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Review

Emerging Technologies in Forensic DNA Analysis

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ABSTRACT: Forensic DNA analysis has fundamentally transformed criminal investigations, providing an unprecedented level of accuracy in identifying suspects, exonerating the innocent, and solving cold cases. This manuscript reviews the emerging technologies that are reshaping the field of forensic DNA analysis, including next-generation sequencing (NGS), rapid DNA analysis, AI-driven forensic workflows, 3D genomics, and mobile DNA platforms. These innovations enhance the speed, precision, and scope of DNA analysis, allowing forensic scientists to process evidence more efficiently, analyze more complex samples, and conduct real-time field-based investigations. While these advancements hold great promise, they also introduce significant challenges, such as ensuring data security, maintaining the integrity of evidence, and navigating the ethical and legal implications of new forensic technologies. Issues related to privacy, consent, and potential bias in DNA databases are becoming increasingly complex as these systems expand. Furthermore, the legal admissibility of cutting-edge technologies like AI-driven DNA analysis and phenotypic prediction must be carefully evaluated to ensure the rigorous standards of forensic evidence in court are met.This review explores the opportunities and challenges associated with these emerging technologies, emphasizing the importance of responsible and ethical use. By examining advances in DNA extraction, spatial DNA analysis, and the integration of AI in forensic workflows, this manuscript provides forensic professionals with a roadmap for navigating the evolving landscape of forensic DNA analysis. The future of forensic DNA analysis lies in balancing technological innovation with the commitment to justice, ensuring that DNA evidence remains a reliable and indispensable tool in pursuing a more equitable legal system.

Keywords: Forensic DNA analysis; Next-Generation Sequencing (NGS); AI in forensics; Rapid DNA analysis; 3D genomics; Mobile DNA platforms; Forensic databases; Ethical issues in DNA analysis; Phenotypic prediction; Spatial DNA analysis; Criminal investigations; Genetic privacy; DNA contamination; Emerging forensic Technologies; Legal considerations in forensics

1. Introduction

Forensic DNA analysis has become a cornerstone of modern forensic science, revolutionizing how criminal investigations are conducted and how justice is administered. The ability to extract and analyze DNA from various biological samples, such as blood, hair, skin cells, and saliva, has provided law enforcement agencies an unparalleled tool to link individuals to crime scenes, identify victims, and exonerate the innocent [1]. DNA evidence is often considered the gold standard in the courtroom due to its high specificity and accuracy in identifying individuals.

Despite its transformative impact, traditional DNA analysis methods face limitations, including time-consuming processes, high costs, and vulnerability to contamination and sample degradation [2]. As forensic DNA databases continue to expand and the demand for DNA analysis increases, there is a pressing need for technological innovations that enhance both the efficiency and accuracy of forensic science [1].

Emerging technologies in forensic DNA analysis, such as next-generation sequencing (NGS), rapid DNA analysis, and the integration of artificial intelligence (AI), offer promising solutions to these challenges. These advancements accelerate the speed and precision of DNA analysis and extend its applications, enabling forensic scientists to work with more degraded samples and extract meaningful information from complex DNA mixtures [1]. These mobile and field-

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deployable DNA platforms have been effectively used in forensic contexts, such as identifying victims in disaster response scenarios or processing crime scene evidence on-site in remote locations [1].

However, the adoption of these emerging technologies brings new challenges. Issues related to cost, validation, and personnel training must be addressed before these innovations can be widely implemented. Moreover, the rapid pace of technological advancement raises important ethical and legal questions regarding privacy, the handling of sensitive genetic data, and the admissibility of new forms of DNA evidence in court [1].

This manuscript provides a comprehensive review of the emerging technologies in forensic DNA analysis, exploring their potential to address the limitations of traditional methods, the challenges associated with their implementation, and their implications for the future of forensic science. Key areas of focus include advances in DNA extraction, next-generation sequencing, rapid DNA analysis, 3D genomics, AI-driven analysis, mobile DNA platforms, and the ethical and legal considerations accompanying these innovations. By examining the opportunities and challenges presented by these technologies, this manuscript aims to equip forensic professionals with a roadmap for navigating the future of DNA analysis in criminal investigations. To further assist forensic professionals, a checklist has been included as supplementary material, providing practical steps and guidelines for implementing the technologies and approaches discussed in this manuscript. Additionally, Table 1 offers a comprehensive summary of the key emerging DNA technologies. The table highlights the major benefits, challenges, level of adoption, and application areas for each technology, serving as a quick reference guide to help professionals select the most appropriate tools for their specific forensic needs.

Table 1. This table provides an overview of key emerging DNA technologies, outlining their main benefits, challenges, practical considerations for their application, current level of adoption, and common forensic scenarios where each technology is most applicable. It serves as a reference tool for forensic professionals looking to navigate the selection of advanced DNA technologies for specific cases.

Emerging Technology	Short Description	Major Benefits	Major Challenges	Practical Guidelines/Considerations	Level of Adoption	Application Areas
Manual Extraction Systems	Traditional method for DNA extraction performed manually by a forensic analyst.	Affordable, widely accessible, suitable for small labs	Prone to human error, longer processing times, variability	Best suited for low-throughput cases; automation is preferred for larger labs.	Widely adopted	Small forensic labs, low-throughput cases
Automated Extraction Systems	Fully automated systems that handle the entire DNA extraction process.	Increases throughput, reduces human error, improves consistency	Initial cost, maintenance, and training requirements	Best for high-volume forensic labs to standardize workflows and minimize errors.	Increasingly adopted	High-volume forensic labs
Rapid DNA Analysis	Portable technology designed to generate DNA profiles in under 2 hours at point-of-need.	Fast results, ideal for time-sensitive cases	Limited to specific sample types, not widely used in routine lab work	Best used in time-sensitive situations (e.g., border control, disasters). Difference from Mobile DNA: Optimized for speed, but limited in the complexity of samples it can handle.	Emerging	Border checkpoints, disaster recovery
Mobile DNA Analysis	Field-deployable DNA analysis platforms for remote or field-based forensic investigations.	Provides DNA analysis on-site in remote locations or during field operations	Equipment can be costly, requires training for effective use	Ideal for use in disaster recovery or crime scenes where immediate results are critical. Difference from Rapid DNA: More versatile and capable of handling complex samples in remote settings.	Emerging	Disaster recovery, battlefield, remote crime scenes
Next-Generation Sequencing (NGS)	High-throughput technology that sequences multiple DNA fragments simultaneously.	Higher resolution, better insights into complex samples	Expensive, requires specialized equipment and expertise	Best suited for analyzing degraded samples or mixtures in complex cases.	Emerging	Cold cases, complex mixture analysis
AI and Machine Learning	Software-driven analysis of large forensic data sets to find patterns and make predictions.	Improves efficiency in data analysis and interpretation	Data privacy concerns, potential for bias in algorithms	Useful in large-scale forensic investigations to aid pattern detection and predictive modeling.	Experimental	Large-scale forensic investigations

3D Genomics and Spatial DNA Analysis	Technology that provides spatial context for understanding DNA evidence at crime scenes.	Provides spatial context for DNA evidence	Technologically complex, still in early stages of adoption	Potential use in crime scene reconstruction and understanding complex DNA mixtures.	Experimental	Crime scene reconstruction, complex DNA mixtures

The emerging technologies discussed in this manuscript were selected based on their increasing use and growing impact in forensic science over the past decade. Technologies such as Next-Generation Sequencing (NGS), AI and Machine Learning in Forensic DNA Analysis, and 3D Genomics and Spatial DNA Analysis are still relatively recent. They will take time to become accessible, affordable, and fully established for regular forensic use. In contrast, technologies like Rapid DNA Analysis and mobile DNA platforms are more commonly needed in specific scenarios, such as disaster recovery, or in particular locations like airports and border checkpoints to speed up the workflow. However, these technologies are not yet used daily in most forensic laboratories, but rather in specific high-priority or time-sensitive contexts. It is important to note that not all forensic technologies are equally accessible worldwide, as factors such as infrastructure, funding, and regulatory environments can significantly affect their adoption and use.

2. Advances in DNA Extraction and Preservation

DNA extraction and preservation are critical steps in the forensic workflow, as the quality of extracted DNA directly impacts the reliability of subsequent analysis. Traditional DNA extraction methods, while effective, are often labor-intensive and time-consuming, requiring a controlled laboratory environment to minimize contamination risks [1]. Moreover, preserving DNA to prevent degradation over time remains a challenge, particularly in cases where evidence is exposed to harsh environmental conditions [2,3]. Emerging technologies in DNA extraction and preservation aim to address these challenges by improving the efficiency, sensitivity, and overall quality of DNA samples.

2.1. Miniaturized and Portable DNA Extraction Kits

One of the most significant advancements in DNA extraction is the development of miniaturized, portable DNA extraction kits. These kits enable rapid, on-site DNA extraction, allowing investigators to process samples at the crime scene rather than transporting them to a lab. Portable DNA extraction kits are particularly valuable in remote locations, disaster areas, or scenarios where immediate results are necessary, such as military operations or border control settings [4].

Miniaturized extraction devices often use microfluidic technology to automate the DNA extraction process on a small scale. These devices reduce the risk of contamination by minimizing manual handling and can extract DNA from various sample types, including blood, saliva, and Touch DNA. For example, using magnetic beads in microfluidic channels efficiently isolates DNA from complex biological matrices, enabling the purification of high-quality DNA in under an hour [5]. This innovation reduces the time required for forensic analysis and facilitates more immediate decision-making at the crime scene.

2.2. Automated Extraction Systems

In addition to portable kits, advances in laboratory-based automated DNA extraction systems have significantly improved the throughput and consistency of DNA extraction processes. These automated systems, such as the PrepFiler Express™ kit used in conjunction with the Automate Express™ platform (Thermo Fisher Scientific, Waltham, MA, USA), can complete DNA extraction in as little as 30 min, compared to the 1–2 h required for manual extraction [2]. The automated system speeds up the process and reduces the likelihood of human error, which is a common source of contamination or sample degradation in manual extraction procedures [6]. Studies have shown that automation improves workflow efficiency while maintaining high-quality results by minimizing variability and reducing processing errors [1].

Automated systems can also be integrated with laboratory information management systems (LIMS), enabling better tracking and documentation of each sample throughout the extraction process. This level of automation and integration enhances the quality of the extracted DNA and improves the overall chain of custody, ensuring that evidence is handled securely and reliably. These systems are increasingly adopted by high-throughput forensic laboratories that manage large volumes of DNA evidence [4].

2.3. DNA Preservation Techniques

DNA preservation is equally critical to maintaining the integrity of forensic evidence. Biological samples collected at crime scenes are often exposed to environmental conditions that can lead to DNA degradation. Factors such as heat, moisture, UV radiation, and microbial activity can compromise DNA, making it difficult or impossible to obtain a reliable genetic profile. Emerging preservation techniques address these challenges by providing better protection for DNA samples under adverse conditions [7].

One promising advancement in DNA preservation is the development of specialized storage materials that prevent DNA degradation. For instance, new formulations of desiccants and stabilizing agents can be incorporated into storage containers to absorb moisture and inhibit microbial growth. These materials are particularly useful for preserving DNA on swabs, fabrics, or other porous surfaces, which are more susceptible to environmental damage [4].

Furthermore, cryopreservation techniques utilizing ultra-low temperatures are being refined for the long-term storage of DNA samples. Innovations in cryogenic storage containers and the use of antifreeze-like compounds help prevent ice crystal formation, which can damage DNA during freezing and thawing cycles [8]. These methods are especially valuable for preserving DNA from sensitive or irreplaceable samples, such as ancient remains or evidence from cold cases [5].

Another emerging DNA preservation technology is dry-state storage. This method involves drying DNA samples and storing them in a stable, inert form at room temperature. Dry-state preservation eliminates refrigeration, reducing the risk of temperature fluctuations during transport or storage. It also simplifies the long-term storage of DNA samples, which is beneficial for forensic labs needing to archive evidence for future reanalysis [6].

2.4. Field-Deployable Preservation Solutions

Beyond lab-based preservation techniques, field-deployable solutions are being developed to ensure DNA samples remain viable from the moment of collection. Portable preservation kits equipped with desiccants, temperature-controlled containers, and chemical stabilizers are now available to law enforcement officers and crime scene investigators. These kits are designed to protect DNA from environmental factors immediately after collection, ensuring the sample's integrity until it can be processed in a lab [8].

For example, portable DNA preservation devices using vacuum-sealing technology to create an airtight environment around a sample are now being deployed in the field. These devices prevent moisture and oxygen from degrading DNA, making them particularly useful for preserving evidence in humid or wet conditions. Together with portable DNA extraction kits, these preservation tools support a more robust and reliable forensic workflow at crime scenes, reducing the time and effort required to preserve and analyze DNA evidence [7].

3. Next-Generation Sequencing (NGS)

Next-generation sequencing (NGS) represents a significant leap forward in forensic DNA analysis, offering unparalleled precision, sensitivity, and the ability to generate more comprehensive genetic profiles compared to traditional short tandem repeat (STR) analysis. NGS allows for the sequencing of entire genomes or targeted regions of the genome with high throughput, making it possible to extract valuable forensic information from degraded samples, contain low quantities of DNA, or involve mixed profiles from multiple individuals [9–11].

3.1. Introduction to NGS in Forensics

NGS, also known as massively parallel sequencing (MPS), has revolutionized genetics by enabling the simultaneous sequencing of millions of DNA fragments. In forensic applications, this technology provides a powerful tool for analyzing complex samples that traditional STR analysis may struggle to resolve. NGS can sequence nuclear and mitochondrial DNA (mtDNA), offering a broader range of genetic markers, particularly in cases involving highly degraded samples [12].

Forensic laboratories are beginning to adopt NGS platforms due to their ability to analyze multiple types of genetic information, such as single nucleotide polymorphisms (SNPs), indels (insertions and deletions), and microhaplotypes, all in a single assay. This multiplexing capability reduces the time and resources needed to generate comprehensive genetic profiles while increasing the discriminatory power of forensic analysis [4].

3.2. Applications of NGS in Forensic Science

The advantages of NGS are being harnessed in several key areas of forensic science:

1. Analysis of Complex Mixtures: Traditional STR analysis often struggles with mixed DNA samples, such as those collected from crowded crime scenes where DNA from multiple individuals may be present. NGS solves these complex mixtures by providing high-resolution sequencing data that can differentiate between multiple contributors. For instance, NGS can identify minor contributors in a DNA mixture, which is particularly useful in sexual assault cases where the victim's DNA may dominate the sample [13].
2. Degraded and Low-Quantity Samples: NGS is highly sensitive and can generate full genetic profiles from degraded or low-quantity DNA samples, which would be challenging for traditional methods. This makes NGS a valuable tool in cold cases, disaster victim identification (DVI), and analyzing ancient or compromised samples. By sequencing shorter regions of the genome, NGS can recover more information from damaged DNA, enabling the identification of individuals from skeletal remains, charred evidence, or samples exposed to environmental stressors [14,15].
3. Ancestry and Phenotypic Prediction: One of the most exciting applications of NGS in forensic science is its ability to provide information beyond identity, including ancestry and phenotypic traits (e.g., eye color, hair color, skin pigmentation). This capability can be especially useful in generating investigative leads when no suspect has been identified. NGS can analyze SNPs associated with ancestry and physical appearance, allowing forensic scientists to create probabilistic profiles that guide investigations [16,17].
4. Mitochondrial DNA Analysis: Mitochondrial DNA (mtDNA) analysis is particularly useful in forensic cases where nuclear DNA is degraded or unavailable, such as in hair shaft analysis or examining old skeletal remains. NGS platforms enable the sequencing of the entire mitochondrial genome, providing higher resolution and greater discriminatory power compared to traditional mtDNA analysis methods. This approach is especially valuable in mass disaster victim identification, historical investigations, or kinship analysis [18,19].
5. Y-Chromosome and X-Chromosome Analysis: NGS also facilitates detailed analysis of Y-chromosome and X-chromosome markers, which can be crucial in cases involving male lineages or mixed male and female DNA samples. Y-STRs, for example, are particularly useful in sexual assault cases where male DNA needs to be distinguished from female DNA [20].

3.3. Challenges and Limitations of NGS

While NGS offers significant advantages, several challenges must be addressed before it becomes a routine tool in forensic laboratories:

1. Cost and Infrastructure: NGS platforms and the reagents required for sequencing are expensive, and many forensic laboratories may lack the infrastructure and budget to implement this technology at scale. The cost of NGS is significantly higher than that of traditional STR analysis, which can be a barrier to adoption, particularly in smaller or resource-limited forensic labs [21].
2. Data Interpretation and Expertise: The vast amount of data generated by NGS requires sophisticated bioinformatics tools and expertise for analysis. Interpreting NGS data is more complex than STR profiles, as it involves understanding multiple layers of genetic information, including SNPs, indels, and haplotypes. Forensic laboratories need trained bioinformaticians and forensic scientists who are capable of accurately handling and interpreting this data [22,23].
3. Validation and Standardization: Forensic laboratories must validate NGS workflows to ensure they meet the rigorous standards required for forensic analysis. This involves extensive testing to confirm that NGS platforms can produce consistent, reliable, and reproducible results across different sample types and conditions. Additionally, there is a need for standardized protocols and guidelines to ensure that NGS data is admissible in court and meets legal standards for forensic evidence [24].
4. Legal and Ethical Considerations: As NGS technology becomes more widespread in forensics, legal and ethical concerns arise. The ability to predict phenotypic traits or ancestry from DNA data raises questions about privacy and potential misuse. Courts will need to address the admissibility of NGS data, particularly when used to make predictions about a suspect's appearance or ethnicity. These concerns will require the development of clear regulations and guidelines to govern the use of NGS in forensic investigations [25].

3.4. Future Potential of NGS in Forensics

Looking ahead, NGS is poised to become a game-changing technology in forensic science. As costs decrease and bioinformatics tools become more accessible, NGS will likely be integrated into routine forensic workflows. In the future, NGS may be used to analyze more complex and diverse types of evidence, including environmental DNA (eDNA) from crime scenes, which could provide insights into the presence of specific individuals or animals [26].

Furthermore, as genetic databases continue to expand, NGS could play a crucial role in linking previously unsolved cases by identifying distant familial relationships or matching genetic profiles across different jurisdictions. This could lead to breakthroughs in cold cases or cases involving serial offenders [20].

Finally, advancements in NGS technology will likely improve the speed of analysis, allowing for rapid DNA profiling in real-time, which could be used in emergencies or field-based investigations [27].

4. Rapid DNA Analysis

Rapid DNA analysis represents a significant advancement in forensic science, enabling the generation of DNA profiles in a matter of hours rather than days or weeks. This technology allows law enforcement and forensic professionals to accelerate investigations, improve the efficiency of DNA processing, and make real-time decisions based on genetic evidence. By eliminating the need to send samples to central laboratories, rapid DNA analysis has the potential to revolutionize the use of DNA in criminal justice and emergency response scenarios [28].

4.1. What Is Rapid DNA Technology?

Rapid DNA technology refers to automated, portable systems that can process DNA samples from collection to analysis within a short timeframe, typically under two hours. These systems are designed to perform all steps of DNA analysis—extraction, amplification, separation, detection, and interpretation—within a single device, often referred to as a “lab in a box” [29].

Platforms such as ANDE and RapidHIT use microfluidic cartridges pre-loaded with reagents for cell lysis, PCR amplification, and electrophoretic separation, enabling the machine to process samples without manual intervention. The resulting DNA profiles can then be compared against existing databases, such as the Combined DNA Index System (CODIS), to identify potential matches [30]. This technology is particularly valuable in scenarios requiring immediate DNA results, such as crime scenes, border security checkpoints, and disaster victim identification [31].

4.2. Applications of Rapid DNA in Forensic Science

Rapid DNA analysis is increasingly being implemented in real-world forensic applications where traditional laboratory-based DNA testing would be too slow or logistically challenging. Key applications include:

1. Crime Scene Investigations: Rapid DNA technology allows investigators to analyze biological evidence directly at crime scenes. In cases involving violent crimes, such as home invasions or assaults, investigators can collect DNA from blood, saliva, or other biological materials and generate a profile that can be immediately checked against local and national DNA databases. This significantly speeds up suspect identification and can prevent further harm [32].
2. Border Security and Immigration Enforcement: Rapid DNA technology has been adopted by immigration authorities to verify family relationships, detect human trafficking, and prevent identity fraud. For example, U.S. Customs and Border Protection (CBP) has utilized rapid DNA technology at border crossings to confirm the familial relationships of migrants, ensuring that children are not being trafficked while expediting the processing of legitimate asylum claims [33].
3. Disaster Victim Identification (DVI): In mass casualty events such as natural disasters, terrorist attacks, or accidents, rapid DNA analysis can be used to identify victims quickly. By comparing DNA from recovered remains with profiles in victim databases or family reference samples, authorities can expedite the identification process, providing families with closure and enabling proper legal documentation of deaths [34].
4. Military and Battlefield Operations: The military has adopted rapid DNA technology for battlefield use to identify casualties, enemy combatants, and detainees. These systems can be deployed in mobile laboratories, allowing forensic teams to operate in remote or hostile environments where traditional lab infrastructure is unavailable [35].
5. Arrests and Booking Procedures: Some law enforcement agencies are piloting the use of rapid DNA systems in booking stations to generate DNA profiles of arrestees. This allows for immediate comparison against databases

like CODIS, potentially linking suspects to unsolved cases or clearing individuals of wrongdoing before they are detained for long periods [36].

4.3. Legal and Operational Considerations

While rapid DNA technology offers significant advantages, its adoption raises several legal and operational challenges that must be addressed to ensure appropriate use in forensic investigations:

1. Chain of Custody: Ensuring the integrity of the chain of custody is critical when using rapid DNA technology. On-site DNA processing outside a controlled laboratory environment increases the risk of mishandling or contamination. Law enforcement agencies must implement strict protocols for documenting the collection, handling, and analysis of DNA samples to preserve their admissibility in court [37].
2. Admissibility in Court: The legal admissibility of DNA profiles generated by rapid DNA systems is still evolving. While some jurisdictions have begun accepting rapid DNA results as evidence, others require further validation and certification before these results can be presented in court. Forensic laboratories and law enforcement agencies must collaborate with legal experts to ensure that rapid DNA profiles meet the standards of admissible evidence, including accuracy, reliability, and proper documentation [38].
3. Privacy and Ethical Concerns: The ability to generate DNA profiles quickly and outside traditional labs raises concerns about privacy and the potential misuse of genetic data. Key issues include how DNA samples are stored, who has access to them, and how long they are retained. In applications such as immigration enforcement or battlefield identification, concerns arise regarding consent and the ethical implications of collecting DNA from vulnerable populations or individuals unable to give informed consent [39].
4. Training and Validation: For rapid DNA technology to be effectively integrated into forensic workflows, law enforcement personnel must be properly trained in the operation of these systems. Although designed to be user-friendly, operators must be able to recognize potential issues such as contamination or instrument malfunctions and know when to seek assistance from forensic experts. Additionally, forensic labs must validate rapid DNA systems to ensure they meet the required standards for accuracy, sensitivity, and reproducibility [40].

4.4. Challenges and Limitations of Rapid DNA

Despite its promise, several challenges and limitations of rapid DNA technology must be considered:

1. Cost: The initial investment in rapid DNA technology can be prohibitive for some law enforcement agencies, particularly smaller departments with limited budgets. In addition to the cost of the machines, agencies must account for ongoing expenses, including consumables, maintenance, and training [41].
2. Technological Limitations: While rapid DNA systems can quickly generate profiles, they may not be as comprehensive as traditional lab-based analysis. For example, some rapid DNA systems are limited to processing short tandem repeat (STR) markers, which may not be sufficient for certain forensic applications. Additionally, these machines may struggle with complex samples, such as those containing degraded DNA or mixtures from multiple individuals [42].
3. Jurisdictional Variability: The use of rapid DNA technology varies across jurisdictions, with some countries and states fully embracing the technology while others remain cautious. This variability can create challenges in cross-jurisdictional investigations, where the admissibility and use of rapid DNA results may differ [43].

4.5. The Future of Rapid DNA

Despite these challenges, the future of rapid DNA analysis is promising. As technology continues to advance, improvements in the accuracy, portability, and affordability of rapid DNA systems are expected. Future iterations of these machines may be capable of processing more complex samples, including those with degraded or low-quantity DNA, and generating profiles that include a broader range of genetic markers [44].

In the long term, rapid DNA analysis could become a standard tool in law enforcement and forensic investigations, not only for real-time decision-making but also for routine DNA processing. As the legal framework around rapid DNA solidifies and training programs expand, widespread adoption of this technology in crime scene investigations, border security, and disaster response is likely [45].

5. Touch DNA and Low-Copy Number DNA

Touch or trace DNA (tDNA) and Low-Copy Number (LCN) DNA analysis have significantly expanded the scope of forensic science, enabling the detection and profiling of DNA from extremely small biological samples. Touch DNA refers to the minute amounts of DNA left behind when an individual touches a surface. At the same time, LCN DNA analysis focuses on working with these low quantities, often containing fewer than 100 picograms [1]. These techniques are invaluable in cases where traditional DNA analysis might not yield results, providing crucial evidence linking suspects to crime scenes, weapons, or other key objects [46–56].

5.1. Understanding Touch DNA

Touch DNA evidence can originate from skin cells, sweat, or other bodily substances. It plays a crucial role in forensic investigations due to its ability to be recovered from a wide range of touched items or surfaces, such as tools, weapons, clothing, and other objects, thereby establishing connections between suspects and crimes [1]. The ability to recover and analyze small amounts of DNA from skin cells left behind by mere contact expands the scope of forensic investigations, making it possible to identify and convict perpetrators even without other types of biological evidence.However, collecting touch DNA presents challenges compared to other biological evidence, as the quantity of DNA collected can be influenced by factors such as the time between deposition and collection, the type of surface, environmental conditions, collection methods, and the DNA profiling technique used [49–63].

Touch DNA is especially important in cases where little or no other biological evidence is available. For instance, in burglaries or assaults where the perpetrator does not leave behind bodily fluids, investigators can swab surfaces like doorknobs, countertops, or weapons to recover touch DNA [64]. Similarly, in stolen vehicle cases, touch DNA recovered from the steering wheel, door handles, or gear shifts can link a suspect to the crime [1,65].

Additionally, touch DNA has proven valuable in cold cases where traditional forensic methods may have failed. Advances in DNA amplification and sensitivity allow forensic scientists to extract viable DNA from items stored for years or decades, re-examining evidence with new techniques that can generate results from even the smallest traces [66,67].

5.2. Advances in Low-Copy Number (LCN) DNA Analysis

LCN DNA analysis is a specialized technique designed to amplify and analyze extremely small amounts of DNA, typically below the threshold used in conventional profiling. This process involves increasing the number of PCR cycles beyond standard for traditional DNA profiling. For instance, while standard DNA profiling uses around 28–32 cycles, LCN analysis often employs 34 or more cycles to enhance sensitivity. However, these additional cycles increase the risk of stochastic effects, such as allelic drop-out (where one allele of a heterozygous pair is not detected) and allelic drop-in (where non-relevant alleles appear in the profile), making LCN DNA interpretation more complex and necessitating careful validation of results to mitigate any misinterpretation [66,68,69].

One key advancement in LCN DNA analysis is the development of more sensitive PCR reagents and protocols, such as the GlobalFiler™ PCR Amplification Kit, which greatly improved the sensitivity and robustness of DNA analysis. These advancements reduce the risk of artifacts like allelic drop-out (where one allele of a heterozygous pair is not detected) and enhance the reliability of LCN DNA analysis, making it particularly valuable in high-stakes cases where only trace amounts of DNA are available. Despite these improvements, the presence of impurities in trace samples, including primers, dNTPs, enzymes, and other PCR reagents, can still hinder downstream applications and compromise the reliability of DNA profiles [70]. To address these challenges, post-PCR clean-up methods, such as the Amplicon Rx™ Post-PCR Clean-up Kit (Independent Forensics), have been developed to purify amplified DNA, eliminate inhibitory substances, and improve the recovery of trace or LCN DNA [70].

LCN DNA analysis is particularly beneficial in the following scenarios:

1. Cold Cases: By reanalyzing old evidence with LCN DNA techniques, such as the Amplicon Rx™ Post-PCR Clean-up Kit, investigators can extract profiles from samples previously considered too degraded or insufficient for analysis [70]. This approach has the potential to resolve many cold cases, including decades-old homicides and sexual assaults.
2. Mixed DNA Samples: In cases where DNA from multiple individuals is present, such as at crowded crime scenes or mass disasters, LCN DNA techniques can help separate and identify individual profiles [67,70]. This is especially useful in sexual assault cases where DNA from both the victim and the perpetrator may be mixed [71].

3. High-Sensitivity Forensic Applications: LCN DNA is used in sensitive forensic applications, such as identifying remains from mass disasters, ancient DNA analysis, and wildlife forensics. Traditional DNA profiling methods may not be sufficient in these contexts due to the small or degraded nature of the DNA samples [72].

5.3. Challenges and Risks in Touch DNA and LCN DNA Analysis

While touch DNA and LCN DNA analysis have opened up new possibilities in forensic science, they also present several challenges:

1. Contamination Risks: The increased sensitivity of LCN DNA analysis amplifies the target DNA andany potential contaminants. Even slight contamination from crime scene investigators, lab personnel, or environmental sources can compromise results. This risk is particularly high when dealing with touch DNA, where small quantities of foreign DNA can skew the results [63]. Forensic teams must implement rigorous contamination control measures at every stage, from evidence collection to analysis [65,67].
2. Secondary Transfer: Secondary DNA transfer refers to the phenomenon where DNA from one person is indirectly transferred to an object or surface via an intermediary. For example, if a suspect shakes hands with another person and that person later touches a doorknob, the suspect's DNA could end up on the doorknob despite not directly interacting with it. This presents a significant challenge for forensic scientists, as it raises questions about interpreting DNA evidence [65,71].
3. Interpretation of Low-Quantity DNA: Analyzing low-copy number DNA presents unique challenges in data interpretation. Due to the small amount of DNA involved, LCN DNA profiles may exhibit stochastic effects, such as allelic drop-in (the appearance of an extra allele that is not part of the true profile) or drop-out. These artifacts complicate DNA profile interpretation and may lead to ambiguous or inconclusive results [72]. Forensic scientists must be highly trained in interpreting LCN DNA data and exercise caution when concluding such evidence [69].
4. Legal and Ethical Considerations: The use of touch DNA and LCN DNA in forensic investigations raises important legal and ethical questions. These techniques detect DNA from minute biological samples, increasing the risk of implicating innocent individuals, particularly in cases of secondary transfer. Courts must grapple with the complexities of interpreting low-quantity DNA evidence and consider whether it meets admissibility standards [68,69].

5.4. Best Practices for Touch DNA and LCN DNA Collection

To mitigate the challenges and risks associated with touch DNA and LCN DNA analysis, forensic professionals must adhere to strict best practices for evidence collection and handling:

1. Proper Swabbing Techniques: Investigators must use suitable sampling methods depending on the nature of the evidence, such as swabbing, cutting, scraping, or tape-lifting [51]. These methods must be carried out using sterile, single-use tools and gloves to prevent contamination.Additionally, when swabbing is employed, swabs should be moistened with sterile water or buffer solution to improve DNA recovery [50,56]. Sampling surfaces must be approached in a consistent and controlled manner to maximize the DNA collected [65].
2. Avoiding Cross-Contamination: To prevent cross-contamination, forensic teams should change gloves and swabs between different items of evidence and ensure that all tools and surfaces are thoroughly sterilized before and after use [66].
3. Pre-Scene Assessments: Conducting pre-scene assessments to identify potential contamination sources, such as environmental factors or nearby personnel, helps investigators plan their collection strategies more effectively [58].
4. Training and Certification: Continuous training in the latest touch DNA and LCN DNA collection and analysis techniques is essential. This includes understanding the specific challenges associated with low-quantity DNA, contamination control, and proper evidence handling [65,71].

5.5. Future Directions in Touch DNA and LCN DNA Analysis

The future of touch DNA and LCN DNA analysis lies in continued advancements in sensitivity, accuracy, and contamination control. Emerging technologies, such as digital PCR (dPCR), offer the potential for more precise quantification of low-copy number DNA, reducing the risk of stochastic effects and improving the reliability of results [69]. Advances in forensic software and bioinformatics are helping automate the analysis of complex DNA profiles, allowing for more accurate interpretation of touch DNA and LCN DNA data [69].

Research into secondary transfer mechanisms is also ongoing, with the goal of developing guidelines and protocols to help forensic scientists differentiate between direct and indirect DNA transfer.This is critical to ensure that touch DNA evidence is interpreted correctly and used appropriately in criminal investigations [67,72].

Touch DNA, and LCN DNA analysis are invaluable tools in forensic science, offering new possibilities for solving crimes where traditional methods fall short. As technology evolves, these techniques will become even more powerful, providing forensic professionals with the tools they need to extract meaningful information from the smallest traces of DNA [65,67].

6. AI and Machine Learning in Forensic DNA Analysis

Artificial intelligence (AI) and machine learning (ML) are revolutionizing forensic science by automating complex tasks, identifying patterns in data, and improving the accuracy and efficiency of forensic investigations. These technologies enable forensic scientists to analyze DNA evidence more rapidly and with fewer errors, reducing case backlogs and accelerating justice [73,74]. This section explores the application of AI and ML in forensic DNA analysis, the benefits and challenges of these technologies, and their future potential in the field.

6.1. Introduction to AI and Machine Learning in Forensics

AI involves creating computer systems capable of performing tasks that typically require human intelligence, such as pattern recognition and decision-making [73,75]. ML, a subset of AI, focuses on training algorithms to recognize patterns in data and make predictions [76]. In forensic DNA analysis, AI and ML are used to automate data interpretation, handle complex DNA mixtures, and streamline forensic workflows [77]. For instance, AI algorithms can analyze large DNA datasets to detect patterns that may not be immediately apparent to human analysts [73,78]. These technologies are particularly valuable in cases involving complex or degraded DNA samples [79].

6.2. Applications of AI and Machine Learning in Forensic DNA Analysis

AI and ML are applied across several key areas of forensic DNA analysis:

1. Automated DNA Mixture Analysis: One of the most challenging aspects of forensic DNA analysis is interpreting mixed DNA samples, containing genetic material from multiple individuals. AI and ML algorithms can automate the analysis of these complex mixtures by identifying individual contributors and quantifying the proportions of DNA from each source [75,80]. Technologies like next-generation sequencing (NGS), AI-driven forensic workflows, and 3D genomics have already demonstrated their utility in resolving complex forensic cases, such as identifying degraded samples or mixtures from multiple contributors [76,77].
2. Pattern Recognition and Data Mining: AI and ML are used to identify patterns in forensic DNA data that might be missed by human analysts. For example, machine learning algorithms can sift through large DNA databases to find matches, detect trends, or identify anomalies [81,82]. This is particularly useful in cold cases or when dealing with vast data from national DNA databases [78]. AI can prioritize cases based on the likelihood of finding a match, helping forensic labs manage their workload more efficiently [83].
3. Ancestry and Phenotypic Prediction: AI and ML are also used to predict an individual's ancestry and phenotypic traits (e.g., eye color, hair color, skin pigmentation) based on their DNA profile [79]. Machine learning models analyze large datasets of genetic information to identify SNPs and other markers associated with specific ancestries or traits. This helps law enforcement narrow down their suspect pool when no know suspect exist [84].
4. Forensic Bioinformatics: AI and ML are being integrated into forensic bioinformatics platforms to streamline the processing and analysis of large genomic datasets. These platforms can automatically align DNA sequences, call variants, and generate reports, reducing the need for manual data analysis [78,85]. AI-driven bioinformatics tools can also identify potential errors in the data, such as contamination or sequencing artifacts, and suggest corrective actions [77,81].

6.3. Challenges and Limitations of AI and Machine Learning

While AI and ML offer significant advantages in forensic DNA analysis, several challenges must be addressed to ensure their effective implementation:

1. Data Quality and Training: Machine learning models are only as good as the data on which they are trained. In forensic DNA analysis, AI and ML algorithms must be trained on high-quality, representative datasets to avoid

biased or inaccurate predictions [84]. Ensuring the quality of training data is critical to the success of AI applications in forensics [80].

2. Interpretability and Transparency: Many AI models' "black box" nature poses challenges in forensic science. For forensic evidence to be admissible in court, it must be explainable and traceable [82,83]. Therefore, developing AI models that are transparent and explainable is essential to ensure that forensic experts and legal professionals can understand and defend the results [84].
3. Ethical and Legal Concerns: The use of AI in forensic DNA analysis raises ethical and legal questions, particularly concerning privacy and bias. AI-driven predictions about phenotypic traits or ancestry could inadvertently reinforce racial or ethnic biases in criminal investigations [81,82]. Ethical guidelines and legal frameworks must be established to ensure the responsible use of AI in forensics [83].
4. Validation and Standardization: For AI and ML to be widely adopted in forensic DNA analysis, rigorous validation is required to ensure their accuracy and reliability [47]. AI algorithms must be extensively tested on real-world forensic cases to confirm that they meet the required standards for forensic evidence [84,85]. Standardized protocols and best practices must also be established to guide AI usage in forensic laboratories [79,82].

6.4. Future Potential of AI and Machine Learning in Forensics

The future of AI and ML in forensic DNA analysis is promising. As these technologies evolve, they will become more accurate, efficient, and accessible to forensic professionals [76,83]. AI-driven tools could eventually automate entire forensic workflows, from evidence collection to DNA profiling and reporting, freeing forensic scientists to focus on interpreting results and solving cases [84].

One area of potential growth is the integration of AI with other forensic technologies, such as digital forensics, facial recognition, and voice analysis [76]. By combining multiple forms of evidence, AI could provide a more holistic view of a case, helping investigators identify suspects and link them to crimes more effectively [78].

Another promising development is the use of AI to analyze environmental DNA (eDNA) from crime scenes. AI could detect the presence of specific species or individuals based on trace amounts of DNA found in the environment, which could be valuable in wildlife forensics, environmental crime investigations, and missing persons cases [84].

Finally, as AI becomes more embedded in forensic workflows, there will be opportunities to develop new training programs and certification standards that equip forensic professionals with the skills needed to work with AI-driven tools [80,83]. These programs could focus on the ethical, legal, and technical aspects of AI in forensics, ensuring that forensic scientists are prepared to harness the full potential of these technologies while mitigating risks [81].

7. 3D Genomics and Spatial DNA Analysis

3D genomics and spatial DNA analysis represent cutting-edge innovations in forensic science, allowing investigators to analyze DNA within the context of its three-dimensional environment. Unlike traditional DNA analysis, which focuses on linear sequences of genetic information, 3D genomics examines the spatial organization of DNA within cells, tissues, and complex biological systems. This approach provides new insights into the relationships between DNA, its surrounding environment, and its functional state, offering forensic scientists powerful tools for addressing complex cases [86,87].

Spatial DNA analysis, which includes techniques for mapping the location of DNA molecules within cells and tissues, is especially valuable in forensic investigations involving tissue samples, degraded remains, or complex mixtures. By studying DNA in its natural context, forensic scientists can better understand how genetic material interacts with other biological components and environmental factors, leading to more accurate interpretations of forensic evidence [88,89].

7.1. Introduction to 3D Genomics

3D genomics is a field of study that focuses on the spatial organization of DNA within the cell nucleus. DNA is not a simple linear molecule; it is intricately folded and packed into the three-dimensional structure of the nucleus, where its organization plays a critical role in gene regulation, replication, and cellular function. Understanding the three-dimensional arrangement of DNA can provide valuable information about gene expression patterns, chromosomal interactions, and the structural integrity of genetic material [90].

In forensic science, 3D genomics offers new possibilities for studying DNA damage, structural variants, and chromatin organization in degraded samples. By analyzing the three-dimensional architecture of DNA, forensic scientists can gain insights into the history of the sample, such as how it was damaged or exposed to environmental factors [91]. This level of detail can be particularly important in cases involving old or highly compromised evidence, where traditional DNA analysis may not provide sufficient information [92].

One of the key technologies driving the field of 3D genomics is Hi-C, a technique used to map the three-dimensional interactions between different genome regions [93]. Hi-C allows scientists to study the physical proximity of DNA sequences that may be far apart in the linear genome but close together in the three-dimensional structure [94]. This information can identify chromosomal rearrangements, structural variations, and other genomic features relevant to forensic investigations [95].

7.2. Applications of Spatial DNA Analysis in Forensics

Spatial DNA analysis provides forensic scientists with the ability to map the location of DNA molecules within their original biological context. This is especially valuable in cases involving complex tissue samples, forensic anthropology, and the study of degraded remains [83]. Key applications of spatial DNA analysis in forensic science include:

1. Tissue-Specific DNA Analysis: Spatial DNA analysis enables forensic scientists to study DNA within specific tissues, helping to identify the origin of biological samples. For example, DNA found in a bloodstain may differ in its spatial organization from DNA in a hair follicle or bone fragment [91]. By analyzing the three-dimensional arrangement of DNA in these different tissues, forensic scientists can determine the source of the sample more accurately, which is crucial in cases where multiple types of biological evidence are present [90].
2. Degraded and Ancient DNA: Spatial DNA analysis is particularly useful in cases involving degraded or ancient DNA, where traditional methods may struggle to recover usable genetic information. By studying the spatial organization of DNA in its original context, forensic scientists can gain insights into how the DNA was damaged, how it degraded over time, and whether any structural variations occurred due to environmental exposure [92]. This is valuable in cases involving skeletal remains, archaeological finds, or evidence exposed to extreme conditions [95].
3. Forensic Anthropology and Identification: In forensic anthropology, spatial DNA analysis can be used to study DNA within bone and other hard tissues. This is especially important in cases involving unidentified remains, mass disasters, or war crimes, where traditional DNA extraction methods may not be sufficient to identify individuals [93]. By mapping the spatial distribution of DNA within bone fragments or teeth, forensic scientists can better understand the sample's history and enhance their ability to extract and analyze genetic material for identification purposes [94].
4. Environmental DNA (eDNA) Analysis: Spatial DNA analysis is also being applied to environmental DNA (eDNA) studies, where DNA is collected from soil, water, or other environmental samples. In forensic investigations, eDNA can provide valuable information about the presence of individuals or animals at a crime scene. By analyzing the spatial distribution of eDNA within its environment, forensic scientists can make more accurate inferences about where the DNA originated and how it was deposited, enhancing their ability to reconstruct crime scenes [86].

7.3. Challenges and Considerations in 3D Genomics and Spatial DNA Analysis

While 3D genomics and spatial DNA analysis offer exciting new possibilities for forensic science, they also present several challenges that must be addressed:

1. Technological Complexity: The technologies used in 3D genomics and spatial DNA analysis, such as Hi-C, cryo-electron microscopy, and spatial transcriptomics, are highly complex and require specialized equipment and expertise [88]. Forensic laboratories must invest in advanced instrumentation and training to implement these techniques effectively [89]. Additionally, the analysis of spatial DNA data requires sophisticated bioinformatics tools, which can be resource-intensive and challenging to interpret [90].
2. Sample Preservation: Spatial DNA analysis relies on preserving the three-dimensional structure of DNA within cells and tissues. This means that samples must be carefully collected, handled, and stored to prevent disruption of the DNA's spatial organization [91]. Degraded or improperly preserved samples may not yield reliable spatial DNA data, limiting the applicability of these techniques in some forensic cases [92].
3. Data Interpretation: Interpreting spatial DNA data is more complex than traditional DNA analysis, as it involves understanding the relationships between DNA, its three-dimensional environment, and the biological context in which it was found. Forensic scientists must be trained to interpret this data accurately and to integrate it with other forms of evidence [93]. Additionally, the three-dimensional nature of the data presents challenges for visualization and reporting, requiring new approaches to presenting forensic findings in court [94].

4. Legal and Ethical Implications: The use of 3D genomics and spatial DNA analysis in forensic investigations raises important legal and ethical questions. For example, the ability to study DNA within its three-dimensional context may provide new insights into an individual's genetic traits, ancestry, or medical history, raising privacy concerns [95]. Additionally, the complexity of the data may make it more difficult to explain to juries, potentially impacting the admissibility of this evidence in court [83]. As these technologies become more widely adopted, forensic scientists must work closely with legal professionals to address these challenges and ensure that spatial DNA analysis is used responsibly [91].

7.4. Future Directions in 3D Genomics and Spatial DNA Analysis

The future of 3D genomics and spatial DNA analysis in forensic science is promising, with ongoing research focused on improving the sensitivity, accuracy, and accessibility of these techniques [90]. Advances in single-cell genomics, spatial transcriptomics, and 3D imaging technologies are likely to drive further innovation in this field, enabling forensic scientists to study DNA at unprecedented levels of detail [92].

One potential growth area is the integration of 3D genomics with other forensic technologies, such as AI and machine learning. By combining spatial DNA data with AI-driven analysis, forensic scientists can automate the interpretation of complex datasets and identify patterns that may not be immediately apparent to human analysts [95]. This could lead to more accurate and efficient forensic investigations, particularly in cases involving large volumes of evidence or complex biological systems [93].

Another area of future development is the application of 3D genomics to personalized forensics, where DNA evidence is analyzed in the context of an individual's unique genetic and environmental background [94]. This approach could provide more precise information about how DNA evidence relates to specific individuals, helping to resolve cases where traditional forensic methods fall short [86].

As 3D genomics and spatial DNA analysis evolve, they will undoubtedly play an increasingly important role in forensic science, providing new tools and techniques for solving complex cases and delivering justice [88].

8. Mobile DNA Analysis and Field-Deployed Platforms

Mobile DNA analysis and field-deployed platforms represent a new frontier in forensic science, enabling the analysis of DNA evidence directly at crime scenes, disaster sites, or other remote locations. These portable systems are invaluable for law enforcement, military, and disaster response teams, offering real-time results that can influence critical decision-making. While both mobile DNA and rapid DNA platforms provide quick results, mobile DNA platforms are designed for more comprehensive field use, capable of processing a broader range of sample types and performing complex analyses in remote environments.

In contrast, rapid DNA platforms focus on speed and are optimized for generating STR profiles in controlled environments like police stations or border checkpoints. They are more specialized and limited in the complexity of samples they can handle, making mobile DNA analysis more suitable for field-based, high-stakes investigations where diverse sample types are present [96].

8.1. Introduction to Mobile DNA Analysis

Mobile DNA analysis involves using compact, portable devices that can perform DNA extraction, amplification, and analysis in the field. These devices are often self-contained units that automate the entire DNA testing process, from sample preparation to data interpretation. For example, CRISPR/Cas-powered platforms have demonstrated amplification-free detection capabilities in real-time settings, offering significant advancements in field-deployable diagnostics [97]. Mobile DNA platforms are designed to be user-friendly, allowing non-experts, such as police officers or military personnel, to operate them with minimal training.

The primary advantage of mobile DNA analysis is its ability to generate DNA profiles in a matter of hours, rather than the days or weeks typically required by traditional forensic laboratories. This rapid turnaround time is particularly valuable in situations where time-sensitive decisions are needed, such as identifying suspects during active investigations, confirming the identities of disaster victims, or verifying family relationships at border checkpoints [98].

8.2. Applications of Mobile DNA Analysis

Mobile DNA analysis is being used in a wide range of forensic and security applications, providing real-time DNA results that can be used to support investigations, identify individuals, and solve crimes. Key applications include:

1. Crime Scene Investigations: Mobile DNA platforms allow investigators to analyze biological evidence directly at crime scenes, providing immediate results that can guide the investigation. DNA recovered from bloodstains, saliva, or other biological materials at a crime scene can be processed on-site, enabling investigators to identify suspects or rule out potential leads quickly. This is particularly useful in high-stakes cases such as homicides or sexual assaults, where timely identification of suspects is critical [99].
2. Disaster Victim Identification (DVI): In mass casualty events, such as natural disasters, terrorist attacks, or accidents, mobile DNA platforms can be deployed to disaster sites to identify victims in real-time. Studies have demonstrated the effectiveness of portable devices in such scenarios, where rapid identification is crucial for managing disaster response and notifying next of kin [100].
3. Military and Battlefield Forensics: The military has adopted mobile DNA analysis for battlefield forensics, enabling the identification of casualties, enemy combatants, and detainees. These platforms can be deployed in remote or hostile environments where access to traditional laboratory infrastructure is limited. They provide real-time DNA results that can support military operations, identify fallen soldiers, and track the identities of captured individuals [101].
4. Border Security and Immigration Enforcement: Mobile DNA platforms are being used by border security and immigration agencies to verify family relationships, detect human trafficking, and prevent identity fraud. For example, the U.S. Customs and Border Protection (CBP) has implemented mobile DNA analysis at border crossings to confirm familial relationships among migrants, ensuring that children are not being trafficked or exploited. This helps authorities process immigration claims more efficiently while protecting vulnerable individuals [102].
5. Humanitarian and Refugee Crises: Mobile DNA analysis is also being used in humanitarian contexts, such as refugee camps or conflict zones, to reunite families separated by war, displacement, or natural disasters. By rapidly verifying family relationships through DNA testing, humanitarian organizations can help reunite children with their parents and prevent trafficking or exploitation in crises [103].

8.3. Challenges and Limitations of Mobile DNA Analysis

While mobile DNA analysis offers significant advantages, several challenges must be addressed to ensure its effective and responsible use in forensic investigations:

1. Accuracy and Reliability: Mobile DNA platforms are designed to generate DNA profiles quickly, but their accuracy and reliability must meet the same high standards as traditional laboratory-based DNA analysis. Ensuring that mobile DNA systems produce consistent, reproducible results is critical for their acceptance in court and use in high-stakes investigations. Ongoing validation and proficiency testing are necessary to confirm the performance of mobile DNA platforms in various real-world scenarios [104].
2. Chain of Custody and Evidence Integrity: Conducting DNA analysis in the field raises concerns about preserving the chain of custody and maintaining evidence integrity. Strict protocols must be implemented for collecting, handling, and analyzing DNA samples to prevent contamination or tampering. Proper documentation of the entire process, from sample collection to data reporting, is essential to ensure that the results can be defended in court [105].
3. Training and Expertise: Mobile DNA platforms are designed to be user-friendly, but operators still require training to ensure proper usage and accurate interpretation of results. Law enforcement and military personnel must be trained in DNA sample collection, device operation, and recognizing potential issues, such as contamination or instrument malfunction. Additionally, forensic experts must be available to provide guidance and oversight when necessary [106].
4. Cost and Accessibility: The cost of mobile DNA platforms and the associated consumables can be prohibitive for some law enforcement agencies, particularly smaller departments with limited budgets. While these systems offer rapid results, they may not be suitable for all types of forensic analysis. For instance, mobile DNA platforms may be limited to processing specific types of samples or generating profiles based on a particular set of genetic markers. Ensuring that mobile DNA systems are accessible and affordable for a wide range of users will be crucial for widespread adoption [107].
5. Legal and Ethical Considerations: The use of mobile DNA analysis raises important legal and ethical questions, particularly concerning privacy and the potential for misuse. Conducting DNA analysis in the field may increase the risk of unauthorized access to sensitive genetic data. Additionally, using mobile DNA platforms in border

security or immigration enforcement contexts raises questions about consent and the ethical implications of collecting DNA from vulnerable populations. Legal frameworks and ethical guidelines must be developed to govern the use of mobile DNA technology and protect individuals' rights [108].

8.4. Future Potential of Mobile DNA Analysis

The future of mobile DNA analysis is promising, with ongoing research focused on improving the sensitivity, accuracy, and portability of these platforms.. As technology continues to evolve, mobile DNA systems are likely to become smaller, faster, and more affordable, making them accessible to a wider range of users [109].

One area of potential growth is the integration of mobile DNA platforms with other forensic technologies, such as digital forensics, facial recognition, and AI-driven analysis. By combining multiple forms of evidence, mobile DNA systems can provide a more comprehensive view of a crime scene or investigation, helping to solve cases more effectively [110].

Another area of future development is using mobile DNA analysis in real-time monitoring and surveillance applications. For example, mobile DNA platforms could be used to monitor wildlife populations, detect the presence of specific species or individuals in an environment, or track the spread of disease in real-time. These applications could significantly affect conservation, public health, and environmental protection [111].

As mobile DNA technology continues to advance, it is likely to become an essential tool in a wide range of forensic and security applications, providing rapid, reliable DNA results that can be used to solve crimes, identify individuals, and protect public safety [112].

9. Forensic DNA Databases and Information Sharing

Forensic DNA databases have become essential tools in modern criminal investigations, enabling law enforcement agencies to identify suspects, link crimes, and exonerate the innocent. By storing and cataloging DNA profiles collected from crime scenes, convicted offenders, and arrestees, these databases allow forensic scientists to compare DNA evidence against a vast repository of genetic information, significantly enhancing the ability to solve cases. However, as DNA databases continue to expand, they raise important questions about privacy, data security, and the ethical use of genetic information. The challenges associated with managing, sharing, and protecting forensic DNA data are becoming increasingly complex, requiring careful consideration of legal, operational, and ethical issues [113,114].

9.1. Introduction to Forensic DNA Databases

Forensic DNA databases are centralized repositories that store DNA profiles generated from biological evidence collected at crime scenes and from individuals who have been convicted of certain offenses or, in some cases, arrestees. The primary purpose of these databases is to enable law enforcement agencies to match DNA evidence from unsolved cases to known individuals, helping to identify suspects and link crimes across jurisdictions [115].

One of the largest and most widely used forensic DNA databases in the United States is the Combined DNA Index System (CODIS), which contains millions of DNA profiles from convicted offenders, arrestees, and forensic evidence. CODIS allows local, state, and federal law enforcement agencies to share DNA data and search for matches across the country. Similar databases exist in other countries, such as the UK's National DNA Database (NDNAD) and the European Union's Prüm system, facilitating cross-border DNA data sharing among EU member states [116,117].

9.2. Applications of DNA Databases in Forensic Investigations

Forensic DNA databases are used in various ways to support criminal investigations and enhance public safety:

1. Crime Scene Investigations: When DNA evidence is collected from a crime scene, forensic scientists can compare the DNA profile against a database to identify potential suspects. This process, known as a "cold hit", can link an unknown perpetrator to previous crimes or a known offender in the database [118]. For example, in cases of sexual assault or burglary, DNA profiles from crime scene evidence can be matched to convicted offenders who have committed similar crimes in the past [119].
2. Linking Serial Crimes: DNA databases can also be used to link crimes committed by the same perpetrator. If DNA evidence from multiple crime scenes matches a single profile in the database, law enforcement agencies can identify patterns of criminal behavior and pursue a serial offender. This has been particularly useful in cases involving serial rapists or murderers [120].

3. Exoneration of the Innocent: DNA databases play a critical role in exonerating individuals who have been wrongfully convicted. By comparing DNA evidence from old cases to profiles in the database, forensic scientists can identify the true perpetrator and clear the name of someone who was falsely accused or convicted [121]. DNA databases have been instrumental in overturning wrongful convictions and freeing innocent individuals from prison.
4. Missing Persons and Disaster Victim Identification: DNA databases are also used to identify missing persons and disaster victims. In cases where human remains are recovered but cannot be identified through traditional means, DNA profiles can be generated and compared against databases of missing persons or their relatives. This helps provide closure to families and ensures that victims are properly identified and accounted for [122].
5. Detecting Patterns in Non-Serious Crimes: While forensic DNA databases are invaluable for linking suspects to serious offenses like homicides and sexual assaults, they also play a significant role in detecting patterns of non-serious crimes, such as burglaries, thefts, and property crimes. Identifying repeat offenders in these cases can disrupt criminal activities that, while less severe individually, have a broader impact on community safety. Early detection of patterns in non-serious crimes can help prevent escalation into more serious offenses, offering a proactive approach to crime prevention and enhancing the overall effectiveness of law enforcement efforts.
6. Ancestry Databases and Investigative Genetic Genealogy: Ancestry databases have become increasingly useful in Investigative Genetic Genealogy (IGG), aiding law enforcement in identifying suspects by tracing distant relatives. These databases offer a larger pool of DNA profiles compared to traditional forensic databases, allowing for breakthroughs in cold cases. However, the use of these databases raises concerns around privacy and consent, as individuals may not expect their genetic data to be accessed for criminal investigations. Clear guidelines are essential to ensure responsible use [119].

9.3. Challenges of Managing Forensic DNA Databases

While forensic DNA databases offer significant benefits, they also present several challenges that must be addressed to ensure their proper use and management:

1. Data Security and Privacy: The expansion of forensic DNA databases raises concerns about the security and privacy of genetic information. DNA profiles stored in these databases contain sensitive information about an individual's genetic makeup, which could be misused if accessed by unauthorized individuals or entities. Ensuring the security of DNA databases is critical to protecting the privacy of individuals whose DNA is stored within them [120]. This includes implementing strong encryption protocols, access controls, and audit trails to prevent unauthorized access and data breaches.
2. Inclusion Criteria and Ethical Considerations: The criteria for inclusion in DNA databases vary across jurisdictions, with some countries allowing DNA collection from arrestees or even individuals who have not been charged with a crime. This raises ethical questions about the scope of DNA collection and the potential for abuse. For example, collecting DNA from individuals who have been arrested but not convicted could disproportionately impact certain populations, leading to concerns about racial or socioeconomic bias in the criminal justice system [116]. Establishing clear guidelines and oversight mechanisms for DNA collection and database inclusion is essential to addressing these ethical concerns.
3. Interoperability and Data Sharing: As DNA databases expand and become more interconnected, ensuring the interoperability of different systems becomes increasingly important. Law enforcement agencies across different jurisdictions must be able to share and compare DNA data efficiently, which requires standardized formats and protocols for data exchange [117]. However, differences in legal frameworks, technical infrastructure, and data privacy regulations can create barriers to effective information sharing. Developing international standards for DNA databases and data sharing is critical to improving the interoperability of forensic systems and enhancing cross-border cooperation [119].
4. Backlogs and Resource Constraints: Many forensic DNA databases face significant backlogs due to the sheer volume of DNA profiles being generated and the limited resources available to process them. This can delay investigations and hinder the ability of law enforcement agencies to solve crimes in a timely manner. Addressing these backlogs requires increased funding, staffing, and investment in new technologies that can automate and streamline DNA analysis [122]. Additionally, prioritizing the processing of DNA profiles based on the severity of the crime or the likelihood of solving a case can help manage the workload more effectively.
5. Retention and Deletion Policies: The retention and deletion of DNA profiles in forensic databases is contentious. Some jurisdictions have strict policies for removing DNA profiles once an individual is acquitted or charges are

dropped. In contrast, others allow DNA profiles to remain in the database indefinitely [121]. Balancing the need for public safety with individual privacy rights is a challenge, and policies governing the retention and deletion of DNA profiles must be carefully considered to ensure they are fair and just.

9.4. Future Directions in DNA Databases and Information Sharing

The future of forensic DNA databases and information sharing lies in the continued development of new technologies and international cooperation. Some of the key trends and future directions include:

1. Expanding the Scope of DNA Databases: As technology advances, the scope of forensic DNA databases is likely to expand to include new types of genetic information, such as mitochondrial DNA (mtDNA), Y-chromosome DNA, and phenotypic markers [118]. These additional data points could provide law enforcement agencies with more detailed information about suspects, including their ancestry, physical traits, and familial relationships. However, expanding the scope of DNA databases also raises new ethical and privacy concerns that must be addressed.
2. Integration with Other Forensic Databases: Forensic DNA databases are increasingly being integrated with other forensic databases, such as fingerprint databases, ballistics databases, and digital forensics databases. This integration allows law enforcement agencies to cross-reference different types of evidence and build a more comprehensive picture of a case [119]. For example, matching DNA evidence to a fingerprint or ballistics record could provide investigators with multiple lines of evidence to support their case.
3. International Cooperation and Data Sharing: The globalization of crime has made international cooperation in forensic investigations more important than ever. DNA databases like CODIS and Prüm facilitate cross-border data sharing, but there is still work to be done to improve international cooperation and harmonize legal frameworks [117]. Developing global standards for DNA databases and data sharing will be critical to enhancing collaboration among law enforcement agencies around the world.
4. Advances in Genetic Privacy and Data Security: As forensic DNA databases grow, there will be increasing pressure to develop new technologies and protocols to protect genetic privacy and data security. This could include using blockchain technology to secure DNA data, advanced encryption methods to protect data during transmission, and new privacy-preserving algorithms that allow DNA data to be searched and compared without revealing the underlying genetic information [116].
5. Public Awareness and Engagement: Public awareness and engagement will be key to the future success of forensic DNA databases. Educating the public about the benefits and risks of DNA databases, and the safeguards in place to protect privacy and prevent misuse, can help build trust and ensure that these systems are used responsibly [121]. Additionally, engaging with communities affected by DNA collection practices, such as minority populations, can help address concerns about bias and ensure that DNA databases are used fairly and equitably.

10. Legal and Ethical Considerations in Forensic DNA Analysis

Forensic DNA analysis has revolutionized criminal investigations by enabling the identification of suspects, exonerating the innocent, and solving cold cases. However, using DNA evidence also raises significant legal and ethical questions, including concerns about privacy, the potential misuse of genetic data, consent, bias, and the implications of new forensic technologies in the criminal justice system. This section explores these challenges and the need for legal frameworks and ethical guidelines to ensure responsible and fair use of forensic DNA analysis.

10.1. Privacy and Genetic Data

One of the most pressing ethical concerns in forensic DNA analysis is the protection of genetic privacy. DNA contains sensitive information about an individual’s identity, ancestry, and health risks, raising concerns about the potential misuse of genetic data by law enforcement, government agencies, or third parties. The expansion of forensic DNA databases, particularly those that include DNA from arrestees or individuals who have not been convicted of a crime, heightens these privacy concerns [123].

Privacy advocates argue that DNA collection and storage should be governed by strict legal controls, including limits on how long DNA can be retained and who can access it [124]. Advances in DNA technology, such as genetic genealogy and phenotypic prediction, raise concerns about the potential for more intrusive forms of surveillance or discrimination based on genetic traits [125]. Regulatory frameworks such as the European Union’s General Data

Protection Regulation (GDPR) and the U.S. Genetic Information Nondiscrimination Act (GINA) provide examples of legislation designed to protect genetic privacy [126].

10.2. Consent and the Use of DNA

Informed consent is a fundamental ethical principle in forensic DNA analysis, especially when DNA is collected from individuals who are not suspects. For example, obtaining informed consent in cases where DNA is collected from family members to identify remains, or where voluntary DNA samples are requested to eliminate individuals from suspicion, is essential [127].

However, DNA collection without explicit consent, such as through discarded items or surreptitious collection, raises ethical questions about privacy [128]. Familial DNA searching, where law enforcement uses partial matches to relatives of suspects, also raises concerns about consent and privacy [129]. Legal and ethical guidelines must clearly define when and how DNA can be collected and whether consent is required to protect individuals' rights [121].

10.3. Bias and Discrimination in Forensic DNA Analysis

Forensic DNA analysis is not immune to bias and discrimination. Concerns have been raised that DNA evidence could disproportionately impact certain racial or ethnic groups, particularly in countries where minority populations are overrepresented in forensic DNA databases [130]. This overrepresentation increases the likelihood of DNA matches involving these groups, raising concerns about racial profiling and systemic bias in the criminal justice system [131].

Bias can also occur during DNA evidence interpretation especially in complex cases involving mixtures or low-template DNA [132]. Implementing blind testing procedures, providing bias-awareness training, and ensuring transparency in forensic laboratories are crucial steps in mitigating bias and ensuring fairness in DNA analysis [133].

10.4. Admissibility of DNA Evidence in Court

The admissibility of DNA evidence in court is a critical legal issue, as the reliability and interpretation of DNA evidence can significantly impact trial outcomes. DNA evidence is often scrutinized under the Daubert or Frye standards, which determine whether scientific evidence is admissible based on its reliability and acceptance in the scientific community [134].

While forensic DNA analysis is generally considered reliable, challenges can arise in cases involving low-template DNA, complex mixtures, or degraded samples [135]. Courts must be vigilant in evaluating the reliability of emerging forensic technologies, such as AI-driven DNA analysis and phenotypic prediction, to ensure they meet admissibility standards [136].

10.5. Ethical Considerations in Emerging Forensic DNA Technologies

As new forensic DNA technologies emerge, such as genetic genealogy, phenotypic prediction, and rapid DNA analysis, ethical considerations must be addressed. These technologies can potentially solve previously unsolvable crimes, but they also raise new ethical concerns about privacy, consent, and potential misuse [137].

For instance, genetic genealogy, which involves using public genealogy databases to identify suspects based on familial DNA, has been instrumental in solving cold cases. However, it has also raised concerns about the privacy of individuals who submit their DNA to genealogy websites without knowing that their genetic information could be used in criminal investigations [126]. Similarly, phenotypic prediction, which predicts physical traits from DNA, raises questions about accuracy and potential bias [128].

To address these ethical challenges, forensic scientists, legal experts, and policymakers must collaborate to develop guidelines and regulations that prioritize protecting individuals' rights while ensuring that forensic DNA analysis remains a valuable tool in the pursuit of justice [134].

11. Summary of Emerging DNA Technologies

To assist forensic professionals in selecting the most appropriate technologies for their specific needs, Table 1 summarizes the key emerging DNA technologies explored in this manuscript. This table highlights each technology's major benefits, challenges, and practical guidelines, as well as its current level of adoption and typical application areas. The aim is to provide a clear overview that allows professionals to make informed decisions based on their specific forensic scenarios, whether dealing with time-sensitive cases, complex DNA mixtures, or remote field operations.

Additionally, a checklist has been provided in the supplementary materials to further assist in implementing these technologies, offering actionable steps and guidance for forensic professionals looking to integrate these innovations into their workflows.

12. Conclusions

Forensic DNA analysis has revolutionized criminal investigations, providing law enforcement with a powerful tool to identify suspects, exonerate the innocent, and solve cold cases. The continued advancement of DNA technologies, including next-generation sequencing (NGS), AI-driven analysis, 3D genomics, and mobile DNA platforms, has further expanded the capabilities of forensic scientists. These innovations enable the rapid, accurate, and efficient processing of evidence, bringing new levels of precision to criminal investigations.

However, with these advancements come challenges that must be carefully managed to ensure the responsible and ethical use of forensic DNA analysis. Contamination risks at crime scenes, during evidence collection, and in laboratories remain persistent threats to the integrity of forensic evidence. To mitigate these risks, it is essential to adhere to strict protocols, provide continuous training, and implement best practices throughout the forensic process.

The integration of emerging technologies, such as spatial DNA analysis and field-deployable DNA platforms, offers exciting possibilities for advancing forensic investigations. Yet, these innovations introduce new complexities, particularly in data interpretation, legal admissibility, and privacy protection. Forensic scientists must navigate these challenges carefully, ensuring that these powerful technologies are applied responsibly and with a commitment to justice.

Forensic DNA databases have proven invaluable in solving crimes, linking serial offenses, and identifying individuals in disaster victim identification (DVI) scenarios. However, expanding these databases raises critical questions about privacy, data security, and the potential for bias. It is crucial to manage DNA databases ethically and securely, with clear guidelines governing data inclusion, retention, and sharing in order to maintain public trust in forensic science.As new technologies and methods emerge, legal and ethical considerations must remain at the forefront of forensic DNA analysis. Policymakers, forensic scientists, and legal professionals must collaborate to develop frameworks that balance the need for public safety with the protection of individual rights. Ensuring that DNA evidence is used fairly and equitably in pursuing justice is paramount.

The future of forensic DNA analysis will be shaped by the continued evolution of technology, the refinement of forensic practices, and a steadfast commitment to ethical principles.By embracing innovation while proactively addressing the challenges and risks it presents, the forensic community can ensure that DNA analysis remains a reliable and indispensable tool in criminal investigations.This, in turn, will contribute to a more just and equitable legal system that serves the public interest.

Supplementary Materials

The following supporting information can be found at: https://www.sciepublish.com/article/pii/279, Checklist for Navigating the Future of DNA Analysis in Criminal Investigations.

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Informed Consent Statement

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