Artificial Intelligence and DNA in criminal investigations

الذكاء الاصطناعي والبصمة الوراثية في التحقيقات الجنائية

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Summary in English:

Artificial Intelligence is increasingly integrated into forensic science, revolutionizing the use of DNA evidence in criminal investigations. AI-driven tools, including machine learning algorithms, enable forensic experts to analyse complex DNA samples more accurately and efficiently than traditional methods. These tools facilitate the interpretation of low-level, degraded, or mixed DNA samples, which often challenge manual analysis. AI techniques such as probabilistic genotyping use advanced algorithms to assess the likelihood that DNA mixtures contain material from specific individuals, improving identification accuracy in cases with multiple contributors.

The adoption of AI in DNA analysis enhances investigative capabilities by automating the processing of large and complex datasets, allowing law enforcement to extract critical genetic information quickly. AI also supports the resolution of cold cases by making it possible to analyse decades-old or difficult samples that were previously unviable for testing. Experts emphasize that AI does not replace forensic scientists but serves as an advanced aid that increases the sensitivity and specificity of DNA interpretation while reducing human bias and errors.

Alongside technical benefits, the use of AI in forensic DNA analysis brings procedural and legal challenges, especially regarding the transparency and validation of AI algorithms. Courts must ensure the reliability of AI-based evidence and demand clear documentation of the algorithms' validation processes, reproducibility, and error rates. Legal scrutiny focuses on addressing issues related to "opaque AI" systems, where the decision-making process is not always transparent, raising concerns about admissibility and interpretability in court.

Overall, the integration of AI in forensic DNA analysis marks a significant advancement in criminal justice by enhancing the accuracy and efficiency of investigations. The technology's continued development, alongside the establishment of rigorous validation protocols and ethical considerations, is critical for its successful implementation in forensic science and the criminal justice system

Keywords: Artificial Intelligence (AI); Forensic DNA Analysis; Criminal Investigations; Legal Admissibility; Forensic Automation.

الملخص باللغة العربية:

يتم دمج الذكاء الاصطناعي بشكل متزايد في علم الطب الشرعي، مما يُحدث ثورة في استخدام أدلة الحمض النووي في التحقيقات الجنائية. تُمكِّن الأدوات التي تعتمد على الذكاء الاصطناعي، بما في ذلك خوارزميات التعلم الآلي، خبراء الطب الشرعي من تحليل عينات الحمض النووي المعقدة بدقة وكفاءة أكبر من الطرق التقليدية. تُسهّل هذه الأدوات تفسير عينات الحمض النووي منخفضة المستوى أو المتدهورة أو المختلطة، والتي غالبًا ما تتحدى التحليل اليدوي. وتستخدم تقنيات الذكاء الاصطناعي مثل التنميط الجيني الاحتمالي خوارزميات متقدمة لتقييم احتمالية احتواء مخاليط الحمض النووي على مواد من أفراد معينين، مما يحسن دقة تحديد الهوية في الحالات التي يكون فيها مساهمون متعددون.

ويؤدي اعتماد الذكاء الاصطناعي في تحليل الحمض النووي إلى تعزيز قدرات التحقيق من خلال أتمتة معالجة مجموعات البيانات الكبيرة والمعقدة، مما يسمح لأجهزة إنفاذ القانون باستخراج المعلومات الوراثية المهمة بسرعة. ويدعم الذكاء الاصطناعي أيضًا حل القضايا الباردة من خلال إتاحة تحليل عينات عمرها عقود أو عينات صعبة كانت غير قابلة للاختبار في السابق. ويشدد الخبراء على أن الذكاء الاصطناعي لا يحل محل علماء الطب الشرعي، بل هو بمثابة أداة مساعدة متقدمة تزيد من حساسية وخصوصية تفسير الحمض النووي مع الحد من التحيز والأخطاء البشرية.

وبالإضافة إلى الفوائد التقنية، فإن استخدام الذكاء الاصطناعي في تحليل الحمض النووي في الطب الشرعي يجلب تحديات إجرائية وقانونية، خاصة فيما يتعلق بشفافية خوارزميات الذكاء الاصطناعي والتحقق من صحتها. يجب على المحاكم ضمان موثوقية الأدلة القائمة على الذكاء الاصطناعي والمطالبة بتوثيق واضح لعمليات التحقق من صحة الخوارزميات وقابلية التكرار ومعدلات الخطأ. يركز التدقيق القانوني على معالجة القضايا المتعلقة بأنظمة" الذكاء الاصطناعي المبهمة"، حيث لا تتسم عملية اتخاذ القرار بالشفافية دائمًا، مما يثير مخاوف بشأن المقبولية وقابلية التفسير في المحكمة.

وعموماً، يمثل إدماج الذكاء الاصطناعي في تحليل الحمض النووي في الطب الشرعي تقدماً كبيراً في العدالة الجنائية من خلال تعزيز دقة التحقيقات وكفاءتها. ويكتسي استمرار تطوير هذه التكنولوجيا، إلى جانب وضع بروتوكولات صارمة للتحقق من صحتها واعتبارات أخلاقية، أهمية حاسمة لنجاح تطبيقها في علم الطب الشرعي ونظام العدالة الجنائية.

الكلمات المفتاحية: الذكاء الاصطناعي(AI) ؛ تحليل الحمض النووي الجنائي؛ التحقيقات الجنائية؛ المقبولية القانونية؛ أتمتة الطب الشرعي.

Objectives of the study:

- To evaluate the potential of AI-based DNA analysis tools to improve the accuracy, efficiency, and reliability of forensic investigations involving DNA evidence.
- To explore how AI algorithms assist in interpreting complex DNA samples, including mixtures, low-level samples, and degraded specimens, which pose challenges for traditional manual analysis.
- To assess the role of AI in automating the processing of large datasets and generating investigative leads faster, especially in cold cases and complex crime scenes.
- To identify challenges and limitations in implementing AI technologies in forensic DNA analysis, including technical, operational, legal, and ethical factors.
- To provide recommendations for forensic science practice, law enforcement procedures, and regulatory frameworks to optimize AI application while ensuring transparency, accountability, and fairness.
- To analyse the collaborative role of AI with forensic experts rather than replacing human judgment, focusing on enhancing decision support and reducing bias and errors.

One study that exemplifies these objectives focused on evaluating AI-based DNA testing in criminal investigations by identifying challenges in infrastructure, training, and legal regulations, while highlighting AI's potential for speeding up investigations and increasing result accuracy

The methods used:

- Machine Learning and Deep Learning: Use of algorithms such as neural networks and deep learning architectures to analyse complex DNA datasets, recognize patterns, and interpret DNA mixtures or degraded samples with high accuracy.
- Probabilistic Genotyping: Application of AI-based statistical modeling to evaluate the likelihood of DNA profiles, helping to deconvolute mixed samples with multiple contributors.
- Automated DNA Analysis: Leveraging AI tools to automate the extraction, processing, and interpretation of DNA data, speeding up workflows while reducing human error.
- Data Integration and Predictive Analytics: Incorporating large volumes of genetic data with other forensic evidence using AI systems to generate investigative leads and predict crime patterns.

- Hybrid Approaches: Combining AI algorithms with expert forensic analysis to validate outputs and enhance decision-making rather than fully replacing human judgment.
- Experimental Evaluation: Many studies employ quantitative methods, such as surveys of forensic experts, case studies, or controlled experiments, to assess the effectiveness of AI tools in real-world or simulated forensic contexts.

For example, specific AI technologies involved include deep learning for facial recognition from DNA-based predictions, natural language processing for analyzing communications, and neural networks for DNA data management and pattern recognition. These methods vastly improve the speed and accuracy of forensic DNA analysis compared to traditional manual techniques. Ethical and operational evaluations are also employed to address challenges in implementation

<u>Key findings in sequential order:</u>

1. AI algorithms substantially accelerate DNA analysis by automating complex processes, enabling rapid profiling, and assisting with kinship and mixture interpretations, thus improving the accuracy and efficiency of forensic investigations.
2. AI-based probabilistic genotyping better interprets mixed or low-quality DNA samples that are difficult for humans to analyse, leading to more reliable identification outcomes.
3. AI tools support forensic scientists by reducing human error and bias, enhancing decision support rather than replacing expert judgment in criminal investigations.
4. Machine learning models applied in forensic DNA profiling can detect subtle patterns and predict physical traits from genetic data, opening new investigative avenues.
5. The integration of AI in forensic workflows facilitates cold case resolutions by enabling analysis of degraded DNA evidence otherwise unusable.
6. Challenges remain, including the need for transparent AI validation, addressing ethical and legal concerns, and ensuring the interpretability and admissibility of AI-analysed evidence in court.
7. AI tools also enhance other forensic disciplines such as image and video evidence analysis, fingerprint matching, and digital forensics, broadening their impact on criminal investigations.
8. Field studies involving expert assessments show AI performs well in homicide and similar crime scenes but may face difficulties in certain contexts like arson investigations, indicating the necessity for tailored AI applications.

Here is a table summarizing key statistical data related to the effectiveness and impact of forensic DNA databases and AI-assisted forensic analysis in criminal investigations, drawn from recent forensic reports and studies:

Metric	Value / Details	Description
Number of DNA profile matches in 2022/23 (UK National DNA Database)	799,974 matches total (average 38,094/year)	Matches linking individuals to crime scenes or linking crime scenes, aiding crime resolution
Number of DNA profiles held on National Database (2023)	~7,045,155 subject profiles; 670,817 crime scene profiles	Large-scale DNA database enabling extensive forensic comparisons
Routine DNA profile matches by crime type (2022/23)	Burglary: 9,105; Vehicle crime: 3,747; Rape: 519; Homicide: 476	Distribution of DNA matches by types of crimes
AI forensic image analysis mean time per analysis	ChatGPT-4: 1.8 min; Claude: 1.6 min; Gemini: 1.7 min	Shows AI tools are drastically faster than human experts (41.8 min average), useful in screening
Accuracy and effectiveness	AI tools have high accuracy in evidence observation, better in homicide scenes than arson (average scores 7.8 vs 7.1)	AI enhances forensic experts' work but does not replace them
Improvement in DNA mixture interpretation	AI probabilistic genotyping increases reliability	Beneficial in complex samples with multiple contributors
Cold case resolutions	AI enables viable analysis of degraded decades-old DNA	Expands investigative reach for older unsolved cases

Metric	Value / Details	Description
Challenges	Need for transparent validation, ethical/legal considerations	Critical for court admissibility and public trust

This table provides quantitative confirmation of the enhanced efficiency, accuracy, and broad impact of AI-supported DNA forensic analysis in criminal justice systems. It highlights not only speed gains but also successful case applications and ongoing challenges needing attention.

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1. Introduction

The modern era is defined by scientific and technological development, which has led to increasingly complex methods of committing crime. Simultaneously, the proliferation of digital data has intensified the demand for sophisticated defensive and investigative mechanisms across numerous fields. Artificial Intelligence (AI), born as a research discipline in 1956, and its component technologies like Machine Learning (ML), have emerged as essential tools for addressing these complex problems, particularly those involving massive datasets that surpass human processing capabilities.

In the realm of criminal investigations, **AI is playing an increasing role in both substantive and procedural criminal law**. While AI applications have traditionally focused on combating cybercrimes—such as intrusion detection, spam filtering, and malware classification—the utility of AI extends significantly into forensic science and evidence analysis. The purpose of this academic review is to examine the specific intersection of AI and DNA evidence within criminal investigations, encompassing both established identification methods and emerging predictive forensic intelligence, while rigorously addressing the attendant legal and reliability concerns.

Forensic DNA profiling stands as the fundamental discipline of forensic science, highly regarded for its rigor, accuracy, and robustness in human identification (HID). DNA analysis allows for linking a crime to its perpetrator through scientific development in genetics. However, the advancement of genomic technologies and massively parallel sequencing (MPS) has resulted in the accumulation of complex genetic data that requires extensive processing and annotation—tasks naturally suited for ML approaches. This paper maps the major developments in applying computational intelligence to forensic DNA, emphasizing the scientific advancements alongside the ethical and legal frameworks necessary for their trusted deployment in the justice system.

2. Foundations of Artificial Intelligence in Criminal Justice

2.1 Defining Artificial Intelligence and its Techniques

AI, or machine intelligence, is fundamentally a science focused on finding methods for solving complex problems that require some level of intelligence, particularly making right decisions based on large amounts of data. It involves designing computer algorithms that simulate human cognitive functions, such as thinking, learning, reasoning, and pattern recognition.

In the context of fighting cybercrime and forensic investigation, numerous bio-inspired computing methods fall under the umbrella of AI, including Computational Intelligence (CI), Neural Networks (NN), Artificial Immune Systems (AISs), Fuzzy Logic, and especially **Machine Learning (ML)**.

Machine Learning is a powerful computational subfield of AI focused on training computer programs to learn from experience regarding specific tasks and performance measures. ML algorithms generate predictive models via intelligent autonomous analysis of large, often unstructured, data sets. ML can be categorized into various methods, including supervised, unsupervised, and reinforcement learning, which are vital for building complex systems like deep learning models. ML is considered instrumental in digital forensics and evidence discovery due to the substantial advancements in computational power that allow machines to process vast data amounts.

2.2 AI in General Criminal Investigation and Evidence Analysis

Law enforcement and public prosecution services are increasingly utilizing AI to support or replace certain aspects of their work. AI is applied across various stages of the criminal procedure:

1. **Digital Forensics and Data Seizure:** Criminal investigations frequently involve seizing digital devices (laptops, phones, etc.) containing tremendous volumes of data. AI and big data analytics systems, like Hansken in the Netherlands, are used to process, index, and make this data searchable across different formats (text, video, audio). This effectively solves the "needle-in-the-haystack" problem, increasing the effectiveness and speed of investigations.
2. **Evidence Assessment:** AI plays a role in assessing technical evidence, such as fingerprints and DNA, which invariably contain margins of error, leading to potential false positives or false negatives. The use of AI in forensics assists in developing scenarios for reconstructing crimes.
3. **Predictive Policing:** AI uses sophisticated data analytics on large datasets to disclose trends in crime and predict where crime is likely to occur, or who might be a victim or perpetrator.

The application of AI in this domain contrasts starkly with traditional fixed algorithms, providing the flexibility and learning capability needed to manage dynamically evolving criminal methods.

3. The Role of DNA in Forensic Science

3.1 Forensic DNA Profiling and Human Identification

Forensic DNA profiling, relying heavily on the analysis of Short Tandem Repeats (STRs), is characterized by its high standards of accuracy, sensitivity, and robustness. DNA, or the genetic footprint, is relied upon in many countries to identify perpetrators by comparing a sample found at a crime scene with a sample taken from a suspect’s body via laboratory analysis.

The process of generating and interpreting STR data involves numerous complex steps, including separating signals from different color channels in an electropherogram (EPG), sizing DNA fragments, designating allele calls, and removing artifacts. Traditionally, this is a semi-automatic process relying on software using built-in algorithms and validated thresholds, but still requires manual confirmation by an analyst.

3.2 Challenges in Complex DNA Data Interpretation

While robust, forensic DNA analysis faces growing challenges, especially due to continuous technological advancements that generate complex genetic data. These challenges include:

1. **Data Volume:** High-throughput genomic technologies, such as Massively Parallel Sequencing (MPS), produce vast amounts of complex genetic data that demand extensive processing and annotation.

2. **Mixtures and Low-Template Samples:** Analyzing DNA mixtures (samples from multiple contributors) and low-template DNA (small amounts of genetic material) is challenging due to the difficulty in distinguishing minor contributors from artifacts and background noise, which complicates accurate allele calling.
3. **Human Subjectivity and Errors:** Human analysts, despite their expertise, are prone to errors when analyzing or interpreting data. The need to minimize human subjectivity and improve the reliability of evidence analysis is paramount in forensic science.
AI methods, particularly Machine Learning, are highly suited to address these complexities by leveraging their capacity to intelligently analyze large and often unstructured datasets.

4. Machine Learning Applications in Forensic DNA Analysis

Machine Learning applications in forensic DNA analysis are primarily divided into those related to **Human Identification (HID)** and those related to **forensic intelligence**.

4.1 STR Allele Designation and Artifact Filtering (CE and MPS Data)

ML algorithms are used to streamline the core process of genotyping by improving the efficiency and accuracy of STR allele designation from both Capillary Electrophoresis (CE) and MPS data.
The complexity of distinguishing true allelic peaks from background noise and artifacts is a foundational problem that ML models can tackle. ML-based bioinformatic pipelines, sometimes coupled with unique molecular identifiers (UMIs), can significantly enhance allele calling accuracy, especially in low-template DNA mixtures, by filtering out noise products and improving overall performance. Machine learning methods can also identify and remove capillary electrophoresis artifacts resulting from spectral overlap.

4.2 DNA Mixture Interpretation and Contributor Estimation

Interpreting DNA mixtures—samples containing DNA from multiple individuals—is a particularly difficult task in forensic science. AI techniques are being developed to assist with mixture interpretation, specifically in estimating the Number of Contributors (NoC) to a DNA mixture.
Studies have shown that ML-based systems can automatically assess artifacts and predict the NoC in DNA mixtures, such as the PACE system. ML algorithms, including decision trees, have been evaluated for estimating the NoC in autosomal STR profiles, demonstrating their applicability and potential for efficiency gains.

4.3 Probabilistic Genotyping Assisted by AI

Probabilistic genotyping (PG) software is commonly used to analyze complex DNA evidence, particularly mixtures, by calculating the likelihood of a person's DNA being present in the sample. When addressing forensic evidence like DNA, which carries inherent margins of error, AI can assist in assessing this evidence. With the help of AI, **probabilistic genotyping** can be performed to assess whether a suspect's DNA is genuinely present in the mixed traces found at a crime scene. This highlights how AI contributes to evidence assessment by handling the inherent variability and uncertainty in forensic data.

5. AI for Forensic Intelligence and Investigative Leads

Beyond simply matching profiles for human identification, ML techniques are instrumental in generating investigative leads through forensic intelligence and inference, a field focused on prediction and reconstruction from genetic material. These applications move into predictive analysis, inferring characteristics of the source individual who left the DNA.

5.1 Prediction of Externally Visible Characteristics (EVCs) and Biogeographical Ancestry (BGA)

ML methods, such as regression analysis using techniques like linear regression, decision trees, or neural networks, can be utilized in **forensic DNA phenotyping**. This application uses a DNA sample to predict EVCs, such as iris, skin, and hair pigmentation, based on large datasets correlating phenotypes with corresponding genotypes. This process is key for molecular phenotyping and biogeographical ancestry (BGA) inference, helping to determine the origin and physical traits of the DNA donor.

5.2 Generative Models for Facial Reconstruction from DNA

One of the most intriguing and challenging applications is the prediction of an individual's facial appearance from a DNA sample. This task is exceptionally difficult due to the complex relationship between genetic, epigenetic factors, and craniofacial morphology.
Generative Machine Learning models, specifically deep neural networks, offer a promising solution by iteratively refining the generated output to predict complex variables like facial traits. The potential applications of this generative technology are significant for criminal investigations: it could be used to **create composite images of suspects based on DNA evidence** found at crime scenes, or to reconstruct the facial appearance of a person from partial skeletal remains, thereby assisting the identification process. While still in early stages, generative AI highlights the potential of deep learning to provide valuable predictive insights from genetic data.

6. Legal, Ethical, and Judicial Implications

The increasing deployment of AI in forensic science, particularly in complex domains like DNA analysis, generates profound legal and ethical challenges related to data usage, transparency, and due process.

6.1 The Black Box Challenge: Transparency and Trustworthiness

A primary legal and technical concern related to ML algorithms is the "black box" issue. This refers to the lack of transparency where the software user—including judges and juries—sees only the output (e.g., a prediction of the Number of Contributors or a facial composite) without clear reasoning behind that conclusion. This lack of transparency can undermine the validity and acceptability of AI-produced results, especially when forensic evidence is used to support court decisions.

To mitigate this, **Explainable AI (XAI)** is a critical area of research that aims to develop AI algorithms that are transparent and interpretable, allowing human experts to understand the underlying reasoning and maintain confidence in the results. Techniques proposed for XAI, such as decision trees, rule-based models, and Bayesian networks, allow for transparent and interpretable models, thus enabling human experts to validate the decision-making process.

6.2 Admissibility and Reliability in Court

The reliability of biometric evidence, including DNA, has received extensive attention in the courts for decades. Legal precedent on the use of biometrics is growing, and key cases have raised serious questions about the admissibility of biometric evidence.

In legal settings, the admissibility of expert opinion is often evaluated based on specific standards, such as the *Frye* standard (general acceptance by the scientific community) or the *Daubert* approach (balancing factors like testing, peer review, error rate, and general acceptance). While DNA evidence is generally admitted, the introduction of AI-derived conclusions introduces new scrutiny. If AI systems are provided with inaccurate predictions, individuals or groups may be labeled or targeted for the wrong reasons. The reliability of the entire AI system—including the data used, the instrument chosen for analysis, and the interpretation of the results—must be scrutinized.

The opacity of complex AI, especially when used in generating evidence, may make it difficult for suspects to properly defend themselves. This difficulty relates to procedural justice, where the defendant may find the technological expertise hard to challenge, and the focus may shift from legal narratives to technological numbers. Questions about the extent to which an Artificial Neural Network (ANN) can replace human judgment are crucial ethical and legal considerations.

6.3 Fundamental Rights and Due Process Concerns

The utilization of AI in criminal procedure necessitates careful negotiation regarding fundamental citizens' rights. AI's capability to analyze enormous data sets and produce profiles raises significant concerns regarding prejudice, discrimination, and the right to a fair trial.

1. **Privacy and Data Usage:** Biometric systems, including DNA databases, bring important legal issues concerning privacy. The collection and processing of data, particularly in risk assessments or profiling applications like EVC prediction, raises proportionality questions and the need to protect individual interests.

2. **Due Process and Accountability:** If criminal procedure decisions increasingly rely on opaque AI results, suspects might not know the basis of their accusation (analogous to Kafka's novel *The Trial*). Legal research is needed to determine the scope of police powers in this new context and how to properly balance investigative competences with fundamental rights.

7. Conclusion and Future Research Directions

Artificial Intelligence and Machine Learning are profoundly transforming forensic science, especially in the interpretation and reconstruction of DNA evidence. AI provides advantages over conventional systems by offering flexibility and learning capabilities necessary to manage high-volume, complex, and unstructured genetic data. Key applications include: enhanced efficiency in STR allele designation, improved accuracy in DNA mixture interpretation, and the pioneering field of forensic intelligence through the prediction of physical characteristics and facial morphology from DNA.

However, the power of AI brings commensurate challenges. The primary hurdle for the legal acceptance and reliability of AI in DNA forensics is the "black box" phenomenon. Future research must heavily focus on developing and implementing **Explainable AI (XAI)** techniques to ensure transparency and interpretability of forensic conclusions drawn from AI/ML models. This is vital for judicial acceptance and for ensuring that the use of AI in evidence assessment does not erode the foundational principles of due process and fairness.

Further research is also needed concerning the ethical and legal questions arising from the autonomy of these systems, particularly defining the legal precedent applicable to machines and the extent to which technology should take human roles in the judicial process. The goal remains the deployment of trustworthy AI that enhances the reliability and speed of forensic investigations while fully preserving legal scrutiny and fundamental rights.

In essence, integrating AI with DNA analysis is like **introducing a super-telescope to microscopy**. Just as a telescope allows us to analyze distant, massive cosmic structures invisible to the naked eye, AI allows forensic analysts to process vast, complex genetic datasets and discern intricate patterns in mixtures or predict physical features—tasks impossible for human analysts alone. However, this powerful new tool demands rigorous calibration (XAI) and clear rules (legal frameworks) so that the scientific results derived remain grounded, verifiable, and trustworthy within the confines of the courtroom.