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**Investigative Frontiers Integration of Science Transforming Criminal Investigation**

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# Biotechnology in the Courtroom: Applications and Frontiers in Criminal Investigation

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**Abstract**

Biotechnology is a game-changing technology for contemporary criminal investigations, bringing together molecular biology, genetics, microbiology, and bioinformatics into forensic science and judicial practices. This review addresses the role of biotechnology in the courtroom, its scientific principles, the key techniques in forensic biotechnology, and the significance of biological evidence in criminal investigations. It addresses major applications such as DNA Profiling, Crime scene investigation, Kinship analysis, Forensic toxicology, Disaster victim identification, Sexual assault investigation, Forensic genealogy, etc. that have greatly enhanced the accuracy and reliability of human identification. The review also delves into new areas like next generation sequencing, forensic epigenetics, transcriptomics, proteomics, microbiomics, artificial intelligence and rapid DNA technologies that are transforming forensic practice. Further, it examines the admissibility, ethical issues and regulations relating to biotechnology evidence in India. Finally, the review highlights future developments that will further support evidence-based investigations, improve judicial decision-making and create a more effective, transparent, and technologically advanced criminal justice system.

***Keywords; Biotechnology, Forensic Science, DNA Profiling, Criminal Investigation, Human Identification.***

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## 1 Introduction

Biotechnology has revolutionized the way criminals are identified, biological evidence is analyzed and criminal events reconstructed, providing new scientific tools for solving crimes with unprecedented accuracy. A courtroom biotechnology is the application of molecular biology, genetics, microbiology, biochemistry and other life sciences to the legal process to supply objective and scientifically sound evidence. Biotechnological techniques allow investigators to draw factual conclusions from measurable biological characteristics, which is an alternative method to traditional investigative techniques, such as eyewitness testimony, confessions, and circumstantial evidence. This change has certainly boosted the value of forensic evidence and helped courts make fair and evidence-based decisions.[2]

Biotechnology in the courtroom is used not only for traditional DNA profiling but for a wide range of forensic applications, such as genomic sequencing, forensic toxicology, microbial analysis, body fluid identification, forensic pathology, and molecular biomarker analysis. The technologies enable the analysis of blood, saliva, semen, hair, skin, bone and tissue samples from crime scenes, helping to identify suspects, determine the victim's identity, establish the biological connections, estimate the post mortem time and reconstruct the sequence of criminal events. The evidence value of biological materials continues to grow as new high throughput sequencing, bioinformatics, and molecular diagnostic technologies are developed, and are often more evident in highly degraded samples or those that are only available in small quantities.[3]

Advancements in biotechnology are increasingly being applied to criminal justice beyond the laboratory to enable broader decision support within the investigative and judicial process. Results obtained using the validated biotechnological approaches have proved to be essential for supporting investigative hypotheses, innocence testing and establishing the admissibility of forensic evidence in court. As a result, biotechnology has become a major scientific force in the criminal investigation field, where laboratory innovation meets judicial decision-making, and has the potential to increase the accuracy, transparency, and confidence in the administration of justice.[4]

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[2] N. Moreira et al., “Biotechnology Applied to Forensic Sciences Nicole,” Appl. Sci., vol. 16, no. 5899, pp. 1–24, 2026, doi: https://doi.org/10.3390/app16125899.

[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: https://doi.org/10.1016/j.fsisyn.2022.100311.

[4] A. A. Gupta, “Biotechnology and Patent Laws: Indian and International Perspective,” Int. J. Innov. Sci. Eng. Manag., vol. 5, no. 2, pp. 1–10, 2026, doi: 10.69968/ijisem.2026v5i21-10.

## 2 Biotechnological Foundations of Forensic Science: Principles, Techniques, and Biological Evidence

Biotechnology is the scientific backbone of modern forensic science; its use allows for the correct examination of biological materials for criminal investigations. This new approach to forensic science, called forensic biotechnology, combines molecular biology, genetics, microbiology, biochemistry, and analytical technologies, enabling investigators to identify individuals, prove biological relationships, determine the source of a biological sample, and reconstruct events involved in crime scenes. Forensic conclusions are not only a result of high tech laboratory techniques, but rely on scientifically sound principles that lead to accurate results, reproducibility, and are acceptable in court. Because of this, biotechnology is now an integral part of the Evidence-Based Criminal Justice (EBCJ) movement.[5]

### A. Principles

Forensic biotechnology relies on the principles of uniqueness, stability and inheritance of biological characteristics. Each person, apart from identical twins, has a unique DNA signature that can be diagnosed by DNA testing. The collection, preservation and analysis of biological evidence should be standardized to avoid contamination and degradation. The principles of scientific validation, quality assurance, chain of custody and reproducibility are fundamental aspects that help guarantee the reliability and acceptability of forensic findings in judicial proceedings.[6]

### B. Techniques

A variety of analytical techniques have been used in modern forensic biotechnology to analyze biological evidence. Short tandem repeat (STR) analysis is the most common technique used for human identification with DNA.[7] Polymerase chain reaction (PCR) is used to amplify small amounts of DNA, thus allowing analysis of degraded or trace samples. Other methods involve mitochondrial DNA analysis, Y-chromosome analysis, next-generation sequencing (NGS), forensic serology, forensic toxicology, protein-based biomarker analysis and microbial

[5] M. Sangeetha, "Critical Study of Biotechnology and Human Genetic Diversity for Its Uses in Forensic Investigation," Int. J. Creat. Res. Thoughts, vol. 9, no. 11, pp. 47–54, 2021.

[6] T. D'Anna et al., "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, vol. 11, no. 634, 2023, doi: https://doi.org/10.3390/ healthcare11050634.

[7] S. Antil and V. Joon, "Biotechnology in Forensic Science: Advancements and Applications," J. Forensic Sci. Res., pp. 7–14, 2025, doi: https://dx.doi.org/10.29328/journal.jfsr.1001073.

profiling. The incorporation of bioinformatics further contributes to the interpretation of complex genetic data, making it more accurate and efficient in forensic investigations.[8]

### C. Biological Evidence

Biological evidence includes any material from living organisms that may be useful to a criminal investigation. Blood, saliva, semen, hair with roots, cells of skin, bone, teeth, tissue, urine and other body fluids are commonly used as forensic specimens. The samples are used for the determination of individual identity, victim or suspect involvement, relationships of living things, estimate post-mortem changes or reconstruct crime events and include DNA, proteins, metabolites or microorganisms. Collection, preservation, transportation, and laboratory analysis of biological evidence are essential to preserve and strengthen the integrity and evidentiary value of the evidence throughout the judicial process.[9]

## 3 Applications of Biotechnology in Criminal Investigation and Human Identification

Biotechnology has transformed criminal investigation by offering the ability to scientifically, reliably and accurately analyze biological evidence. Advances in molecular biology, genetics, microbiology, and analytical biotechnology have greatly enabled the forensic scientist to be able to identify individuals, make links between suspect and crime scene, reconstruct a criminal event, and assist in judicial decisions. Modern biotechnological methods allow even small and/or damaged biological remains to be examined, thus allowing the analysis of these remains to be of great value in complex cases. Consequently, Biotechnology is one of the most critical scientific tools available to ensure objective and evidence-based criminal investigations and to enhance the administration of justice.[10]

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[8] 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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[10] F. Althobaiti, A. L. T. Alanazi, A. A. Abuharbah, L. A. A. Alharbi, Y. A. S. Alhussaini, and G. A. Alhazmi, "Biotechnological Applications In Forensics: Questioning The Effect Of Sun Light Conditions On Dna Integrity Extracted From Blood And Hair Samples," J. Popul. Ther. Clin. Pharmacol., vol. 31, no. 02, pp. 2000–2007, 2024, doi: 10.53555/jptcp.v31i2.4569.

**Important Applications of Biotechnology in Criminal Investigation and Human Identification**

i. **DNA Profiling and Human Identification:** The most important application of biotechnology in forensic science is DNA profiling. It allows to identify suspects, victims and missing persons based on the unique genetic profile derived from blood, saliva, semen, hair, bone, and skin cells.[11]
ii. **Crime Scene Investigation:** Biotechnology provides the ability to detect, collect, and analyze biological evidence at crime scenes, which can be used to connect suspects, victims, weapons, and scene sites and to reconstruct the sequence of events in a crime.
iii. **Kinship and Parentage Analysis:** In criminal, civil and disaster victim identification, establishing biological relationships such as parentage, siblings, and family lineage by DNA-based testing is broadly used.[12]
iv. **Sexual Assault Investigations:** Identification of perpetrators, confirmation of victim statements, and good forensic evidence in sexual offence cases are all possible with molecular analysis of semen, saliva, epithelial cells, and mixed DNA samples.[13]
v. **Post-Mortem and Disaster Victim Identification:** In mass disasters and investigations of unidentified bodies, bones, teeth, and preserved tissues are analyzed using biotechnology to identify human remains that have been decomposed, burned, and/or fragmented.[14]
vi. **Forensic Toxicology:** During criminal investigations, drugs, alcohol, poisons, and toxic substances are detected using biotechnological methods to determine intoxication or poisoning or the cause of death.
vii. **DNA Database Comparison:** DNA profiles produced through crime scene evidence are matched to national forensic DNA databases to find repeat offenders, link serial crimes and exclude innocent people from investigations.

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[11] O. C. Maxwell and C. C. Prince, "Application of DNA Forensic Evidence in Criminal Justice System," Int. J. Res. Innov. Appl. Sci., vol. X, no. III, pp. 312–320, 2025, doi: 10.51584/IJRIAS.

[12] R. Allen, "Parentage Testing and Kinship Analysis," in Encyclopedia of Forensic Sciences, Third Edition (pp.100-112), 2022, pp. 100–112. doi: 10.1016/b978-0-12-823677-2.00215-4.

[13] A. Apostolov, "Medical Biotechnology: Differentiation of mixed biological traces in sexual assaults using DNA fragment analysis," Biotechnol. Biotechnol. Equip., vol. 28, no. 2, pp. 301–305, 2014, doi: http://dx.doi.org/10.1080/13102818.2014.909171.

[14] D. Tawfik, "Disaster victim identification: a narrative review of innovations and ethical considerations," J. Emerg. Disaster Med., vol. 2026, 2026, doi: https://doi.org/10.1007/s44467-026-00010-3.

viii. **Forensic Genealogy:** Using advanced DNA analysis and genealogical information helps investigators identify unknown victims and criminal suspects by using biological family members, especially in long unsolved cases.

ix. **Cold Case Investigation:** Advances in molecular technology make it possible to reconstruct cases that were previously unsolvable and to revisit old biological evidence for a new investigation, and to do so with greater scientific precision.

x. **Exoneration of Wrongfully Convicted Individuals:** DNA evidence is helping to re-evaluate convictions, fill in investigative gaps and prove innocence, and thus strengthening the integrity and legitimacy of the criminal justice system.

In these applications, the use of biotechnology technology has come to be an essential part of modern forensic science. Biotechnology is continuing to advance criminal investigations and improve the accuracy, transparency, and integrity of justice, with the ability to identify a person, analyse biological evidence, and provide scientifically sound investigative results.

## 4 Emerging Frontiers in Forensic Biotechnology

The field of forensic science is undergoing rapid development in the area of biotechnology and is no longer limited to conventional DNA profiling and biological evidence analysis. Genomics, epigenetics, microbiology, bioinformatics and computational sciences are all evolving and improving the information that can be extracted from a biological specimen, making it more complete and accurate than ever before for a forensic investigator. These new technologies enable better analysis of degraded or trace evidence, better human ID, better crime scene reconstruction, and new understanding of individual characteristics and the contexts of criminal events. While some of these methods are still in the process of undergoing scientific validation and standardization, they are the next generation of forensic tools that could revolutionize criminal investigations and judicial decision making.

### Emerging Frontiers in Forensic Biotechnology

i. **Next-Generation Sequencing (NGS):** Allows the simultaneous analysis of millions of DNA fragments for increased discrimination, better analysis of a mixture of DNA and superior analysis of highly degraded DNA evidence.

ii. **Forensic Epigenetics:** Analyzes DNA methylation and other epigenetic markers for estimating biological age, the distinction of identical twins, body fluid identification and studying the effect of environment on gene expression.[15]

iii. **Forensic Transcriptomics (RNA Analysis):** Improves biological evidence characterization by confidently identifying body fluids (blood, saliva, semen, and vaginal secretions) through the use of messenger RNA (mRNA) and microRNA (miRNA) biomarkers.[16]

iv. **Forensic Proteomics:** Identifies biological materials, estimates post-mortem interval, determines tissue origin, and analyzes samples lacking DNA or where DNA is degraded, by examining protein biomarkers.

v. **Forensic Microbiomics:** Examines the microbiota of the human body and its environment, and how these communities can be used to help identify an individual, to estimate the time of death, to determine the geographic location of a body, and to reconstruct a crime scene.[17]

vi. **Rapid DNA Technology:** Automated extraction and amplification of DNA combined with profiling in mobile systems, enabling investigators to get DNA results within a couple of hours, rather than several days.

vii. **Forensic Phenotyping:** When no suspect is available for comparison, makes predictions about external features e.g. eye color, hair colour, pigmentation and origin of ancestry based on DNA.

viii. **Artificial Intelligence and Machine Learning:** Implements forensic biotechnology by automating the process of DNA mixture interpretation, pattern recognition, data analysis and predictive modeling, leading to greater accuracy and human error reduction.[18]

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[15] O. A. Mahmoud, D. A. Muhammed, S. M. Ibrahim, M. A. Hameed, S. H. Muhi, and F. B. Abd, "Epigenetic Technologies in Forensic Sciences: A New Frontier for Human Identification," Baghdad J. Biochem. Appl. Biol. Sci., vol. 7, no. 1, pp. 22–30, 2026, doi: https://doi.org/10.47419/bjbabs. v7i1.432.

[16] S. Shao, L. Yang, G. Hu, L. Li, Y. Wang, and L. Tao, "Application of omics techniques in forensic entomology research," Acta Trop., vol. 246, p. 106985, 2023, doi: https://doi.org/10.1016/j.actatropica.2023.106985.

[17] J. M. Robinson, Z. Pasternak, C. E. Mason, and E. Elhaik, "Forensic Applications of Microbiomics: A Review," Front. Microbiol., vol. 11, pp. 1–13, 2021, doi: 10.3389/fmicb.2020.608101.

[18] V. Bugelli, F. Calabrò, J. Camatti, R. Cecchi, M. Di Paolo, and L. Franceschetti, "Artificial intelligence in forensic science: a systematic review. Part II: long-range postmortem interval estimation," Int. J. Legal Med., 2026, doi: https://doi.org/10.1007/s00414-026-03856-4 REVIEW Artificial.

ix. **Bioinformatics in Forensic Analysis:** Uses sophisticated computational tools to analyze, interpret and manipulate large-scale genomic and molecular data from modern sequencing technologies.

x. **Single-Cell Genomics:** Allows DNA testing on a single cell, resulting in better interpretation of complex mixed biological materials typical of sexual assault and violent crime cases.

xi. **Portable and Lab-on-a-Chip Forensic Devices:** Miniaturized analytical platforms enable expedient on-site discovery and preliminary analysis of biological evidence, minimizing laboratory turnaround time and aiding rapid investigations.

These emerging frontiers are examples of the continuous development of forensic biotechnology from a molecular-based analysis to a very integrated and data-driven forensic system. As these technologies are validated and adopted into the forensic field, their use is expected to increase the rapidity, accuracy and confidence of criminal investigations and augment the scientific evidence available for use in judicial proceedings.

## 5 Legal Admissibility, Ethical Challenges, and Regulatory Frameworks for Biotechnological Evidence

The increasing use of biotechnology in criminal investigations has significantly enhanced the accuracy and reliability of forensic evidence. But scientific evidence with biotechnological applications does need a legal aspect, an ethical responsibility, and a regulatory oversight to ensure that justice is applied fairly. The use of biotechnology based forensic evidence including DNA analysis is becoming increasingly significant in Indian criminal cases involving homicide, sexual crimes, missing persons, disaster victim identification and terrorism. However, the admissibility of such evidence is not only based on the scientific reliability but also on the adherence to the legal procedures, compliance of evidence collection, the chain of custody, the accreditation of the laboratory and respect for the rights of the individual. The future of forensic biotechnology poses a dilemma for India, as it has to reconcile with constitutional safeguards, ethics and judicial norms along with advancing technology.

### A. Legal Admissibility

Biotechnological evidence, as an important aspect of judicial proceedings, is regulated mainly by Bharatiya Sakshya Adhiniyam, 2023, which introduces the concept of scientific and electronic evidence. If collected, preserved, analysed and presented in accordance with prescribed scientific methods, then DNA evidence is readily accepted in the Indian courts. Forensic evidence is admissible only if it has been properly maintained in a continuous chain of custody, the laboratory has quality control, the analytical method has been validated, and the

expert will explain the scientific findings in a clear manner. In assessing biotechnology evidence, courts consider the evidence in conjunction with other corroborating evidence to assure it is scientifically sound, relevant, and legally accepted.[19]

### B. Ethical Challenges

Biotechnology is increasingly being used, and presents several ethical issues with respect to privacy, informed consent, confidentiality and the responsible use of genetic information. DNA samples carry a wealth of personal and family data, and not only is this information valuable for identification, but it can also be accessed, misused, or used for discriminatory purposes. There are also ethical concerns with collecting biological specimens from vulnerable persons, with long term storage of genetic samples, and with the growing size of forensic DNA databases. Algorithms, artificial intelligence, and forensic genealogy are among the emerging technologies that also cast new light on the impact of such practices on personal privacy, algorithmic bias, transparency, violations of fundamental rights, and more. Ethical principles must be followed to address these concerns, which will promote human dignity and effective criminal investigations.[20]

### C. Regulatory Frameworks

Over the years, India has been making significant strides in strengthening its regulatory framework for forensic biotechnology, with a focus on legislative changes, judicial oversight, and institutional development. Bharatiya Nyaya Sanhita, 2023 includes scientific evidence in criminal investigations and prosecution while Bharatiya Nagarik Suraksha Sanhita, 2023 spells out the legal provisions for medical examination of accused, collection of biological samples during criminal investigations. The DNA Technology (Use and Application) Regulation Act, 2025 provides for a comprehensive legal regime for the collection, processing, storage, use and destruction of DNA data, including protections of privacy, quality assurance, accreditation of DNA laboratories and establishment of DNA data banks. Apart from this, the Digital Personal Data Protection Act, 2023 offers a general legal framework for safeguarding personal data, which can encompass sensitive information that could be relevant to forensic investigations. These regulations are also designed to promote the responsible and responsible use of

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[19] I. Podroykina, A. Gabercorn, L. Popova, A. Sirakanian, and N. Tovmasyan, "Legal, Technical, And Ethical Challenges in the Use of Biotechnology for Crime Scene Examination," Veredas do Direito, 2026, doi: http://dx.doi.org/10.18623/rvd.v23.6042.

[20] O. Varypaiev, N. Serohina, N. Serediuk, I. Dorozhko, And O. Silvestrova, "Ethical Challenges In Biotechnology: Exploring The Boundaries Of Scientific Intervention," Synesis, vol. 17, no. 1, pp. 1–20, 2025, doi: 10.5281/zenodo.15095501.

biotechnology, its scientific integrity and compliance with the rule of law and constitutional principles and in conjunction with guidelines from the forensic science institutions and accreditation standards adhered to by forensic laboratories.[21]

## 6 Future Perspectives on Biotechnology-Driven Criminal Investigation

Biotechnology innovations will have a growing impact on the future of criminal investigation, particularly in the accuracy, speed, and reliability of a forensic analysis. New technologies like next-generation sequencing, forensic epigenetics, proteomics, microbiomics, and rapid DNA analysis are predicted to amplify the range of biological evidence, allowing investigators to be able to be able to get meaningful information from highly degraded, mixed or trace evidence. The innovations will enhance human identification, crime scene reconstruction, victim identification, and the solving of the most complex cases that still would be difficult with traditional forensic techniques.

Biotechnology coupled with artificial intelligence, machine learning and bioinformatics will undoubtedly revolutionize forensic laboratories into intelligent analytical systems that will process vast amounts of genetic and biological data with greater accuracy and efficiency. In addition to the various types of portable forensic devices and automated laboratory platforms will help to save analysis time, enabling investigators to provide timely findings and scientific accuracy. These innovative technologies will enhance evidence-based investigations and the effectiveness of criminal justice.[22]

In spite of these encouraging advances, the achievement of the successful application of biotechnology in the criminal investigation process will rely on ongoing scientific validation, procedures, laboratory certification, and on-going training of the forensic practitioners. Equally important is the development of solid legal and ethical guidelines to protect privacy and prevent use of genetic information without consent, as well as ensuring public confidence in forensic technologies. In India and other nations, improving the infrastructure of forensic science, fostering research partnerships, and encouraging multi-disciplinary innovation will be vital to realizing the full potential of biotechnology. With the continued evolution of biotechnology, it is anticipated that it will become an integral part of the modern criminal investigation process

[21] M. Res, T. Covid-, T. Ebola, E. M. Agency, and U. S. Food, “Revisiting regulatory framework in India for accelerated vaccine development in,” no. August, pp. 156–163, 2020, doi: 10.4103/ijmr.IJMR.

[22] V. Bugelli, F. Calabrò, J. Camatti, R. Cecchi, M. Di Paolo, and L. Franceschetti, “Artificial intelligence in forensic science: a systematic review. Part II: long-range postmortem interval estimation,” Int. J. Legal Med., 2026, doi: https://doi.org/10.1007/s00414-026-03856-4 REVIEW Artificial.

contributing to the more accurate investigation, fair judicial outcome, and transparent, efficient, and technologically advanced criminal justice system.[23]

## 7 Conclusion

Biotechnology has dramatically changed the practice of criminal investigation with scientifically sound, reliable and objective techniques that can be used for the analysis of biological evidence and identification of individuals. Biotechnology has made forensic science more than just traditional investigative methods, with DNA Profiling and Forensic Toxicology and now such new technologies as Next Generation Sequencing, Forensic Epigenetics, Microbiomics and Artificial Intelligence. These innovations have enhanced the accuracy of crime scene reconstruction, human identification, disaster victim identification and the value of forensic findings in judicial proceedings, and have assisted the resolution of complex and cold cases. In India, the effective use of biotechnology is supported by the evolving legislations such as the Bharatiya Sakshya Adhiniyam, 2023, Bharatiya Nagarik Suraksha Sanhita, 2023, Bharatiya Nyaya Sanhita, 2023, Digital Personal Data Protection Act, 2023 and DNA Technology (Use and Application) Regulation Act, 2025, which all encourage the scientific, ethical, and legal use of the forensic evidence. However, ongoing priority should be given to the protection of privacy, ethical governance, laboratory accreditation and professional training. Advances in biotechnology, interdisciplinary research and technological innovation will continue to enhance the forensic capabilities and help build a more accurate, transparent, efficient, and evidence-based criminal justice system.

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