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Identity at the Molecular Level: Advances in Forensic Biology and Human Identification

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Abstract

Analyses based on genetic material have been transformed by molecular forensic biology, which allows for the accurate and reliable analysis of DNA. The use of new technologies such as DNA Profiling, short tandem repeat (STR), mitochondrial DNA analysis, single nucleotide polymorphism (SNP) genotyping and rapid DNA systems has enhanced the examination of biological evidence in routine and complex forensic cases. New molecular techniques, including next-generation sequencing, forensic epigenetics, transcriptomics, and microbiome analysis, have also broadened the forensic science toolbox to help with age estimation and tissue identification, or to improve the analysis of degraded or mixed samples. These technologies can be used in crime scene investigation, disaster victim identification, kinship testing, and wildlife forensics. While all of this has been achieved, there are still problems of ethical governance, genetic privacy, laboratory standardization and the interpretation of complex genetic evidence, especially in developing forensic systems like India. Investment in advanced technologies, skilled personnel, accredited laboratories and robust regulatory frameworks will help to further develop molecular forensic biology and facilitate the accurate, ethical and efficient identification of human remains in the criminal justice system.

Keywords; Molecular Forensic Biology; Human Identification; DNA Profiling; Next-Generation Sequencing; Forensic Genetics

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1 Introduction

At the molecular level, the concept of identity has transformed the forensic science by allowing the identification of humans by analysing genetic material. Molecular identification is based on key genetic information, such as DNA, that can offer a unique genetic profile except for identical twins, whereas traditional identification methods are based on physical traits or personal records. DNA is relatively stable and can be extracted from a wide range of biological sources, including blood, saliva, hair, bone, and tissue, and has emerged as one of the most powerful tools for assigning identity, establishing biological relationships and connecting people to forensic evidence.[2]

The advent of forensic biology has greatly improved the accuracy and breadth of molecular HUMID. DNA profiling, short tandem repeat (STR) analysis, mitochondrial DNA analysis, single nucleotide polymorphism (SNP) genotyping and next-generation sequencing technologies have helped in the examination of degraded or limited biological samples. More recently, new techniques like forensic epigenetics, transcriptomics and microbiome analysis have extended the capacity to estimate the age of biological material, to identify the tissue of origin and to support forensic investigations beyond DNA analysis.[3]

While these technological developments will help address some of the challenges facing molecular forensic science, quality of evidence, interpretation of complex genetic information, ethical issues, privacy protection, and standardization of analytical procedures remain important issues. These issues must be addressed to keep molecular evidence reliable and admissible in court. This review addresses the core principles of forensic biology, recent developments in DNA technologies, new molecular techniques, significant forensic applications, ethical issues and future prospects of molecular human identification.

2 Foundations of Forensic Biology and Molecular Human Identification

Forensic biology is a specialized area of forensic science that involves detecting, collecting, examining and interpreting biological evidence in legal investigations. Biological materials like blood, saliva, semen, bone, teeth, skin cells and soft tissues provide DNA for identification and reconstruction of events, such as those in criminal and civil cases. The field uses analytical

[2] N. Sharma, A. Dey, A. Balayan, T. Millo, and S. K. Gupta, "Molecular Techniques used for Determination of Genetic Identity in Forensic Samples," J. Forensic Chem. Toxicol., vol. 4, no. 1, pp. 51–57, 2018, doi: DOI: http://dx.doi.org/10.21088/jfct.2454.9363.4118.5.

[3] J. M. Butler, "Recent advances in forensic biology and forensic DNA typing: INTERPOL review 2019–2022," Forensic Sci. Int. Synerg., vol. 6, p. 100311, 2023, doi: 10.1016/j.fsisyn.2022.100311.

science, biochemistry, genetics, and molecular biology to identify, preserve, and analyze biological evidence in a way that will preserve the evidence's evidentiary value during the investigative process.[4]

The basis of molecular human identification is that each person has a unique genetic makeup. Except for identical twins, every individual has a unique DNA sequence derived from both parents making it the best biological identifier of any person. Some parts of the human genome exhibit variation, not the whole sequence, which can be used to provide the discriminatory power needed for forensic comparisons. These genetic differences can help forensic scientists link the evidence to a single person, determine biological relationships and to identify unknown human remains with a high degree of scientific certainty.[5]

Molecular-based technologies have revolutionized forensic biology from a serological-based science to a genetic-based science. A well-defined molecular approach is used in modern forensic laboratories to better and more accurately identify remains with greater sensitivity and repeatability, even when biological specimens have suffered degradation or are present in minute amounts. Thus, molecular forensic biology has become an essential tool in modern forensic investigations, disaster victim identification, kinship analysis and judicial decisions, and is a powerful scientific tool to support the fair administration of justice.[6]

3 Advances in DNA Technologies for Human Identification

Recent developments in DNA technology have significantly improved the accuracy, sensitivity and efficiency of human identification in forensic investigations. Forensic scientists can now use modern molecular techniques to analyse a wide range of biological samples, regardless of

[4] A. A. Shah, I. U. Malik, R. M. Fazal, S. Umar, and S. H. Ahmad, "Evolution of Laboratory Techniques in Forensic Biology: From Conventional Methods to Modern Molecular Approaches," Phys. Educ. Heal. Soc. Sci., vol. 4, no. 1, pp. 765–776, 2026, doi: https://doi.org/10.63163/jpehss.v4i1.1216.

[5] N. Girdhar, D. Sharma, R. Kumar, M. Sahu, and C. Lin, "Emerging trends in biomedical trait-based human identification: A bibliometric analysis," SLAS Technol., vol. 29, 2024, doi: https://doi.org/10.1016/j.slast.2024.100136.

[6] M. Kowalczyk, E. Zawadzka, D. Szewczuk, M. Gryzińska, and A. Jakubczak, "Molecular markers used in forensic genetics," Med. Sci. Law, vol. 58, pp. 201–209, 2018, [Online]. Available: https://api.semanticscholar.org/CorpusID:52892668

the quality or quantity, and enhance the identification of individuals in criminal, civil and humanitarian cases.[7]

A. DNA Profiling and STR Analysis

DNA profiling is still the primary method for forensic human identification. The technique fundamentally involves the use of Short Tandem Repeats (STRs), parts of the human genome that are highly polymorphic, meaning they are very different among individuals. Comparing STR profiles from biological evidence to a reference sample or DNA database can help a forensic scientist determine with a high level of statistical certainty who the individuals are. A small amount of DNA is all that is required for STR and it is very useful in routine forensic cases.[8]

B. Mitochondrial DNA and Y-Chromosome Analysis

When conventional STR profiling is limited, mitochondrial DNA (mtDNA) and Y-chromosome analysis can be used as excellent alternatives. It is important to note that mtDNA exists in multiple copies per cell, so it is very useful for the analysis of highly degraded samples like bones, teeth, and hair shafts. Y-chromosome markers, on the other hand, are passed down by the male, and help identify male contributors in mixed biological samples and resolve paternal relationship investigations.[9]

C. Single Nucleotide Polymorphisms (SNPs) in Forensic Genetics

Single Nucleotide Polymorphisms (SNPs) are single-base changes that are scattered across the entire human genome. Individual SNPs have a lower discriminatory power than STRs, but large SNP panels can be used for reliable identification from degraded DNA and ancestry inference, phenotype prediction, and kinship analysis. The stability and compatibility of these with advanced sequencing platforms have broadened their forensic genetics uses.[10]

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[7] M. Kayser, W. Branicki, W. Parson, and C. Phillips, "Recent advances in Forensic DNA Phenotyping of appearance, ancestry and age," Forensic Sci. Int. Genet., vol. 65, p. 102870, 2023, doi: https://doi.org/10.1016/j.fsigen.2023.102870.

[8] S. Panneerchelvam and norazmi M. Nor, "DNA Profiling in Human Identification: From Past to Present," Malays J Med Sci., vol. 30, no. 6, pp. 5–21, 2023, doi: https://doi.org/10.21315/mjms2023.30.6.2.

[9] A. Amorim, T. Fernandes, and N. Taveira, "Mitochondrial DNA in human identification: a review," PeerJ, 2019, doi: 10.7717/peerj.7314.

[10] N. M. M. Novroski and J. C. Cihlar, "Evolution of single-nucleotide polymorphism use in forensic genetics," WIREs Forensic Sci., vol. 4, no. 6, p. e1459, Nov. 2022, doi: https://doi.org/10.1002/wfs2.1459.

D. Rapid DNA Technology and Automation

Rapid DNA technology combines automated DNA extraction, amplification, separation and profile generation in a portable device that can generate DNA profiles in a few hours. Automation cuts down on repetitive tasks, potential contamination and speeds up investigation decision making. These systems have enhanced timely processing of forensic evidence, disaster victim identification and border security applications while also ensuring standardized analytical procedures.[11]

4 Emerging Molecular Approaches in Forensic Biology

With the rapid development of molecular biology, novel techniques are emerging that complement traditional DNA analysis. The new technologies offer genetic and biological information, which can bypass the constraints of degraded samples, complex DNA mixtures and samples where conventional DNA profiling is insufficient. Consequently, they are increasingly being incorporated into forensic research and focused investigations.[12]

A. Next-Generation Sequencing (NGS) in Forensic Science

Forensic genetics has been revolutionized by Next Generation Sequencing (NGS) which allows millions of DNA fragments to be sequenced at once in a single run. NGS can analyze STRs, Single Nucleotide Polymorphisms (SNPs), mitochondrial DNA, and other markers within a single workflow, compared to traditional capillary electrophoresis methods. The high throughput capacity enhances analysis of degraded samples, complex DNA mixtures, or low template DNA, and offers higher genetic resolution for human identification.[13]

B. Epigenetic Markers for Age and Tissue Identification

Epigenetic markers are chemical changes to the DNA that affect how it is expressed without changing the bases in the DNA sequence. Of these, the DNA methylation profile has been found to be quite useful in forensic applications such as biological age estimation and tissue source

[11] 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.

[12] N. Sharma, "A Landscape of Molecular Methods in Forensic Investigations," Rom. J. Leg. Med., vol. 33, pp. 261–270, Sep. 2025, doi: 10.4323/rjlm.2025.261.

[13] 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.

determination of blood, saliva, or semen. These markers are informative and help in the interpretation of the forensic information, in addition to the traditional DNA markers.

C. Forensic Transcriptomics and RNA Biomarkers

Forensic transcriptomics is the study of RNA molecules for the purpose of characterizing biological samples. The tissue-specific expression pattern of those RNA biomarkers allows for forensic scientists to accurately differentiate between body fluids and tissues. It is especially useful when a DNA profile cannot be used to determine the source of a sample, in order to reconstruct events in the crime scene and aid interpretation of the biological evidence.[14]

D. Microbiome-Based Human Identification

Human identification based on the microbiome is a new area of research focused on human-associated microbial communities. Individuals can have different microbial populations and different body sites can have different populations, leading to different microbial signatures. Investigation of these signatures can help identify persons at objects or locations, estimate post mortem interval, and aid in forensics when traditional genetic data is sparse. While additional validation and standardization is needed, there is potential for the use of microbiome analysis as a complementary tool to existing molecular forensic methods.[15]

5 Applications of Molecular Forensic Biology in Criminal and Civil Investigations

The use of molecular forensic biology has made it an invaluable tool in contemporary criminal and civil investigations and has proven to be a scientifically sound way to identify individuals and analyze biological evidence. DNA related technologies have other uses such as in humanitarian, legal, environmental and conservation settings, reflecting the wide scope of molecular technologies in the administration of justice.

A. Crime Scene Investigation and Biological Evidence Analysis

The proper collection and analysis of blood, saliva, semen, hair, skin cells, and other body fluids are critical to crime scene investigation. Forensic scientists can use molecular techniques to obtain DNA profiles from these samples, provide a link between suspects, victims and crime scenes and attempt to reconstruct the sequence of events. Advanced molecular techniques can

[14] F. Lei et al., "Forensic Transcriptomics: Research Progress of the Past Two Decades.," Genomics. Proteomics Bioinformatics, Feb. 2026, doi: 10.1093/gpbjnl/qzag007.

[15] W. K. Mousa, F. Chehadeh, and S. Husband, "Recent Advances in Understanding the Structure and Function of the Human Microbiome," Front. Microbiol., vol. 13, 2022, doi: 10.3389/fmicb.2022.825338.

be used to provide valuable forensic information from even trace or degraded biological material.[16]

B. Missing Persons and Disaster Victim Identification

The analysis of DNA is vital in identifying missing persons and victims of natural disasters, accidents, armed conflicts, and mass casualty incidents. Biological samples found in human remains are matched with reference samples collected from personal effects or other biological family members to determine identity. When regular DNA samples are highly degraded or are not available, specialized DNA markers are invaluable, such as mitochondrial DNA.[17]

C. Kinship, Paternity, and Relationship Testing

Molecular forensic biology offers highly accurate means of establishing biological relationships based on DNA comparisons of inherited genetic markers. The screening with DNA is very common in paternity and maternity tests, inheritance claims, immigration matters, verification of adoption and family reunification. Comparing genetic profiles by statistics helps to determine the biological relationship with scientific certainty.

D. Wildlife and Environmental Forensic Applications

The molecular forensic biology principles are now being used more and more in wildlife conservation and protecting the environment. DNA analysis can help determine the identity of illegally traded animal species, aid wildlife investigations and wildlife trafficking investigations, and confirm the source of biological materials. Environmental DNA (eDNA) has also proven to be a valuable tool for biodiversity assessment, endangered species detection, and environmental law enforcement. The following applications show that molecular forensic methods can not only be applied to the field of criminal justice, but are also relevant to the conservation of biodiversity and sustainable environmental management.[18]

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[16] H. Rajput, "Biological Evidence for Crime Investigation," J. Digit. Secur. Forensics, vol. 1, no. 1, pp. 34–52, 2024, doi: 10.29121/DigiSecForensics.v1.i1.202 4.23.

[17] D. North, L. M. Howes, and J. Dwyer, "The scene phase of disaster victim identification (DVI): Lessons learned from deployments, training, and police and defence force collaborative exercises," Sci. Justice, vol. 66, p. 101430, 2026, doi: https://doi.org/10.1016/j.scijus.2026.101430.

[18] M. De Bruyn, C. K. Harper, and M. Theresa, "A septennium review of wildlife forensic DNA analysis in South Africa," Forensic Sci. Int. Genet., vol. 80, 2026, doi: https://doi.org/10.1016/j.fsigen.2025.103339.

6 Ethical Considerations, and Challenges in Molecular Forensics

Molecular forensic technologies have had tremendous growth and now have the ability to enhance the accuracy of human identification and criminal investigation. Yet, the growing applications of DNA Profiling, genetic databases and the new sequencing technologies have also introduced important ethical, legal and operational issues. The acceptance of molecular forensic evidence in India is increasing in criminal investigations and judicial proceedings with the development of forensic infrastructure and modernization of forensic laboratories. However, for them to be applied in an ethical and responsible manner, there must be ethical guidelines, strong legal protections and established scientific procedures.

A. Ethical Considerations

Ethical use of molecular forensic techniques is necessary to ensure the protection of individual rights and the public's trust in the criminal justice system. The collection, storage, and analysis of DNA profiles involve sensitive genetic information and, for this reason, privacy and confidentiality are paramount concerns. For civil cases like paternity testing and kinship testing, informed consent is an important factor, while in criminal cases, care must be taken to ensure that DNA collection meets the requirements of the applicable laws and may be subject to judicial control. Governance is important to ensure that DNA databases are established and managed safely and effectively without unauthorized access, misuse of genetic information, or discrimination on the basis of genetic data in the Indian context. Ethical forensic practice also requires transparency, an impartially given interpretation of the results, and use of scientifically proven methods in such a way that molecular evidence is presented in the interest of justice, but not the infringement of individual rights.[19]

B. Challenges

Although significant strides have been made, there are still a number of impediments to the use of molecular forensics in India. Forensic laboratories often face high case loads, a lack of cutting edge analytical equipment, and a lack of forensic geneticists and technical staff. Mishandling of crime scenes, contamination, and degradation of the samples during collection and transportation also can result in poor quality forensic evidence. Furthermore, complex DNA mixtures and low template samples are still a scientific challenge and demand expert skills. The consistency and reliability of forensic results are also influenced by the differences in the

[19] L. J. Heathfield, S. Maistry, L. J. Martin, R. Ramesar, and J. De Vries, "Ethical considerations in forensic genetics research on tissue samples collected post- mortem in Cape Town, South Africa," BMC Med. Ethics, vol. 18, no. 66, pp. 1–8, 2017, doi: 10.1186/s12910-017-0225-6.

laboratory infrastructure, quality assurance procedures and accreditation standards. Therefore, it is imperative to tackle these challenges by investing in infrastructure, training, implementing standardized protocols, and enforcing regulations to improve the credibility and effectiveness of molecular forensic science in India.[20]

7 Future Perspectives in Forensic Biology and Human Identification

The future of forensic biology looks promising with ongoing progress in molecular technologies, AI, and bioinformatics, which will enhance human identification with greater accuracy, speed, and comprehensiveness. The use of advanced analytical techniques coupled with standardized laboratory procedures will enhance the reliability and efficiency of forensic investigations, as the use of genetic evidence becomes more important. The modernization of forensic laboratories in India and the increasing use of molecular diagnostic technologies are anticipated to enhance the country's ability to solve the complex criminal investigations and humanitarian identification processes.[21]

Other new technologies such as next generation sequencing (NGS), forensic DNA phenotyping, epigenetic analysis and microbiome profiling are expected to supplement traditional DNA profiling with extra data regarding an individual's physical appearance, biological age, tissue origin, and ancestry. The use of artificial intelligence and machine learning in forensic data analysis could provide additional tools for deciphering complex DNA mixtures, assist with pattern matching, and help minimize analytical errors. Portable Rapid DNA systems will also aid in prompt identification in disaster victim management, border security and crime scene investigation.[22]

Technological innovations will be the only way forward for future progress but in the Indian context, the next step will involve building up the forensic infrastructure, extending the number of accredited laboratories and building out a very skilled workforce in molecular genetics and forensic science. Close collaboration between research institutions, universities, forensic institutes, police and judicial authorities will be needed to put the scientific innovations into practice. Moreover, the development of strong regulations, ethical management of genetic information and fostering ongoing research and capacity development will help India maximize

[20] P. Sahoo, “Ethical issues in forensic DNA analysis,” 2026, pp. 407–423. doi: 10.1016/B978-0-443-30128-5.00027-8.

[21] J. Butler, “Recent advances in forensic biology and forensic DNA typing: INTERPOL review 2019–2022,” Forensic Sci. Int. Synerg., vol. 6, p. 100311, Jan. 2023, doi: 10.1016/j.fsisyn.2022.100311.

[22] A. K. Rana, “The Future of Forensic Biology,” J. Biomed., vol. 3, 2018, doi: 10.7150/jbm.22760.

the benefit of molecular forensic biology while protecting individual rights and public confidence in the justice system.[23]

8 Conclusion

At the molecular level, identity has changed the course in forensic biology, offering some of the most reliable molecular tools for human identification. DNA technologies, emerging molecular methods are making the ongoing forensic investigation more and more accurate, sensitive and efficient, with the ability to process degraded DNA, complex mixtures of DNA and trace biological evidence. In addition to the criminal investigation applications, molecular forensic biology is also a vital tool for disaster victim identification, kinship analysis, missing persons investigations and wildlife conservation. Meanwhile, the growing applications of genetic data have placed a strong spotlight on ethical issues, the need for data protection, and the need for uniform laboratory procedures. To maximize the benefits of molecular forensic technologies in India, it is crucial to strengthen forensic infrastructure, augment the number of accredited laboratories, build skilled human resources, and establish comprehensive regulatory frameworks. The inclusion of artificial intelligence, bioinformatics and advanced sequencing platforms in the future will likely further enhance the forensic capabilities as well. In general, molecular forensic biology will remain a key component in providing reliable human identification and in the development of a clear, evidence-based and scientifically sound justice system.

9 Reference

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[23] I. A. Gutiérrez-hurtado, M. E. García-acéves, Y. Puga-carrillo, M. Guardado-estrada, D. S. Becerra-loaiza, and V. D. Carrillo-rodríguez, “Past, Present and Future Perspectives of Forensic Genetics,” Biomolecules, vol. 15, no. 713, 2025, doi: https://doi.org/10.3390/ biom15050713.

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[12] 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.

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