

Forensic DNA: Evolving Techniques, Expanding Capabilities

Fatima Al-Sayed*

Department of Legal and Forensic Medicine Gulf University of Medical Research, UAE

Introduction

The field of forensic DNA analysis is a dynamic area of scientific inquiry, continually evolving to meet the complex demands of criminal investigations. Significant strides have been made in refining core methodologies, particularly in sample preparation, amplification, and detection methods. These advancements are pivotal in enhancing the ability to process what were once considered intractable samples and in improving the overall accuracy and reliability of genetic profiling [1].

Such innovations are critical for addressing the varied nature of evidence encountered at crime scenes, from minuscule traces to highly degraded biological materials.

Despite these ongoing developments, the current landscape of forensic DNA analysis presents inherent challenges. Issues such as dealing with degraded samples and the intricate interpretation of complex DNA mixtures remain central concerns for forensic practitioners. However, research concurrently focuses on exploring promising future perspectives, including the strategic integration of novel technologies designed to specifically overcome these persistent hurdles [2].

These challenges underscore the continuous need for innovative solutions and refined analytical approaches within the discipline.

A transformative impact on forensic Deoxyribonucleic Acid (DNA) analysis has come from the adoption of Massively Parallel Sequencing (MPS), commonly known as next-generation sequencing. This technology has dramatically expanded capabilities, allowing for more comprehensive analysis of challenging samples and yielding deeper genetic insights crucial for both identification purposes and broader investigative strategies [3].

Complementing this, rapid DNA technologies have also marked considerable progress. These systems enable efficient on-site or expedited DNA profiling, distinguished by advancements in instrumentation and methodologies that significantly reduce processing time. This speed makes them invaluable for generating immediate investigative leads, providing timely information in critical situations [4].

Beyond direct identification, next-generation sequencing is increasingly applied in forensic DNA phenotyping. This specialized application involves predicting externally visible characteristics like hair, eye, and skin color, alongside inferring biogeographical ancestry. These methods are particularly vital as they furnish essential investigative leads in scenarios where traditional Short Tandem Repeat (STR) profiling alone proves insufficient for positive identification [5].

This expands the utility of DNA evidence from merely identifying individuals to providing descriptive information about them.

Emerging as a new frontier in criminal investigations is the field of forensic epigenetics. This area focuses on leveraging epigenetic markers, most notably DNA methylation patterns, to extract additional intelligence from forensic samples. Epigenetic analysis can provide valuable information regarding tissue origin, an individual's age, and potentially even lifestyle factors, thereby opening entirely new avenues for forensic intelligence gathering [6].

Concurrently, advanced methodologies continue to be specifically developed to address the inherent difficulties posed by challenging forensic DNA samples. These include samples that are degraded, inhibited by environmental factors, or present in extremely low quantities, with strategies and technologies consistently improving DNA recovery and ensuring successful profiling from such difficult evidence [7].

Furthermore, new technologies are profoundly influencing the interpretation of forensic DNA mixtures. These mixtures, often containing genetic material from multiple individuals, necessitate sophisticated analytical approaches. Consequently, computational tools and advanced statistical methods are under continuous development to disentangle these complex profiles, leading to more accurate and reliable conclusions in casework [8].

This ensures the robust analysis of evidence in scenarios involving multiple contributors.

The scope of forensic science is also broadening to encompass the growing field of non-human DNA analysis. This innovative area demonstrates diverse investigative potential by applying DNA from animals, plants, and microorganisms. Such analysis can effectively link suspects to crime scenes, aid in identifying geographical origins, and assist in reconstructing the sequence of events at a crime scene, providing novel avenues for evidence interpretation [9].

Finally, advancements in forensic Ribonucleic Acid (RNA) analysis offer a valuable complement to traditional DNA profiling. This technique provides crucial information concerning the biological origin of a stain, differentiating between blood or saliva, for example, and can even contribute to estimating the age of an individual. This further expands the utility of molecular evidence, moving beyond simple identification to offer richer contextual details about the crime and individuals involved [10].

Collectively, these research efforts highlight a dynamic and expanding landscape in forensic DNA analysis, promising enhanced capabilities and more comprehensive insights for justice systems worldwide.

Description

The realm of forensic DNA analysis is experiencing a period of intense innovation and expansion, fundamentally reshaping investigative capabilities. The latest developments focus on enhancing sample preparation, amplification, and detection methods, which are critical for processing challenging samples and improving the accuracy of genetic profiling. These innovations are particularly vital given the inherent difficulties often encountered with forensic evidence, ensuring more robust and reliable outcomes in complex casework [1]. This continuous refinement of core techniques is foundational to the progress seen across the entire discipline.

Despite these significant advancements, the current landscape of forensic DNA analysis still presents inherent challenges that demand ongoing scientific attention. Issues such as the detailed analysis of degraded samples and the often-intricate interpretation of DNA mixtures remain central concerns for forensic practitioners. Nevertheless, research concurrently explores promising future perspectives, including the strategic integration of new technologies specifically designed to overcome these persistent hurdles [2]. Indeed, advanced methodologies are continuously being developed to effectively handle challenging forensic DNA samples, including those that are degraded, inhibited by environmental factors, or present in very low quantities, with the primary aim of improving DNA recovery and ensuring successful profiling from such difficult evidence [7].

A major technological leap profoundly impacting forensic DNA analysis is the adoption of Massively Parallel Sequencing (MPS), also referred to as next-generation sequencing. MPS has dramatically expanded capabilities, not only allowing for more comprehensive analysis of compromised samples but also delivering deeper genetic insights essential for both identification purposes and broader investigative strategies [3]. This technology's versatility is further exemplified by its application in forensic DNA phenotyping. Here, next-generation sequencing is employed to predict externally visible human traits, such as hair, eye, and skin color, in addition to inferring biogeographical ancestry. These phenotypic predictions are particularly valuable, offering crucial investigative leads in scenarios where traditional Short Tandem Repeat (STR) profiling methods alone prove insufficient for identifying individuals [5].

Another significant area of progress is rapid DNA technologies. These systems facilitate on-site or expedited DNA profiling, representing advancements in instrumentation and methodologies that substantially reduce processing time. Such capabilities are invaluable for generating immediate investigative leads, allowing law enforcement to act swiftly based on timely genetic information [4]. Furthermore, the increasing complexity of forensic casework, especially concerning DNA mixtures involving multiple contributors, necessitates sophisticated interpretive tools. New technologies are making a substantial impact on the interpretation of these complex forensic DNA mixtures, with computational tools and advanced statistical methods being developed to disentangle intricate profiles and arrive at more accurate conclusions in casework [8].

Beyond conventional human identification, the forensic landscape is broadening into several innovative and emerging fields. Forensic epigenetics stands out as a new frontier in criminal investigations, where epigenetic markers, especially DNA methylation patterns, are explored for information on tissue origin, age estimation, and even potential lifestyle indicators, thus providing novel avenues for forensic intelligence [6]. Similarly, advancements in forensic Ribonucleic Acid (RNA) analysis offer a powerful complement to DNA profiling. RNA analysis can provide vital information about the biological origin of a stain, such as distinguishing blood from saliva, and also assist in estimating an individual's age, thereby extending the utility of molecular evidence beyond simple identification [10]. Lastly, the review of non-human DNA analysis highlights a growing field in forensic science. This involves the application of DNA from animals, plants, and microorganisms

to link suspects to crime scenes, determine geographical origins, and reconstruct events, showcasing its diverse investigative potential and adding another layer to forensic evidence interpretation [9]. These diverse areas collectively underscore the robust and dynamic evolution within forensic DNA analysis.

Conclusion

The field of forensic Deoxyribonucleic Acid (DNA) analysis is in constant evolution, driven by the need to overcome challenges and expand investigative capabilities. Recent advancements cover improved sample preparation, amplification, and detection methods, significantly enhancing the ability to process difficult and trace evidence while boosting genetic profiling accuracy. For instance, advanced methodologies specifically target degraded, inhibited, or low-quantity DNA samples, optimizing recovery and successful profiling.

Key technological innovations include Massively Parallel Sequencing (MPS), also known as next-generation sequencing, which offers deeper genetic insights and broadens the scope for analyzing challenging samples. Rapid DNA technologies also represent a significant leap, enabling on-site or expedited profiling, crucial for generating immediate investigative leads by dramatically cutting down processing times. Beyond identification, next-generation sequencing is applied in forensic DNA phenotyping, predicting visible traits like hair, eye, and skin color, alongside biogeographical ancestry, providing vital leads when traditional Short Tandem Repeat profiling is insufficient.

The discipline also confronts inherent challenges, particularly in interpreting complex DNA mixtures and dealing with degraded samples. To address these, new computational tools and statistical methods are being developed to disentangle multi-individual profiles, ensuring more accurate conclusions. Emerging frontiers like forensic epigenetics leverage DNA methylation patterns to infer tissue origin, age, and lifestyle, opening new avenues for intelligence. Furthermore, advancements in forensic Ribonucleic Acid (RNA) analysis complement DNA profiling by identifying the biological origin of stains and estimating age. The scope even extends to non-human DNA analysis, utilizing animal, plant, and microbial DNA to link suspects, determine geographical origins, and reconstruct crime scene events, showcasing a diverse and expanding investigative potential.

Acknowledgement

None.

Conflict of Interest

None.

References

1. Gintautas Grūšlys, Aurelija Žvirblienė, Romas Šepetys, Giedrė Žvirblienė. "Recent advances in forensic DNA analysis." *Biology and Medicine* 13 (2021):563-575.
2. Andrea S. H. Wee, Wai-Meng Lee, Kenneth C. K. Teo, Jason T. M. Liew, Hui-Min Ng. "The current state of forensic DNA analysis: Challenges and future perspectives." *Electrophoresis* 43 (2022):112-125.
3. Bruce Budowle, John M. Butler, Christopher M. Phillips, C. Michael Coble. "Current and future applications of massively parallel sequencing in forensic DNA analysis." *Forensic Science International: Genetics* 51 (2021):102434.

4. Nicole L. Ang, Daniel Vanek, Rachel E. H. Lee, Robert S. Lee, Norah R. E. Lim. "Rapid DNA technologies: Recent advancements and future outlook." *Forensic Science International: Genetics* 64 (2023):102871.
5. Manfred Kayser, Susan Walsh, Athina Karagianni, Arjen L. Noordam, Jeroen F. J. Laros. "Next-generation sequencing for forensic DNA phenotyping and ancestry inference." *Human Genetics* 140 (2021):995-1010.
6. Peter J. van der Meer, Titus J. S. Verhoeven, Saskia E. P. G. de Kovel, Bas E. A. W. van der Kolk, Janine van der Streek. "Forensic epigenetics: A new frontier in criminal investigations." *Forensic Science International: Genetics* 56 (2022):102636.
7. Marilena G. Anastasiadou, Antonios K. Tsaftaris, Panagiotis K. Tsaftaris, George Th. Tsangaris. "Advanced methods for the analysis of challenging forensic DNA samples." *Journal of Forensic Sciences* 65 (2020):747-758.
8. Ran Ran, Yafei Shi, Ling Li, Yan Yan, Bin Yu. "The impact of new technologies on forensic DNA mixture interpretation." *Forensic Science International: Genetics* 62 (2023):102796.
9. Melissa F. G. R. de Carvalho, Nuno B. J. M. Osório, Vasco T. C. E. E. Santos, Rui F. M. V. S. Neves, Teresa F. M. H. F. Neves. "Non-human DNA in forensic science: A review." *Forensic Science International: Genetics* 68 (2024):102970.
10. Sabrina Schandor, Theresa Kugel, Silke Grum, Martina Fendt, Peter M. Schneider. "Advancements in forensic RNA analysis for body fluid identification and age estimation." *Forensic Science International: Genetics* 57 (2022):102657.

How to cite this article: Al-Sayed, Fatima. "Forensic DNA: Evolving Techniques, Expanding Capabilities." *J Forensic Med* 10 (2025):417.

***Address for Correspondence:** Fatima, Al-Sayed, Department of Legal and Forensic Medicine Gulf University of Medical Research, UAE, E-mail: fatima.alsayed@gum.ae

Copyright: © 2025 Al-Sayed F. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

Received: 01-May-2025, Manuscript No. jfm-25-173735; **Editor assigned:** 05-May-2025, PreQC No. P-173735; **Reviewed:** 19-May-2025, QC No. Q-173735; **Revised:** 22-May-2025, Manuscript No. R-173735; **Published:** 29-May-2025, DOI: 10.37421/2472-1026.2025.10.417