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Beyond the Double Helix: Emerging Trends in Forensic DNA Technologies

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Abstract

Advances in forensic DNA technology have been remarkable, growing from the use of classic DNA profiling to sophisticated molecular technologies that deliver full genetic information for criminal investigations and human identification. This review discusses the development of forensic DNA technologies that have transcended the original model of the DNA double helix, covering recent advances in DNA profiling, sequencing and new molecular technologies. Forensic DNA technologies have advanced greatly, most notably through the use of Forensic Investigative Genetic Genealogy (FIGG), Short Tandem Repeat (STR) profiling, Rapid DNA, Next-Generation Sequencing (NGS), Single Nucleotide Polymorphism (SNP) analysis, forensic DNA phenotyping, epigenetic markers, microbial forensics, and environmental DNA. The review also explains how these technologies are used in crime scene investigation, disaster victim identification, missing persons, forensics in wildlife and cold case resolution. Finally, it critically scrutinises the ethical, legal and scientific issues of the use of advanced forensic DNA in the Indian context, highlighting the importance of proper governance, standardisation and responsible implementation.

Keywords; Forensic DNA Technologies; Next-Generation Sequencing (NGS); Forensic Genetic Genealogy; Human Identification; Forensic DNA Phenotyping.

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1 Introduction

In 1953, the double helix structure of DNA was discovered by James Watson and Francis Crick, laying the molecular basis of modern genetics and revolutionizing biology. The double helix represents the distinct genetic code that each person possesses, which is important in the field of forensics science for making reliable identifications using biological evidence.

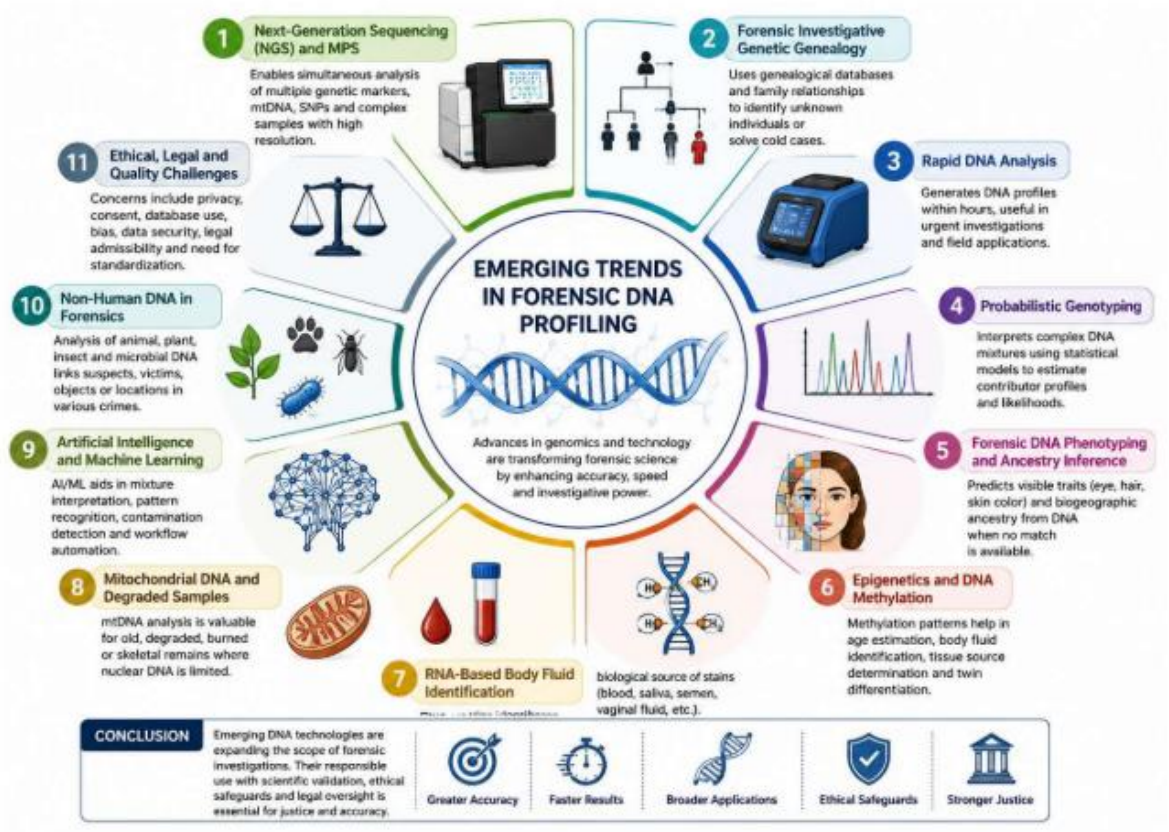

Figure 6: Emerging Trends in Forensic DNA[2]

"Beyond the Double Helix" suggests the transition from conventional DNA-based forensic genetics to the second generation of technologies that provide much more information than just identity matching. Advances in molecular sequencing, bioinformatics, epigenetics, forensic genetic genealogy, and molecular biomarkers have increasingly become tools of modern

[2] P. Dessai et al., "A Review on Emerging Trends in Forensic DNA Profiling and Analysis," Int J Drug Deliv Technol, vol. 16, no. 46s, 2026, doi: 10.25258/ijddt.16.46s.34.

forensic investigations, allowing inferences of ancestry, prediction of externally visible traits, estimation of biological age, source of tissues, and solving complex cases that were previously thought to be unsolvable. Forensic DNA science has therefore grown to cover more than just the structure of DNA, but to encompass full molecular analysis and data-based interpretation.[3]

Forensic DNA technologies are the science of recovering, analysing, interpreting, and comparing DNA for legal and investigative purposes. The traditional method used in forensic DNA analysis was based on Short Tandem Repeat (STR) profiling, which is widely used in many countries across the world because of its high discriminatory power and the fact that it is reproducible. But constant advancements in technology have led to the development of Rapid DNA systems, Next-Generation Sequencing (NGS), Single Nucleotide Polymorphism (SNP) analysis, mitochondrial DNA sequencing, and sophisticated computational tools that have increased the sensitivity, accuracy and breadth of forensic investigations. The new technologies have greatly enhanced the examination of degraded samples, mixed DNA profiles, disaster victim identification, missing person investigations, wildlife forensics, and cold case resolution. Forensic DNA technologies are continuing to develop, providing new and exciting avenues for the enhancement of criminal investigations and also highlighting scientific, ethical, legal and privacy concerns that need to be resolved to ensure responsible and reliable use of these technologies in the justice system.[4]

2 Advances in DNA Profiling and Sequencing Technologies

Forensic DNA profiling and sequencing are recent advancements that have revolutionized the forensic analysis and interpretation of biological evidence. Although human identification using traditional DNA profiling techniques is reliable, new technologies have enhanced the work of forensics by making it faster, more sensitive, and able to analyze a larger amount of DNA from a biological sample. These new innovations allow forensic labs to better analyze degraded or mixed DNA samples, find new people that were not previously identified and speed up their investigative processes. Sequencing platforms, automated analytical systems, and computational tools have led to the improvement in accuracy and efficiency of forensic investigations.

[3] S. Neidle, “Beyond the double helix: DNA structural diversity and the PDB,” J. Biol. Chem., vol. 296, p. 100553, 2021, doi: https://doi.org/10.1016/j.jbc.2021.100553.

[4] S. K. Alketbi, “Emerging Technologies in Forensic DNA Analysis,” SCIEPublish, pp. 1–24, 2024, doi: https://doi.org/10.70322/plfs.2024.10007.

A. Forensic Investigative Genetic Genealogy (FIGG)

Forensic Investigative Genetic Genealogy (FIGG) is a combination of forensic DNA and genealogical database to determine the identity of an unknown person through an indirect pathway by locating biological relatives. The primary data used to reconstruct family relationships from the FIGG is Single Nucleotide Polymorphism (SNP) data, as opposed to the traditional forensic DNA profiling approach. This method is proving to be very efficient in cases of cold cases, UHSR and missing persons when traditional DNA database searches yield no direct match.[5]

B. Short Tandem Repeat (STR) Profiling: Recent Developments

The high discrimination power and reproducibility of Short Tandem Repeat (STR) profiling has made it the world standard method to forensic human identification. Recent improvements include increased STR marker panels, miniSTRs for degraded DNA samples, and more sensitive multiplex amplification systems which also decrease analysis time and increase compatibility with other international DNA databases.[6]

C. Rapid DNA Technology

Rapid DNA technology combines DNA extraction, amplification, separation and profile generation within a single automated instrument that is able to generate DNA profiles in about two hours. It is used to speed up the process of suspect identification, disaster victim identification, border security, military operations and other applications to shorten the turnaround time and achieve standard analysis procedures.[7]

D. Next-Generation Sequencing (NGS) in Forensic Genetics

Forensic DNA analysis has been enhanced by Next-Generation Sequencing (NGS) that allows for the sequencing of many different genetic markers such as STRs, SNPs, mitochondrial DNA, and the ancestry-informative markers. Compared to the standard capillary electrophoresis, NGS

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[5] M. Wang, H. Chen, L. Luo, and Y. Huang, "Forensic investigative genetic genealogy: expanding pedigree tracing and genetic inquiry in the genomic era," J. Genet. Genomics, vol. 52, pp. 460–472, 2025, doi: https://doi.org/10.1016/j.jgg.2024.06.016.

[6] A. A. P. Nitisara and L. H. P. S. Purba, "A Mini Review of Short Tandem Repeat (STR) as DNA Profiling Markers in Forensic Biology," Sainmatika J. Ilm. Mat. dan Ilmu Pengetah. Alam, vol. 22, no. 1, pp. 51–63, 2025, doi: 10.31851/sainmatika.v22i1.17388.

[7] S. Dishon, A. Gold, L. Sapir, E. Palit, and M. Amiel, "Enhancement of DNA recovery in rapid DNA technology: A novel pre-extraction protocol," Forensic Sci. Int., vol. 380, p. 112826, 2026, doi: https://doi.org/10.1016/j.forsciint.2026.112826.

offers a higher genetic resolution to interpret complex DNA mixture, and greater advantage when dealing with low template samples or degraded DNA.[8]

E. High-Throughput and Automated DNA Analysis Platforms

High throughput and automated DNA analysis platforms utilize robotics to handle samples, automated extraction devices, multiplex PCR and built-in bioinformatics software to process a large number of forensic samples with minimal manual effort. Such systems allow laboratories to increase their efficiency, minimise contamination and human error, ensure analytical consistency and enable forensic laboratories to cope with the growing volume of cases whilst remaining quality assured.[9]

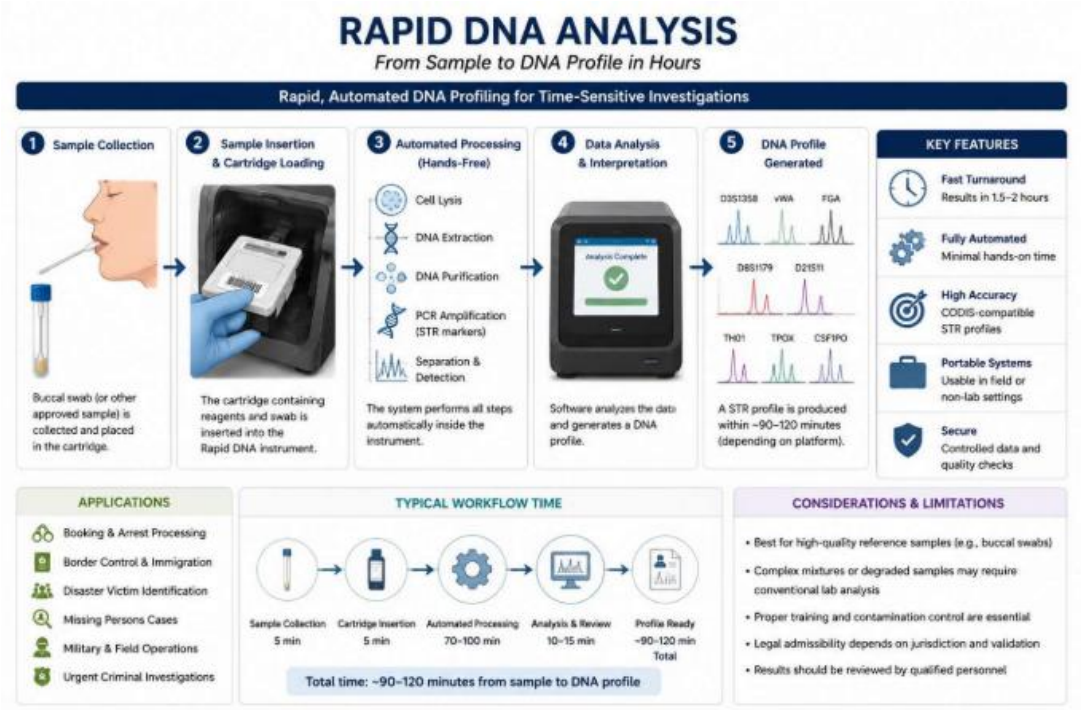

Figure 7: Rapid DNA Analysis[10]

[8] Y. Yuguda, "Application of Next Generation Sequencing (NGS) technology in forensic science: A review," GSC Biol. Pharm. Sci., vol. 23, pp. 155–159, May 2023, doi: 10.30574/gscbps.2023.23.2.0199.

[9] Y. Ma, Z. Zhang, B. Jia, and Y. Yuan, "Automated high-throughput DNA synthesis and assembly," Heliyon, vol. 10, p. e26967, 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e26967.

[10] P. Dessai et al., "A Review on Emerging Trends in Forensic DNA Profiling and Analysis," Int J Drug Deliv Technol, vol. 16, no. 46s, 2026, doi: 10.25258/ijddt.16.46s.34.

3 Emerging Molecular Approaches in Human Identification

The use of emerging molecular techniques that offer additional biological and investigative information has enhanced human identification beyond the traditional DNA profiling. DNA-based forensics usually compare DNA to determine if two samples are the same individual, but modern molecular techniques can determine ancestry, physical traits, biological age, and tissue source, and even environmental associations, from DNA. These methods would be useful in identifying unknown persons, in interpreting difficult forensic evidence and in supporting existing DNA profiling techniques in complex criminal investigations.[11]

i. **Single Nucleotide Polymorphism (SNP) Analysis:** Single Nucleotide Polymorphisms, or SNPs, are single-base differences in the human genome that can be useful for ancestry and kinship studies and for analyzing highly degraded DNA that may be more challenging to profile using conventional STRs.

ii. **Forensic DNA Phenotyping:** The prediction of externally visible characteristics such as eye color, hair color, and skin color from genetic markers is known as forensic DNA phenotyping. It offers investigative clues when no suspect or database match exists, but will not confirm the identity of a person.

iii. **Forensic Genetic Genealogy:** Forensic genetic genealogy is a new field which merges SNP-based DNA analysis and genealogical data to use them to identify unknown people by reconstructing family relationships, for cold case investigations and missing persons identifications.

iv. **Epigenetic Markers for Age and Tissue Identification:** Contextual information of forensic samples can be provided by epigenetic markers, especially DNA methylation patterns, which can be used for the estimation of biological age.

v. **Microbial Forensics and Microbiome Profiling:** The field of microbial forensics focuses on microorganisms found on people, objects and in places. Microbiome profiling may help determine time of death, exposure to the environment, and pinpointing evidence to a location.

vi. **Environmental DNA (eDNA) in Forensic Investigations:** Environmental DNA (eDNA) is DNA that is collected from environmental sources like soil, water or air. eDNA can be used in forensic science to link people or things to a specific place and to assist with the investigation of environmental and wildlife crimes.

[11] C. Gurkan, O. Bulbul, and K. K. Kidd, "Editorial: Current and Emerging Trends in Human Identification and Molecular Anthropology," Front. Genet., vol. 12, pp. 10–12, 2021, doi: 10.3389/fgene.2021.708222.

4 Applications of Emerging DNA Technologies in Modern Forensic Science

Recent advances in DNA technology have expanded the field of forensic science, allowing for examination of difficult-to-dissemble biological evidence that could not previously be analyzed. Technologies like Next-Generation Sequencing (NGS), Rapid DNA, Single Nucleotide Polymorphism (SNP) analysis and forensic genetic genealogy have improved the accuracy, sensitivity and efficiency of forensic studies. Such technologies can enhance human identification and contribute to humanitarian efforts and environmental and public safety investigations by delivering dependable genetic information in a variety of investigative situations.[12]

i. **Crime Scene Investigation and Complex DNA Mixtures:** The analysis of complex DNA mixtures derived from several sources is enhanced by advanced DNA technologies. The high resolution of sequencing methods and the use of powerful bioinformatics tools allow forensic scientists to differentiate individuals from trace or degraded biological evidence to better reconstruct scenes of crime.
ii. **Disaster Victim Identification:** DNA has been an important tool for determining victim identity in mass disaster events such as natural disasters, aircraft accidents, terrorist incidents and other mass fatality incidents. DNA profiling of remains can be compared with that of known biological samples from a person or with sample(s) in a database to establish identity where standard identification techniques cannot.
iii. **Missing Persons and Unidentified Human Remains:** Recent advances in DNA technologies, such as forensics genetic genealogy and SNP analysis, have been of great benefit in the identification of missing persons and unidentified human remains. These techniques can help investigators connect distant family relationships and extricate from long-standing unidentified cases.
iv. **Wildlife Forensic Investigations:** DNA has become a tool to fight against illegal wildlife trade and species poaching and in habitat-related crimes. Genetic analysis can help identify a species, its geographical location and verify wildlife products that are used as evidence in a court of law.
v. **Human Trafficking and Mass Casualty Investigations:** DNA technologies are used to facilitate identification of trafficking victims, family reunification and victim

[12] M. S. Petrovick et al., "Analysis of complex DNA mixtures using massively parallel sequencing of SNPs with low minor allele frequencies," Forensic Sci. Int. Genet., vol. 46, p. 102234, 2020, doi: https://doi.org/10.1016/j.fsigen.2020.102234.

recognition in mass casualty situations. Genetic evidence is especially useful when there are no personal identification documents or they are unreliable.

vi. **Cold Case Investigations Using Advanced DNA Technologies:** The new and improved forensic DNA technologies have revolutionised the investigation of cold cases by allowing for re-analysis of the stored DNA material with greater sensitivity. Forensic genetic genealogy, enhanced STR profiling, and Next-Generation Sequencing have proven to be valuable techniques for identifying unknown victims and offenders, and for giving investigators new investigative leads, all of which have helped to solve decades-old crimes and cases.[13]

5 Ethical, Legal, and Scientific Challenges in Advanced Forensic DNA Analysis

Forensic DNA technologies have seen tremendous growth and are now playing a crucial role in crime investigation, human identification, interpretation of evidence and resolution of cases. The growing application of newer technologies like forensic genetic genealogy, Next-Generation Sequencing (NGS) and DNA databases has added a layer of complexity to the ethical, legal and scientific issues that have arisen. These challenges assume a special significance in India where the preservation of forensic evidence is essential but it must be balanced with constitutional protections, individual rights, scientific acceptability and judicial review. Responsible application of DNA technologies is critical to sustaining the public trust and the integrity of the criminal justice system.[14]

A. Ethical Challenges

Ethical issues related to genetic information collection, storage, and analysis include privacy, informed consent, and data security. DNA comprises delicate personal and familial information that goes beyond individual identity, and unauthorized access or use is of serious concern. The adoption of these new technologies, such as forensic genetic genealogy and large DNA databases, also questions the presence of family members who are not directly involved in investigations. Ethical issues in India include issues of transparency and accountability in

[13] A. Caglià, P. Stefanoni, and A. La Rosa, "Cold cases: New technologies for DNA analysis allow the reopening and solution of unsolved cases," Forensic Sci. Int. Genet. Suppl. Ser., vol. 3, no. 1, pp. e230–e231, 2011, doi: https://doi.org/10.1016/j.fsigss.2011.09.001.

[14] P. Dessai et al., "A Review on Emerging Trends in Forensic DNA Profiling and Analysis," Int J Drug Deliv Technol, vol. 16, no. 46s, 2026, doi: 10.25258/ijddt.16.46s.34.

governance, access to genetic data and protection against discrimination or abuse of genetic information.[15]

B. Legal and Constitutional Challenges

Forensic DNA evidence admissibility and utilization in India should abide by the constitutional safeguards, such as the right to life and personal liberty guaranteed under Article 21 of the Constitution of India, including the right to privacy enshrined by the Supreme Court of India. Ensuring the chain of custody and the reliability of the evidence, DNA evidence must be collected, preserved and analyzed in a manner that complies with established legal procedures. The implementation of the Criminal Procedure (Identification) Act, 2022 has increased the number of biological measurements taken for identification and the Digital Personal Data Protection Act, 2023 gives a wider ambit for personal data protection. As these legal developments show, there is a need to strike a balance between effective criminal investigation and the safeguarding of individual rights and constitutional protection.[16]

C. Scientific Challenges

Although technology has improved, science limitations are still a factor. Analytical accuracy can be compromised by degradation of DNA, contamination, mixed biological samples, low template DNA and interpretation of complex genetic profiles. Standardized laboratory procedures, validated analytical methods, quality assurance systems and experienced forensic staff are also essential for advanced sequencing technologies. Variances in laboratory facilities, accreditation and technical skills in DNA labs in India still affect the uniformity and reliability of DNA analysis. The solution to these scientific challenges lies in standardizing procedures, ongoing education and training, and investing in state-of-the-art forensic equipment and infrastructure to maintain the validity and reliability of complex DNA evidence and its use in court.[17]

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[15] M. Yasir, M. Q. Adnan, and M. M. Zaman, "FORENSIC DNA ANALYSIS: ADVANCEMENTS AND OBSTACLES IN ITS APPLICATION AT CRIME SCENES," FORENSIC INSIGHTS Heal. Sci. Bull., vol. 4, no. 1, pp. 11–20, 2026, doi: https://doi.org/10.56770/fihsb2026413.

[16] S. Deo, "DNA as an Evidence: Legal and Ethical Challenges," SSEN elibrary, 2025, doi: http://dx.doi.org/10.2139/ssrn.6071086.

[17] B. Abebe, T. Mitiku, and N. Birhane, "Advancements in Forensic DNA Analysis: Challenges and Future Directions in Molecular Biology," Biomed. Sci., vol. 10, no. 3, pp. 51–61, 2024, doi: https://doi.org/10.11648/j.bs.20241003.11.

6 Conclusion

Forensic DNA technologies have developed beyond the basic concept of DNA profiling to become a multi-disciplinary science that can provide forensic scientists with a complete genetic intelligence for cases. Advancements in emerging technologies like Forensic Investigative Genetic Genealogy, Next-Generation Sequencing, Rapid DNA technology, Single Nucleotide Polymorphism analysis, forensic DNA phenotyping, epigenetic markers, microbial forensics and environmental DNA have greatly enhanced the identification of individuals, interpretation of complex biological evidence, and resolution of challenging cases. These innovations have enhanced the work of investigators in fields such as disaster victim identification, wildlife crime investigation, and crime scene reconstruction, among others, and have bolstered evidence collection in cold case investigations. As the application of advanced DNA technologies continues to grow, however, there are also important ethical, legal, and scientific issues to consider with respect to privacy, constitutional rights, data protection, laboratory standardization, and evidentiary reliability. The responsible use of these technologies demands robust regulations, forensic uniformities, qualified people and ongoing investment in the laboratory infrastructure in the Indian context. Going forward, technological innovation and ethical governance and legal accountability will need to be combined to maximize the contribution forensic DNA can make to the delivery of justice while protecting individual rights and maintaining the public confidence in the criminal justice system.

7 Reference

[1] S. Neidle, “Beyond the double helix: DNA structural diversity and the PDB,” J. Biol. Chem., vol. 296, p. 100553, 2021, doi: https://doi.org/10.1016/j.jbc.2021.100553.

[2] S. K. Alketbi, “Emerging Technologies in Forensic DNA Analysis,” SCIEPublish, pp. 1–24, 2024, doi: https://doi.org/10.70322/plfs.2024.10007.

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[6] S. Dishon, A. Gold, L. Sapir, E. Palit, and M. Amiel, “Enhancement of DNA recovery in rapid DNA technology: A novel pre-extraction protocol,” Forensic Sci. Int., vol. 380, p. 112826, 2026, doi: https://doi.org/10.1016/j.forsciint.2026.112826.

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[10] C. Gurkan, O. Bulbul, and K. K. Kidd, “Editorial: Current and Emerging Trends in Human Identification and Molecular Anthropology,” Front. Genet., vol. 12, pp. 10–12, 2021, doi: 10.3389/fgene.2021.708222.

[11] M. S. Petrovick et al., “Analysis of complex DNA mixtures using massively parallel sequencing of SNPs with low minor allele frequencies,” Forensic Sci. Int. Genet., vol. 46, p. 102234, 2020, doi: https://doi.org/10.1016/j.fsigen.2020.102234.

[12] Caglià, P. Stefanoni, and A. La Rosa, “Cold cases: New technologies for DNA analysis allow the reopening and solution of unsolved cases,” Forensic Sci. Int. Genet. Suppl. Ser., vol. 3, no. 1, pp. e230–e231, 2011, doi: https://doi.org/10.1016/j.fsigss.2011.09.001.

[13] P. Dessai et al., “A Review on Emerging Trends in Forensic DNA Profiling and Analysis,” Int J Drug Deliv Technol, vol. 16, no. 46s, 2026, doi: 10.25258/ijddt.16.46s.34.

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