated with PCR amplification are allele dropout, stutter peaks, and mispriming. Understanding these errors and their implications is crucial for forensic scientists and legal professionals involved in cases where DNA evidence is presented<sup>23</sup>.

### 1. Allele Dropout:

Allele dropout is the failure to amplify one allele at a particular locus during PCR. This phenomenon typically occurs when the DNA sample is low-quality, degraded, or contains inhibitors that interfere with amplification. When one allele fails to amplify, the resulting DNA profile will show only one allele at that locus, leading to a false homozygote result. This can be particularly problematic when analyzing mixed DNA samples, as allele dropout can mask the presence of one contributor's DNA, potentially leading to a missed identification or a false exclusion<sup>24</sup>.

In the Indian legal context, allele dropout can significantly impact DNA evidence interpretation. Suppose the prosecution relies on a DNA profile exhibiting allele dropout. In that case, the defense may argue that the missing allele could belong to the actual perpetrator, thus creating reasonable doubt about the defendant's guilt. The defense might also argue that the low quality of the DNA sample casts doubt on the reliability of the entire DNA profiling process. In such cases, the court must carefully scrutinize the forensic report and the testimony of the forensic expert to determine whether the possibility of allele dropout was adequately considered and whether it could have affected the conclusions drawn from the DNA evidence<sup>25</sup>.

### 2. Stutter Peaks:

Stutter peaks are artificial bands that appear alongside the true allele peaks in electropherograms, which are graphical representations of the amplified DNA fragments. These stutter peaks are typically smaller than the true allele peaks and arise from polymerase slippage during PCR. Polymerase slippage occurs when the DNA polymerase enzyme, responsible for synthesizing new DNA strands, "stutters" or pauses during amplification,

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<sup>23</sup> Vajpayee, K., Dash, H. R., Suri, K. P., Sitwala, H. C., Parekh, P. B., & Shukla, R. K. (2023). An Indian perspective of implications of inconclusive DNA reports of biological samples on the final outcome of the trial. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4660370>

<sup>24</sup> Shestak, A. G., Bukaeva, A. A., Saber, S., & Zaklyazminskaya, E. V. (2021). Allelic dropout is a common phenomenon that reduces the diagnostic yield of PCR-based sequencing of targeted gene panels. *Frontiers in Genetics*, 12, 620337. <https://doi.org/10.3389/fgene.2021.620337>

<sup>25</sup> Stevens, A. J., Taylor, M. G., Pearce, F. G., & Kennedy, M. A. (2017). Allelic dropout during polymerase chain reaction due to G-quadruplex structures and DNA methylation is widespread at imprinted human loci. *G3: Genes, Genomes, Genetics*, 7(3), 1019-1025. <https://doi.org/10.1534/g3.116.038687>

creating short, extra DNA fragments. These fragments appear as stutter peaks in the electropherogram<sup>26</sup>.

Stutter peaks can be misinterpreted as true alleles, especially when analyzing mixed DNA samples or samples with low amounts of DNA. This misinterpretation can lead to the inclusion of incorrect alleles in the DNA profile, potentially resulting in a false match or a misidentification. In Indian courts, the presence of stutter peaks can be a point of contention. The defense may argue that the stutter peaks were not properly accounted for by the forensic expert, leading to an inaccurate DNA profile<sup>27</sup>. The forensic expert must be able to clearly distinguish between true allele peaks and stutter peaks and explain the methodology used to differentiate them. The court will likely examine the expert's qualifications, experience in interpreting electropherograms, and the laboratory's protocols for handling stutter peaks.

### 3. Mispriming:

Mispriming occurs when the PCR primers, which are short DNA sequences designed to bind to specific target regions of DNA, bind to non-target DNA sequences instead. This non-specific binding can amplify incorrect DNA regions, leading to false matches or misleading DNA profiles<sup>28</sup>. Mispriming can be caused by various factors, including low-quality DNA, high primer concentrations, or the presence of contaminating DNA.

In the Indian legal context, mispriming can have serious consequences. If a DNA profile generated from misprimed DNA is used to identify a suspect, it could lead to a wrongful arrest or conviction. The defense may argue that the forensic laboratory did not adequately address the possibility of mispriming and that the DNA evidence is unreliable. The court will likely scrutinize the laboratory's quality control procedures to ensure measures were in place to prevent and detect mispriming<sup>29</sup>. The forensic expert must explain the steps taken to ensure the specificity of the PCR reaction and rule out the possibility of mispriming.

### Presence of Mixed DNA Profiles

Forensic DNA analysis often encounters mixed DNA profiles, especially in cases of sexual assault, homicide, and violent crimes. These mixtures arise when biological material from multiple individuals is present at a crime scene. For example, in a sexual assault case, a sample may contain DNA from both the victim and the perpetrator. Similarly, in a homicide, DNA

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<sup>26</sup> D'Angelo, O., Vandepoele, A. C. W., Adelman, J., & Marciano, M. A. (2022). Assessing non-LUS stutter in DNA sequence data. *Forensic Science International: Genetics*, 59, 102706. <https://doi.org/10.1016/j.fsigen.2022.102706>

<sup>27</sup> Seo, S. B., Ge, J., King, J. L., & Budowle, B. (2014). Reduction of stutter ratios in short tandem repeat loci typing of low copy number DNA samples. *Forensic Science International: Genetics*, 8, 213–218.

<sup>28</sup> Lorenz, T. C. (2012). Polymerase chain reaction: Basic protocol plus troubleshooting and optimization strategies. *Journal of Visualized Experiments*, (63), e3998. <https://doi.org/10.3791/3998>

<sup>29</sup> Frey, U. H., Bachmann, H. S., Peters, J., & Siffert, W. (2008). PCR-amplification of GC-rich regions: 'Slowdown PCR'. *Nature Protocols*, 3, 1312–1317. <https://doi.org/10.1038/nprot.2008.112>

from the victim, the perpetrator, and potentially other individuals present at the scene might be found. Analyzing these mixed samples presents a significant challenge.

The complexity of interpreting mixed DNA profiles stems from the difficulty of separating and distinguishing the individual DNA contributions. Traditional DNA profiling methods are designed to analyze single-source DNA samples<sup>30</sup>. When multiple individuals' DNA is present, the resulting profile becomes a composite, making it difficult to discern the individual genetic markers. This is further complicated because the mixture's contributors may have different DNA levels present. One individual's DNA might be more abundant than others, potentially masking the presence of less abundant DNA.

Resolving mixed DNA profiles requires advanced computational tools and specialized expertise. These tools employ statistical methods to deconvolve the mixed profile, attempting to separate the individual DNA contributions. This process involves complex algorithms that consider factors such as the number of contributors, the relative amounts of DNA from each contributor, and the possibility of allele dropout or other PCR artifacts<sup>31</sup>. Interpreting the results of these analyses requires specialized training and experience. Forensic scientists must be able to assess the reliability of the deconvolution process, evaluate the statistical significance of the results, and present their findings clearly and understandably to the court.

In Karnataka and across many forensic laboratories in India, access to advanced computational tools and a shortage of specialized expertise in mixed DNA profile interpretation are often limited. Outdated technology and a lack of adequately trained personnel can hinder the ability to analyze mixed samples effectively. This can lead to inconclusive results, potentially jeopardizing investigations and hindering the pursuit of justice. Furthermore, even with advanced tools and expertise, interpreting mixed DNA profiles can be subjective, adding another layer of complexity to the legal proceedings<sup>32</sup>.

The legal implications of mixed DNA profiles are substantial. Defense attorneys may argue that the complexity of the mixed profile, coupled with the limitations of the analytical methods, casts doubt on the reliability of the DNA evidence. They may question the deconvolution process's accuracy and the results' interpretation. On the other hand, the prosecution must demonstrate that the analysis was conducted using validated methods, that the forensic experts are qualified, and that the conclusions drawn from the mixed profile are robust and reliable. The court, faced with conflicting interpretations, must carefully evaluate the evidence and expert testimony to determine the probative value of the mixed DNA profile.

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<sup>30</sup> Bright, J. A., Kelly, H., Kerr, Z., McGovern, C., Taylor, D., & Buckleton, J. S. (2019). The interpretation of forensic DNA profiles: An historical perspective. *Journal of the Royal Society of New Zealand*, 50(2), 211–225. <https://doi.org/10.1080/03036758.2019.1692044>

<sup>31</sup> Butler, J. M., Kline, M. C., & Coble, M. D. (2018). NIST interlaboratory studies involving DNA mixtures (MIX05 and MIX13): Variation observed and lessons learned. *Forensic Science International: Genetics*, 37, 81–94. <https://doi.org/10.1016/j.fsigen.2018.07.024>

<sup>32</sup> Gill, P. (2019). DNA evidence and miscarriages of justice. *Forensic Science International*, 294, e1–e3. <https://doi.org/10.1016/j.forsciint.2018.12.003>

## Lack of Standardized Replication Protocols

Another significant challenge facing forensic DNA analysis in India is the lack of standardized replication protocols. The absence of uniform procedures across different laboratories can lead to discrepancies in how DNA evidence is processed and presented in court. This inconsistency can raise concerns about the reliability and comparability of DNA evidence across different cases. It can also create opportunities for challenges to the admissibility of DNA evidence based on procedural variations.

Variations in protocols might include differences in DNA extraction methods, PCR amplification conditions, and data analysis software. While some variation is inevitable, significant differences can lead to inconsistencies in results and interpretations. For example, different DNA extraction methods might yield different amounts of DNA from the same sample, potentially affecting the sensitivity of the subsequent PCR amplification<sup>33</sup>. Similarly, variations in PCR conditions can influence the amplification efficiency and the likelihood of PCR artifacts, such as stutter peaks or allele dropout.

The lack of standardized protocols also affects the comparability of DNA profiles stored in national forensic databases. If different laboratories use different protocols, comparing DNA profiles generated by different labs can be difficult. This can hinder the effectiveness of DNA databases in linking crimes and identifying suspects. A national DNA database is only as effective as the quality and consistency of its data<sup>34</sup>.

## Legal and Ethical Challenges in DNA Replication in the Indian Context

DNA technology has revolutionized forensic science and criminal investigations in India, offering powerful tools for identifying suspects, linking them to crime scenes, and even exonerating the innocent. However, using DNA evidence is challenging, particularly concerning its admissibility in Indian courts and the ethical considerations surrounding its collection, storage, and application. These challenges necessitate a careful examination of the legal framework, judicial interpretations, and ethical implications to ensure this powerful technology's fair and just application.

## Admissibility of DNA Evidence in Indian Courts

Section 63 of the Bharatiya Sakshya Adhinyam, 2023, deals with the admissibility of electronic records<sup>35</sup>. It essentially states that electronic records are deemed admissible in evidence if certain conditions are met, making them equivalent to documents. These conditions

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<sup>33</sup> Yang YJ, Prinz M, McKiernan H, Oldoni F. (2022), American Forensic DNA Practitioners' Opinion on Activity Level Evaluative Reporting. *Journal of Forensic Sciences*. 67(4):1357-69. doi:10.1111/1556-4029.15063.

<sup>34</sup> Wild J, McKinnon A, Wilkins A, Browne H. (2022), Post-Traumatic Stress Disorder and Major Depression among Frontline Healthcare Staff Working During the COVID-19 Pandemic. *British Journal of Clinical Psychology*. 61(3):859-66. doi:10.1111/bjc.12340.

<sup>35</sup> *The Bharatiya Sakshya Adhinyam, 2023, s 63*

relate to creating, storing, and processing information by computers or communication devices. These criteria include:

- **Authenticity:** The electronic record must be authentic and free from tampering or manipulation. This requires establishing the source of the record and ensuring that it has not been altered during storage or transmission. In the context of DNA reports, this means demonstrating the integrity of the sample collection, the chain of custody, and the laboratory procedures.
- **Integrity:** The data in the electronic record must be complete and accurate. This requires ensuring that the DNA analysis was performed correctly and the results accurately represented in the report. Issues like allele dropout, stutter peaks, and mispriming, discussed earlier, become relevant here, as they can affect the integrity of the DNA profile.
- **Reliability:** The method used to generate the electronic record must be reliable. This means that the DNA replication and analysis techniques must be scientifically sound and validated. The court may inquire into the laboratory's accreditation, quality control procedures, and the expertise of the personnel involved.
- **Admissibility of the device:** The electronic device used to generate the record must function properly and without defects. The section allows for using electronic records in court without the need for the original physical document or further proof.

Courts in India have frequently debated several issues related to the admissibility of DNA evidence, including:

- **Reliability of DNA replication methods:** The courts scrutinize the reliability of the PCR-based DNA replication methods used by forensic laboratories. They examine whether the laboratory follows established protocols, uses validated reagents and equipment, and performs regular quality control checks. Challenges to the reliability of the methods can arise from issues like contamination, degradation, or errors in the amplification process.
- **Possibility of manipulation or tampering with results:** The courts are concerned about the possibility of manipulation or tampering with DNA samples or results. Maintaining a robust chain of custody is crucial to ensure the integrity of the evidence. Any break in the chain of custody can cast doubt on the authenticity of the DNA report. The courts also examine the security measures to prevent unauthorized access to or modification of DNA data.
- **The right of an accused to challenge forensic evidence under Article 21 (Right to Fair Trial) of the Indian Constitution:** Article 21 guarantees the right to a fair trial, which includes the right to challenge evidence presented against the accused. This right

extends to forensic DNA evidence<sup>36</sup>. The accused has the right to cross-examine forensic experts, request independent testing of the DNA sample, and present their expert testimony. Denying the accused the opportunity to challenge DNA evidence effectively can violate their right to a fair trial.

### Case Law:

Several landmark cases have shaped the jurisprudence on DNA evidence admissibility in India.

- **Kishanbhai v. State of Gujarat (2014):** The Supreme Court emphasized the importance of proper forensic handling of DNA evidence. The court held that improper handling could lead to the wrongful conviction of an innocent person. This case highlights the need for strict adherence to established sample collection, storage, and analysis protocols. It also underscores the importance of maintaining a clear and unbroken chain of custody<sup>37</sup>.
- **Surendra Koli v. State of U.P. (2011):** This case established that forensic DNA evidence must be corroborated with other material evidence. The court ruled that DNA evidence alone is not sufficient for conviction. It must be supported by other evidence on record, such as eyewitness testimony, circumstantial evidence, or other forensic evidence. This ruling emphasizes that DNA evidence is not infallible and should not be considered in isolation<sup>38</sup>.

The courts have also addressed other issues related to DNA evidence, such as the admissibility of DNA evidence in paternity disputes, the use of DNA databases, and the ethical implications of DNA technology. The legal landscape surrounding DNA evidence constantly evolves as new technologies and challenges emerge.

### Ethical Concerns:

Beyond legal admissibility, several ethical concerns surround using DNA technology in the Indian context. These include:

- **Privacy:** The collection and storage of DNA samples raise concerns about individual privacy. DNA contains vast personal information beyond identity, including predispositions to certain diseases and familial relationships. The potential for misuse of this information is a significant ethical concern. Robust data protection measures and clear guidelines on accessing and using DNA data are essential.
- **Consent:** The issue of informed consent for DNA collection is crucial. Individuals should be fully informed about the purpose of DNA collection, how the DNA will be

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<sup>36</sup> Article 21, Constitution of India

<sup>37</sup> *State of Gujarat v. Kishanbhai*, (2014) 5 SCC 108.

<sup>38</sup> *Surendra Koli v. State of Uttar Pradesh*, (2011) 4 SCC 80.

used, and how long the DNA will be stored. Coercion or deception in obtaining consent is unethical.

- **Data security:** DNA databases must be protected from unauthorized access and misuse. Data breaches can have serious consequences, as sensitive genetic information could fall into the wrong hands. Strong security measures and strict access controls are necessary to safeguard DNA data.
- **Potential for misuse:** There is a potential for misuse of DNA technology, such as for discriminatory purposes or for creating a genetic underclass. Safeguards must be in place to prevent such misuse and ensure that DNA technology is used ethically and responsibly.

The legal and ethical challenges surrounding DNA replication and its use in forensic science require ongoing attention and dialogue. As DNA technology advances, the legal framework and ethical guidelines must be updated to address new challenges and ensure this powerful tool's fair and just application. Education and training for legal professionals, forensic scientists, and law enforcement personnel are crucial to ensure that DNA evidence is properly collected, analyzed, and interpreted. Public awareness of DNA technology's legal and ethical implications is also essential for fostering informed debate and ensuring that the use of DNA evidence serves the interests of justice while protecting individual rights and freedoms<sup>39</sup>.

### Findings of the Study

The study on the role of forensic science in DNA profiling, specifically in Karnataka, India, reveals significant insights into the role of DNA evidence in criminal justice. These findings focus on DNA evidence's reliability, admissibility, and legal implications, emphasizing technical, ethical, and procedural challenges. By analyzing the evolving forensic landscape, the study highlights the impact of recent legislative developments in DNA profiling and its transformative effect on the criminal justice system.

### Role and Importance of DNA Evidence in Criminal Trials: Admissibility, Reliability, and Judicial Impact

One of the study's key findings is the increasing reliance on DNA evidence in criminal trials, particularly in Karnataka. The judiciary recognizes DNA profiling's scientific accuracy and ability to establish an individual's identity beyond reasonable doubt. Courts in Karnataka, especially in cases of homicide, sexual assault, and missing persons, have acknowledged the pivotal role of DNA evidence in corroborating other forensic and circumstantial evidence. However, the admissibility of DNA evidence is contingent on strict procedural safeguards, including the proper chain of custody, forensic expert testimony, and corroborative evidence.

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<sup>39</sup> D'Anna, T., Puntarello, M., Cannella, G., Scalzo, G., Buscemi, R., Zerbo, S., & Argo, A. (2023). The chain of custody in the era of modern forensics: From the classic procedures for gathering evidence to the new challenges related to digital data. *Healthcare (Basel)*, 11(5), 634. <https://doi.org/10.3390/healthcare11050634>

These safeguards ensure that DNA evidence does not stand alone but complements other investigative findings.

### **Admissibility of DNA Evidence**

The study confirms that the legal framework surrounding the admissibility of DNA evidence has evolved in response to recent legal reforms, particularly the Bharatiya Nagarik Suraksha Sanhita, 2023 and the Bharatiya Sakshya Adhinyam, 2023. These reforms reinforce the requirement for rigorous protocols to be followed in collecting and handling DNA evidence. The study also highlights the consistent judicial challenges DNA evidence faces regarding sample integrity, with defense lawyers often questioning the possibility of contamination or mishandling of samples.

### **Reliability of DNA Evidence**

DNA evidence is highly reliable when analyzed under standardized conditions, but the study identifies persistent challenges in its application. Inconsistent lab results due to degraded DNA samples, human error, and misinterpreting statistical probabilities remain significant obstacles. Judicial caution in interpreting DNA evidence, particularly in low-template DNA cases, highlights the balance courts must maintain between forensic evidence and other forms of proof, such as eyewitness testimony.

### **Impact on Judicial Outcomes**

DNA profiling has significantly influenced criminal adjudication in Karnataka, with findings indicating Higher conviction rates in cases where DNA evidence corroborates other investigative findings; Increased exonerations, especially for those wrongfully accused, underscoring DNA's role in ensuring justice; A reduction in the reliance on flawed eyewitness testimony, which has been historically prone to errors.

However, inconsistent use and understanding of DNA evidence, especially in rural districts, suggest that further training and standardization are required for equitable application across the judicial system.

### **Challenges and Obstacles in DNA Profiling: Technical, Ethical, and Legal Issues**

The study identifies multiple challenges impeding the full utilization of DNA profiling in Karnataka. These include technical, ethical, and procedural obstacles, many exacerbated by the lack of infrastructure and legal frameworks.

#### **Technical Challenges**

The limited capacity of forensic laboratories in Karnataka is a major bottleneck. Overburdened labs and insufficient skilled personnel contribute to significant backlogs in DNA analysis, delaying justice. The study also identifies disparities in the DNA analysis techniques used by different labs, which can lead to inconsistent results.

## Ethical Concerns in DNA Profiling

Ethical concerns surrounding the collection and use of DNA evidence are significant. Issues of involuntary DNA collection, misuse of forensic databases, and potential racial and socio-economic biases in DNA sampling raise critical questions. One notable case involved a wrongful accusation where DNA evidence was collected without proper consent, leading to significant human rights concerns.

## Legal and Procedural Gaps

The study highlights several gaps in India's legal framework for DNA evidence. Notably, the absence of a dedicated DNA law results in unclear DNA collection, storage, and use guidelines in legal proceedings. Additionally, there is a lack of standardized forensic training among legal professionals, making it difficult for judges and lawyers to interpret complex DNA reports correctly.

## Suggestions

The study recommended the following:

- **Strict Guidelines for DNA Sample Collection and Chain of Custody:** Law enforcement agencies must follow rigorous protocols when collecting DNA samples to prevent contamination, loss, or tampering. A digital tracking system should ensure that every step of the chain of custody is documented and verifiable in court.
- **Introduction of DNA Awareness Programs for Law Enforcement Officers:** Many police officers in India lack training in forensic science, leading to errors in DNA sample collection and interpretation. Regular workshops and certification programs should be introduced to educate officers on DNA evidence's significance, limitations, and legal implications.
- **Ethical Guidelines on DNA Evidence in Civil and Family Law Cases:** DNA profiling is increasingly used in paternity disputes, inheritance cases, and immigration issues. The legal system must develop ethical guidelines to ensure that DNA testing in civil matters is conducted transparently, with informed consent, and without coercion.
- **Specialized DNA Forensic Units in Karnataka:** Karnataka should have a dedicated DNA forensic unit equipped with modern technology and staffed by trained forensic experts. This will ensure timely processing of DNA evidence and reduce the backlog of cases requiring forensic analysis.
- **Strengthening Protection Against DNA Evidence Tampering:** Laws should be introduced to criminalize the intentional tampering or falsification of DNA evidence in Karnataka. Penalties should be imposed on forensic personnel, police officers, or legal professionals manipulating forensic findings for personal or political motives.

## Conclusion

The study provides a comprehensive understanding of the role of DNA profiling in the Indian criminal justice system, particularly within Karnataka. The research highlights that DNA profiling has become an indispensable forensic tool that aids in criminal investigations, ensuring accurate identification of suspects, exoneration of the wrongfully accused, and strengthening judicial outcomes. However, despite its scientific accuracy and evidentiary strength, DNA profiling in Karnataka still faces challenges related to infrastructure, legal admissibility, ethical concerns, and public perception. The findings of this study underscore the urgent need for legal and procedural reforms, the expansion of forensic capabilities, and a greater understanding of DNA evidence among legal professionals and law enforcement agencies.

The study also identifies significant technical and procedural challenges associated with DNA profiling in Karnataka. A primary concern is the limited forensic infrastructure, with forensic labs facing severe case backlogs, delays in processing, and a shortage of trained DNA analysts. These issues hinder timely justice delivery and can lead to misinterpretations of forensic findings, thereby affecting judicial decisions. Additionally, errors in DNA sample collection, preservation, and analysis have raised concerns about the integrity and reliability of forensic DNA evidence. Ensuring standardized forensic protocols and investing in forensic training programs for law enforcement and forensic experts are critical to mitigating these challenges.

Ethical and legal concerns surrounding DNA profiling also remain unresolved, particularly in the context of privacy rights, involuntary DNA collection, and potential misuse of forensic databases. The absence of a comprehensive legal framework governing DNA profiling in India leaves grey areas regarding data protection, collecting and storing DNA samples, and consent-based sample extraction. The study highlights the potential risks of DNA misuse, particularly when forensic data is retained without clear regulatory guidelines, leading to concerns over mass surveillance and wrongful incrimination.

DNA profiling has transformed forensic investigations and judicial decision-making in Karnataka, offering an unparalleled scientific method for identifying suspects, exonerating the innocent, and reinforcing the credibility of legal proceedings. However, its full potential remains hindered by infrastructural, ethical, and legal limitations. Addressing these concerns requires a multi-stakeholder approach, bringing forensic experts, legal practitioners, policymakers, and civil society organizations together to create a robust, ethical, and legally sound forensic DNA framework. Suppose Karnataka and India are to embrace the power of forensic DNA technology fully. In that case, it is imperative to prioritize forensic standardization, judicial training, ethical safeguards, and public trust in forensic science. DNA profiling can only serve as an instrument of justice while safeguarding individual rights and due process.

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