Application of DNA Forensic Evidence in Criminal Justice System

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ABSTRACT

The present paper explored the constructive contribution of DNA in forensic science and how it has influenced criminal cases. It also examined how STR analysis and PCR amplified forensic evidence, making producing accurate and precise results easier. The study also brought in aspects such as NGS and the pilot of these aspects for such problems as degraded or low template samples. Further, the paper also discussed the applicability of DNA databases like CODIS in attaching suspects to crime scenes and solving serial offenses in cases of wrongfully convicted people. The presented findings identified this DNA as serving a role in convicting the guilty and in acquitting the innocent, raising the value of DNA hugely in modern-day criminal justice. Still, there were problems such as technical problems involving the use of hybrid or low-quality profiles for matching, ethical issues like privacy concerns regarding DNA databases, and other staff issues, including a shortage of trained personnel and lack of proper resources, among others. The listed challenges were Inadequate IT staffing, Multiple challenges for IT staffing in the global economy, Emerging technologies, and Expanded global collaborations. The effective solutions identified based on CBT were Emerging technologies and expanded global collaborations. The paper also reiterated what currently is a major challenge in forensic DNA analysis and what more needs to be done to overcome these limitations while upholding the principle of ethical practice. DNA evidence could still make more tremendous contributions to justice systems worldwide by maintaining innovation and responsibility in equal measures.

Keywords: DNA profiling, forensic evidence, crime investigation, CODIS, STR analysis, polymerase chain reaction (PCR).

INTRODUCTION

Criminal forensics is used in the contemporary world as a technique for analysing crime scenes and finding out the killers of criminals. Of all its kinds, DNA profiling has stood out as one of the most vital pieces of evidence for forensic procedures because of its exceptional capability in identifying the people involved. Criminal cases have been incredibly solved, and justice has been achieved since the combination of the forensic tool called DNA profiling during the early 1980s. This paper will also discuss how DNA is used in crime, review the development of DNA technologies and look at the shortcomings of using DNA in crime investigation.

For this reason, DNA is among the most favoured and trusted forms of forensic evidence available. Several current researches describe new developments in DNA technology that improved its efficiency. For instance, NGS can analyse multiple loci at once, enhancing a specimen's STR typing resolution even if the samples used are degraded, mixed or both (Butler et al., 2019). Likewise, advancements in DNA technology have compressed processing times down to a mere 3-4 hours to allow for the utilisation when responding to a crime scene (Hares, 2020). These innovations have opened up the use of DNA in conducting investigations, from identifying the suspect to freeing people whom other individuals committed.

The development of COODIS (Combined DNA Index System) and other DNA databases have enhanced the use of DNA in suspect identification at crime scenes. Such a database has been found to enhance the outcomes

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of criminal-related investigations by comparing the DNA profiles throughout the country (NIST, 2021). Furthermore, investigative genetic genealogy has recently become a highly effective method for solving cold profiles based on family similarities with publicly available genetic databases (Greytak et al., 2019).

However, some shortcomings have been realised in the use of DNA samples. Some challenges include contamination risks, samples with a small template or mixed samples resulting in somewhat difficult interpretations, and ethical concerns related to loss of privacy in genetic databases (Jobling & Gill, 2020). Moreover, the variation in adopting new, more sophisticated forensic technologies worldwide also calls for joint integrated efforts and the equitable distribution of resources across countries.

This paper hopes to analyse these developments while examining operational and ethical issues. Recent scholarship and technologies reinforce the message that DNA is the way to go in defending justice and fighting crimes.

Historical Context

The scientific study and application of DNA profiling in forensics seriously revolutionised the concept of crime investigation, where the accuracy of identifying a culprit is very high. The event that started this journey started in 1984 when Dr. Alec Jeffreys, at the University of Leicester, identified hypervariable regions in human DNA referred to as Variable Number Tandem Repeats (VNTRs) that could individualise people. This discovery of cDNA prepared the world for DNA fingerprinting, a technique that would disrupt forensic science analysis (Jeffreys et al., 1985; Butler et al., 2019).

DNA profiling is a relatively new method; its first application in a criminal case was used in England in 1986. Dr Jeffreys was consulted to help solve the rape and murder Of two young girls in Narborough, England. His reasoning excluded an innocent suspect and pointed to the right criminal – Colin Pitchfork – by conducting a groundbreaking mass screening of the local men's DNA samples. This case was the first time that *DNA* was used to both exonerate an innocent suspect and put away a guilty one, showing the capability of *DNA* to bring justice (Invention & Technology Magazine, 2020).

In the United States, the first court DNA case was in 1987 in the Tommie Lee Andrews rape trial, where Andrews was convicted through the Blood typing method when the semen taken by forensics matched his blood sample. In this landmark case, Restriction Fragment Length Polymorphism (RFLP), an early DNA profiling technique, was affirmed as accurate despite being time-consuming and requiring good sample quality (Police1, 2023; PBS, 2024). It was around the same time that other high-profile cases, for instance th, the conviction of Timothy Wilson Spencer for multiple murders, helped to affirm DNA, an essential component of associating the perpetrators of the crimes with the crime scenes (ACS, 2024).

This is because forensic DNA methodologies have developed through the years. Thus, RFLP was replaced by PCR-based techniques owed to their potential to amplify small or degraded samples. The STRs introduced in the 1990s replaced the previous method of forensic DNA profiling due to extended sensitivity and discrimination abilities based on small sample amounts. Like other methods of analysis, the STR analysis also helped the multiplexing, which means that more than one locus can be analysed simultaneously, making the processes faster and more accurate (MyBioSource, 2023; NIST, 2021).

These have improved crime-fighting and enabled individuals who have been wrongly gaoled to be freed through projects such as the Innocence Project. Looking at trends from VNTRs, STRs, and PCR methods, this particular paper explains how forensic DNA profiling has improved criminal justice systems worldwide.

DNA Profiling Techniques

Methods of Analysis

Short Tandem Repeats (STRs):

Short Tandem Repeats (STRs) are probably the most popular markers in forensic DNA typing because they provide high discrimination powers and variability. Speaking of STRs, these are short sequences of 2-6 base

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pairs in replication and structured as tandem repeats, and the analysis is most efficient even with degraded DNA. Incorporating STR loci into forensic samples has enhanced the process of global DNA profiling with deltation by capillary electrophoresis as a primary method to identify these STRs (Butler et al., 2018). STR analysis has turned out to be a gold standard for human identification since it can work with small samples, and it can be put together with multiplex PCR systems that establish the amplification of several loci simultaneously (Hares, 2020).

Y-Chromosome and Mitochondrial DNA Analysis:

Y-chromosome STRs (Y-STRs) are especially helpful in the identification of individuals in situations that concern only males, for example, with the mixture of male and female DNA in rape cases. Y-STRs give lineage data because, like mtDNA, they are not shuffled during sperm production and, therefore, helpful in identifying male donors in cases of sample mix-ups (Kayser, 2017). Nevertheless, they cannot be used to distinguish people who belong to the same paternal line. By comparing the mitochondrial DNA contents of two samples, it can be easily determined if they are related; thus, mtDNA is maturated and a good material for analysing bone or hair shafts. This fact helps obtain the results from the limited or old samples but with less discriminating power than the nuclear DNA copy (Parson & Roewer, 2018).

Polymerase Chain Reaction (PCR):

PCR has brought significant changes in forensic studies since it allows the amplification of either small or degraded DNA samples. This technique allows for millions of copies of particular DNA regions for further analysis. The PCR-based techniques have allowed better transfer from the older RFLP techniques to better STR analysis, including with badly degraded samples. Higher efficiency is provided by the systems of multiple PCR, in which several loci are amplified at once, which is necessary to obtain a wide range of data from scanty materials (Gill et al., 2019).

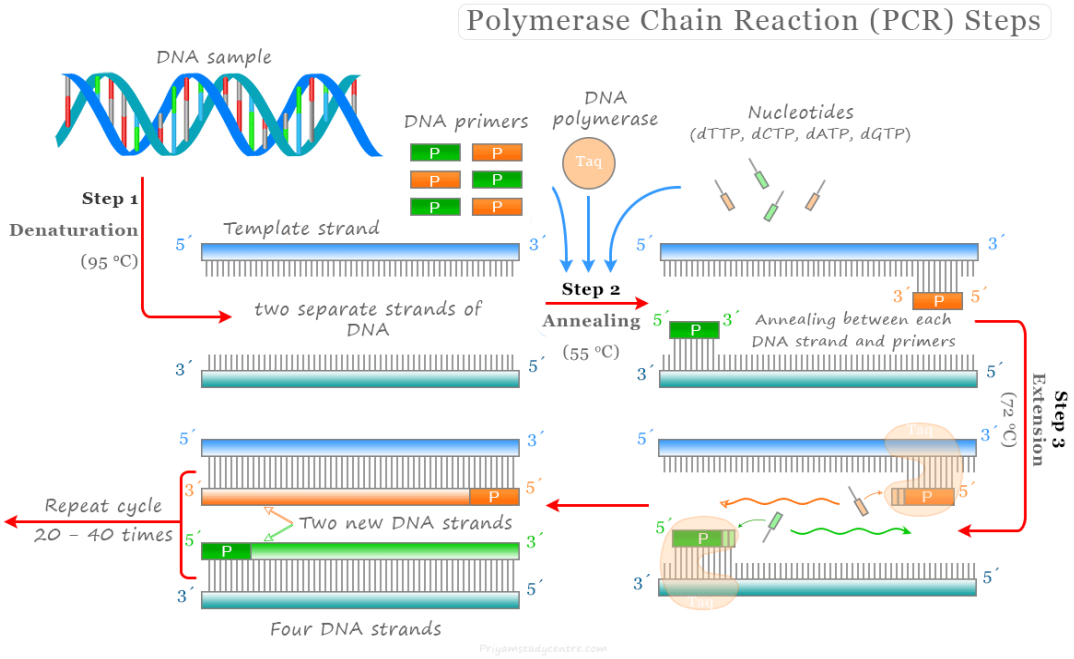

Fig 1: Polymerase Chain Reaction (PCR) Steps (https://www.priyamstudycentre.com/2024/01/polymerase-chain-reaction-pcr.html)

DNA Databases

CODIS and Its Role:

The Local DNA database linking is managed by the FBI and is called the Combined DNA Index System (CODIS), which links local, state and national DNA banks to store for examination or comparison DNA

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Profiles of crime scenes and convicted offenders. CODIS has helped solve the crimes through the connexion of the offender to several crimes in different states and identifying the repeat offender. The CODIS, as of 2021, reportedly had more than 14 million offender indexes and has helped crack hundreds of thousands of cases with database hits (Hares, 2021). Therefore, extending database coverage of profiles from unsolved cases and arrestees is crucial based on the efficiency of the used system (Budowle et al., 2020).

International Collaboration:

INTERPOL's DNA Gateway is only one of the non-domestic databases and programmes that can support international cooperation in criminal matters. It means that such systems help police worldwide exchange genetic information and connect crimes in different countries, increasing the coverage of forensic research (Kayser & de Knijff, 2021).

Sample Collection and Preservation

Sample collection and handling are key contributing factors to the success of any forensic analysis of biological samples. Samples should also be collected using aseptic and surgical gloves to minimise contamination to internal controls. Samples should be placed in paper-based bags or envelopes, not plastics because moisture can affect DNA. Biological materials for long-term storage are advised to be preserved in a refrigerator or a freezer (Dinis-Oliveira et al., 2016). The goal of a chain of custody is also important to account for evidence from collection through to presentation in Court (Gill et al., 2019).

Fig 2: Sample Collection (https://www.azolifesciences.com/article/Role-of-DNA-in-Forensic-Science.aspx)

Applications in Crime Investigation

Identification

Tests like DNA have made it easier to identify individuals involved in criminal activities, whether suspects or victims involved in a crime. Forensic DNA profiling comparing crime scene samples and suspects or databases has become one of the best methods of solving cases. For instance, forensic DNA profiling compares biological samples like blood, saliva, hair and so on with the recognised profiles to distinguish criminals efficiently (Butler, 2012). In mass disasters, the identity of the victims due to the remains state may not be identified using other methods such as fingerprints. Kinship and familial DNA matching is done using mitochondrial DNA and other techniques where the victims' DNAs are compared to relative DNAs in such disasters as the 2004 Indio tsunami disaster and the September 11, 2001 World Trade Centre disaster (Montelius & Lindblom, 2012). This method also makes identification accurate, offering closure for relatives and helping in legal matters (Parson & Roewer, 2018).

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Exoneration

Forensic practices such as clandestine post-conviction DNA testing have been used to expose stereotype vices in the justice system. To the best of the knowledge of the Innocence Project, there were over 375 post-1989 DNA-based exonerations were documented in the United States, of which flawed forensic practices, mistaken eyewitness identification, and false confessions were some of the key causes. For instance, Dion Harrell was released after serving over 30 years in prison for a crime he did not commit after DNA tests ruled him out as possessor of biological evidence (NIJ, 2017). Major research indicates that post-conviction DNA testing not only exonerates the innocent but also prevents future mistakes by modifying the methods of enquiry and increasing understanding of the strengths and weaknesses of conventional types of evidence (Saks & Koehler, 2005).

Linking Crimes

CODIS (Combined DNA Index System) and other DNA databases match the crimes performed by the same culprit with different crimes. Using the profiles in combination with common entries helps the investigators have an inkling of the criminal offence and link up to the serial crime to be committed. For instance, CODIS has enabled a link between multiple unidentified offences and specific suspects in various regions (Budowle et al., 2020). Also, new methods such as Familial searching and Investigative Genetic Genealogy have enlarged the concept of linkage of crimes. These methods employ partial matches to alibi relations of unknown criminals and have been crucial in solving dormant cases such as serial killer cases (Kayser & de Knijff, 2021). Alitmap is aware of one that involved pinpointing the suspect's brother with the help of FDR. They convicted a serial offender (Haesler et al., 2021).

Challenges in Forensic DNA Analysis

Technical Limitations

Issues with Low-Template or Degraded Samples:

Due to their limited quality and quantity, LT-DNA and degraded DNA samples are particularly difficult to analyse in the forensic context. LT-DNA is also called LCN DNA and generally samples with less than 200pg of DNA. Such samples are more susceptible to stochastic effects, such as alleles drop-out – non-amplification of certain alleles, and alleles drop-in – amplification of some unrelated alleles, which can negatively affect the reliability of obtained profiles (Gill et al., 2018). While contaminated DNA is that which is mixed with other substances in such a way that the target DNA is no longer intact, degraded DNA is that which has been subjected to conditions such as heat or humidity or may have been attacked by microorganisms and therefore is fragmented. Such degradation commonly results in disparate row or column presences and inessential profile incompleteness; it also enhances the potential for analysis errors (Butler et al., 2018; Parson & Roewer, 2018).

To cope with these issues, forensic scientists have introduced complex methods, including mini-STRs, which specify strand sizes that will likely amplify from a degraded sample. According to the study by Gill et al., 2019, mini-STRs can increase the chance of obtaining the usable profile in highly degraded samples. Furthermore, NGS suggests new ways of analysing degraded samples or samples that contain low templates by increasing sensitivity and allowing the analysis of small fragments of DNA (Parson & Roewer, 2018).

Interpretation Challenges with Mixed Profiles:

Another major issue in forensic DNA analysis is the presence of mixed DNA, a sample containing DNA from two or more persons. Such mixtures frequently lead to masked alleles that are challenging to screen individual contributors of in a mixture. This is especially a challenge with increasing contributors; some of the challenges are allele masking (where a minor contributor has his allele masked by the major ones), noise from stutter peaks or drop-in/drop-out events (Gill et al., 2019; Kayser & de Knijff, 2021).

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In the last few years, enhancements of probabilistic genotyping software have enhanced complexity analysis by integrating statistical models used to define the odds of various contributor combinations. They assist forensic specialists in offering even more accurate findings as they also seek to minimise the use of plainly subjective interpretations (Taylor et al., 2021). However, looming problems are still in harmonising protocols among the laboratories and ensuring reproducible results in the inter-laboratory calibration (Budowle et al., 2020).

Legal and Ethical Considerations

Admissibility Standards for DNA Evidence in Court:

The rules which apply to the admission of DNA evidence are the Frye rule, which requires that scientifically produced evidence must be acceptable in the scientific community, and the Daubert rule, which evaluates the scientific reliability of a theory by checking on the rate and frequency of errors and the quality of peer review. Forensic DNA evidence has been admitted under these frameworks because of its scientific nature, for example, in United States v. In Jakobetz 1992, the court affirmed DNA profiling as admissible and valid, recognising its credibility and pertinency (Kaye, 1991; Urban Law Journal 1993). However, identified difficulties occur when the laboratories do not adhere to a standard procedure or when the custody of items is broken, leading to handling distorting the weight of the item rather than its relevancy to the court (NCBI, 1996). Other concerns that have also been raised include prejudice that juries develop for the defendant once they are associated with a DNA link, meaning that there is strict evaluation of what goes on in the laboratory (Penn State Law eLibrary, 2024).

Privacy Concerns Surrounding DNA Databases:

Concerns have been raised on the increase of forensic DNA databases for expansion, which has been an area of major concern regarding privacy and ethical issues. Meanwhile, these databases are incredibly helpful when it comes to solving crimes, they are connected with such negative aspects as genetic surveillance and misuse of the given information. Bennett (2018) countered that storing DNA samples of those who did not commit a crime violates people's rights, most notably the right to a clean record, and does not close the door to prejudice or misuse. There is a privacy violation in open-source databases used for investigation: uploading a suspect's DNA can reveal close kin'skin'skin's genetic data (Guest, 2019). In order to mitigate such issues, scholars suggest introducing stricter administration of databases and work with genetic information and the other, informing the public about the use of such data (Scholarly Commons Law Review, 2018).

Operational Challenges

Training Requirements for Forensic Personnel:

Simultaneously with the growth of the methodologies used inside forensic practise, it is still necessary to train the forensic personnel. High-throughput sequencing methods, including MPS and probabilistic genotyping, require expertise to optimise the performance of the techniques when interpreting the results (PMC, 2021). However, such disparities create inconsistencies in training programmes amongst the jurisdictions, and mistakes are bound to happen. One of them pointed out that a lack of staff training in the new technology still poses a hurdle to standardisation in forensic laboratories (ResearchGate, 2021). These unique approaches to forensic science call for increased interprofessional collaboration and standardisation of training programmes globally to ensure that forensic science practice is given the importance it deserves (Journal of Forensic Sciences, 2018).

Need for Advanced Infrastructure and Funding:

Challenges some forensic laboratories experience may include Decentralised advancement in infrastructure and limited resources and funding. Delays in DNA casework are still very common since there is inadequate capital to enable efficient tackling of the backlog. For instance, the research and forensic laboratories in the small budget constraining countries are not in a position to invest in sophisticated technologies such as

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automated systems for DNA extraction or storage of huge databases (ResearchGate, 2019; SCIEPublish, 2024). Top management requires investment in modern structures as this strategic asset enhances results' effectiveness and time utility. Furthermore, funding programmes like NIJ: Capacity Enhancement Programme have been found to have played a pivotal role in the elimination of backlogs but still lack funds to fill the demand (NIJ Report, 2017).

Future Directions

Emerging Technologies: Next Generation sequencing (NGS)

The NGS, genomics/physical-based MPS, became one of the most revolutionary tools in the field of forensic science. In contrast to other techniques, including capillary electrophoresis (CE), which affords a single analysis of distinct DNA fragments, NGS simultaneously enables the analysis of various genetic markers, including SNPs and STRs. This capability makes it especially useful in samples with low template, degraded, or a mixture, which are common in forensic cases (Butler et al., 2018; Parson & Roewer, 2018). They also state that NGS can analyse mitochondrial DNA at higher resolution, making it essential to identify remains found in mass disaster cases or missing persons where there may be no nuclear DNA (Gill et al., 2019).

Also, NGS provides an opportunity for forensic DNA phenotyping, which consists of the ability to predict traits like eye and hair colour and biogeographical origin. These give direction in the investigation when there are no IDs in the database, as pointed out by Kayser (2017). According to Alvarez-Cubero et al. (2023), NGS may soon replace conventional technologies because of its potential for creating more informative genetic maps and because it is more suitable for multifaceted cases.

Expanding Global Collaboration Through Shared Databases

For terrorism and human trafficking, among other cross-national crimes, it has become crucial to share DNA data across borders. International frameworks like INTERPOL's DNA Gateway and the European Union's Prüm system allow for rapid sharing of DNA profiles across jurisdictions, enabling law enforcement agencies to link crimes and identify offenders more efficiently (Jakovski et al., 2017; Haesler et al., 2021). Nonetheless, some issues are still critical regarding legal comparability and harmonisation of legislation and database standards for effective cooperation; preserving privacy rights is still an issue (Kostiuchenko & Vynohradova, 2024).

In this regard, the latest research focuses on developing an international network of DNA databases that coordinate their action to fight transnational criminality. For example, Budowle et al. (2020) stress the need to develop a standard for reducing such false-positive matches, enhancing the discriminating ability of shared data. Apart from this, for utilising familial DNA to identify missing persons and the victims of disasters, INTERPOL, through its service known as I-Familia, also enhances international cooperation.

Addressing Ethical Concerns Through Improved Data Governance

The growth of forensic DNA databases is extraordinary, and new professional institutions and techniques frequently contribute to new ethical questions regarding privacy, rights, or misusing. Some critics state that the storage of DNA samples of persons who were never found guilty of any offence violates the rights of the persons and that it discriminates against minorities who are, in most cases, arrested by the criminal justice system (Bennett, 2018; Murphy, 2020). To this end, scholars suggest strong data governance strategies that place a premium on public openness and organisational responsibility. For instance, Helen Wallace (2024) argued that there is a lack of policy regarding the right people can possess DNA data and the right circumstances. She also stresses so much on using databases for the right purpose but not for parading or discriminating against people. Besides, recent discoveries in encryption, as well as anonymisation frameworks, can surely ensure that the chains of the DNA databases have more value in the probes of an offender even as it implements shields that can safeguard the discrete details concerning the lineage of an individual (Scholarly Commons Law Review, 2018).

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The utilisation of DNA databases will remain a challenge, especially with the increasing advancements in forensic science; the integration of technology while close attention to ethnic issues will be vital in maintaining public confidence and ensuring that DNA as forensically extracted evidence will not be misused.

CONCLUSION

It is, without any doubt, that DNA has revolutionised forensic science, how crimes are solved and justice delivered. Precise identification of people that can not be paralleled makes it one of the core staples of investigations in the contemporary world, including matching a suspect to the crime scene or of victims in mass disasters, linking different and similar offences, and solving old or cold cases. DNA profiling has been seen to be an essential apparatus for police forces all over the world.

Popularly known for its application in cases to convict criminals, DNA has also played important roles in acquitting the innocent. All of the examinations that followed the wrongful convictions debunked through the post-conviction DNA testing underscore the problematics in the justice system as well as stress the relevance of the scientific approach in criminalistics. This DNA duality means an investigation tool and a protection shield of justice and equity.

All the same, there is still room for improvement, an aspect that underwent a revolutionary change after the launch. Areas, for example, identifying and quantifying low copy numbers or(plugin mixed samples), privacy concerns regarding DNA databases, and practical constraints in the forensic facilities underpin the imperative for progression. Other possibilities include using such approaches as next-generation sequencing (NGS) and the global exchange of best practices using databases; however, achieving success in these approaches requires permanent funding for research, staff development, and information technology.

The concept of forensic science is expanding year by year, but abandoning ethical principles when sounding an innovation is also significant. Thus, by improving current shortcomings and guaranteeing the appropriate utilisation of DNA, it is possible to enhance its ability to bring justice and protect public confidence in forensic transcripts.

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