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Review Paper

Forensic Science in the 21st Century: Innovations, Challenges, and Future Perspectives

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Abstract

The 21st century is characterized by a rapid, transformative evolution in forensic science driven by technology, biology, digital sciences, and cross-field collaboration. This review analyses technological modernizations in forensic practices, specifically in DNA profiling, digital forensics, AI, forensic toxicology, and 3D imaging. Further, it discusses important hindrances to the integration of these technologies, including ethical issues, data privacy, legal admissibility, and the lack of universal compliance frameworks. The document also discusses AI-empowered forensic decision-making, microbiome forensics, and virtual autopsies, underscoring innovations that sharpen criminal investigation precision, efficiency, reliability, and trustworthiness. The review aims to highlight the need for policy changes and interdisciplinary cooperation by exposing the forensic science digitization opportunities and challenges.

Keywords: Forensic Science, Innovations, 3D Imaging, Digital Forensics and DNA Profiling

1. Introduction

The field of forensic science, which combines aspects of law and science, is undergoing a major change in the twenty-first century and undergoing revolutionary changes all across the globe. The changes are being brought about by new technologies, cooperation between different scientific disciplines, and changes in the methods of collecting, analysing and interpreting evidence in investigative processes. Remarkable developments in the fields of DNA and digital forensics, artificial intelligence, forensics toxicology, and 3D imaging are driving such change (Ahluwalia & Sharma, 2023) (Rana, 2018). At the same time, new legal, social and technical challenges are emerging which, in turn, demand that forensic scientists, legal experts and policymakers adapt the old standards and practices (Jonnalagadda et al., 2024).

The introduction and development of forensic genetic DNA profiling is considered one of the most powerful changes in the forensic science of the twenty-first century. The use of short tandem repeat (STR) analysis has been the gold standard for individual identification. New technologies, such as massively parallel sequencing and forensic DNA

phenotyping are capable of analysing degraded samples, estimating biological characteristics of individuals and generating investigation leads are changing the scope of DNA evidence (Haddrill 2021); (Alketbi, 2023); (Romeika & Yan, 2014). These technological leaps allow forensic experts to reconstruct identities and events with unprecedented accuracy, even from minimal biological material.

The application of forensic science as a branch of science that interfaces with legal disciplines is undergoing an unprecedented change in the 21st century. Collaboration across disciplines, as well as new technology, is changing the methods used to collect, analyse, and interpret evidence in criminal investigations. There is an advancement in DNA profiling, digital and AI forensics, forensic toxicology, and 3D imaging (Ahluwalia & Sharma, 2023; Rana, 2018). Additionally, there is a need to redefine age-old policies and methods due to emerging new ethical, legal, and technical concerns which is intensifying the work of forensic scientists, legal practitioners, and policymakers (Jonnalagadda et al., 2024).

The transformation of DNA profiling stands out as one of the most significant breakthroughs in modern forensic science. For a considerable period, the identification of individuals through short tandem repeat (STR) analysis has been a benchmark. Advances in forensic DNA phenotype analysis, genetic genealogy, and even massively parallel sequencing are enabling investigators to work on more degraded samples (Haddrill, 2021; Alketbi, 2023; Romeika & Yan, 2014). Such pronounced advancements allow forensic scientists to reconstruct identities and associated events with remarkable precision, even from scant biological samples.

Alongside advancements in biology, the forensics field has grown in importance with the digitalization of human activities. Due to the adoption of smartphones, cloud services, and social media, the amount of available digital evidence has reached unprecedented levels (Fraser, 2020). Forensic work today involves recovery of data, analysis of the metadata, and interpreting communications, which requires a combination of legal, technical, and meticulous procedural compliance (Fatima, 2020). The use of AI technologies in this field facilitates the identification of crucial information in large datasets, the identification of outliers, and even anticipates criminal acts through the application of sophisticated pattern recognition and machine learning algorithms (Ashwini & Dineja, 2025).

AI's use is not confined to digital forensics. In the wider field of forensic science, it's being used for facial recognition, postmortem examinations, and even anticipatory analytics. As discussed by (White et al., 2011), these systems have the ability to make and identify extremely fine-grained decisions and patterns that surpass humans, surpassing in precision. At the same time, the use of AI brings up major ethical issues pertaining to bias, AI Ethics, and Accountability. In the case of (Alketbi,2023), one of the issues is the use of 'black box' technologies which are opaque in nature and AI systems that are opaque in nature give cause for concern in the law-and-order sphere where transparency and reproducibility of evidence is the golden standard.

The detection and quantification of minute amounts of drugs and poison in biological samples has tremendously improved in forensic toxicology. Improved understanding of drug metabolism and tolerance is being achieved through advanced techniques in mass spectrometry, chromatography, and pharmacogenomics (Ahluwalia & Sharma, 2023). This is beneficial for postmortem examinations and for live analyses in suspected cases of poisoning (Morelato et al., 2013). Modern forensic science has also been transformed by the 3D Imaging Spatial technology. 3D facial reconstruction, virtual autopsies, and crime scene digitization enable the analysis and reconstruction of events in a non-invasive manner (Rana, 2018). These technologies are very useful in cases where traditional autopsies are restricted due to cultural or legal reasons. This improves the dialogue between the forensic community, law enforcement, and jury by conveying information in a more visually understandable way (Lacasella & Cirulli, 2025).

Regardless of these developments, numerous issues remain unresolved. Global standardization in forensic practices is one of the most critical gaps. The existence of varying approaches, accreditation, and quality control in different jurisdictions hampers the forensic evidence's reliability and acceptability (Jonnalagadda et al., 2024). Moreover, privacy, data security, and consent issues especially concerning genetic information are of greater importance in a world where people's data can be easily accessed and shared (Amankwaa et al., 2019).

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Looking ahead, forensic science convergence with other biological and computational disciplines can pave new pathways. An instance is microbiome forensics, a field that examines the distinct bacterial residues that people may leave behind which may later aid in their identification and estimation of the time since death (Rana, 2018). AI and imaging technologies enable virtual autopsies, which can be performed remotely, non-invasively, and drastically faster, making them ideal for resource-limited or high-throughput environments. In addition, forensic scientists can expect faster and more objective evidence review and interpretation through the deployment of AI-powered forensic software and evidence processing algorithms alongside expert decision-making frameworks (Ashwini & Dineja, 2025).

Forensic science is undergoing a paradigm shift propelled by scientific innovation and digital transformation. While these advances promise to increase the reliability, speed, and scope of forensic investigations, they must be integrated thoughtfully, balancing scientific rigor with ethical and legal safeguards. The path forward will require robust research, standardized policies, and interdisciplinary collaboration to fully realize the potential of modern forensic science in an increasingly complex and digitized world.

2. Methodology

The 21st century brought one of the swiftest changes in forensic science, now requiring a complete shift in methodology. Forensic science used to be practiced in a forensic laboratory, but now a forensic scientist must employ a multidisciplinary approach that includes biology, chemistry, physics, computer science, law, and many more fields. This part describes the salient features of modern forensic methodology, in which to focus on evidence acquisition, laboratory work, and cooperation with other specialists to derived accurate and court-admissible findings.

1. Evidence Collection and Preservation

The investigative procedure starts with the crime scene, which is the main source of physical and electronic evidences. The forensic evidence and materials gathered and analysed during this stage determine the forensic conclusions. The Forensic methodologies include payment of the crime scene, DNA swabbing, fingerprint sampling, collection of conveniently visible traces, digital evidence collection through write blocker devices, and 3D scanning for crime scene recreation (Vodanović and Brkić, 2012 and Rana 2018).

2. Laboratory Analysis

Evidence is tested undergoing a specific process in a particular laboratory.

a. DNA Profiling: STR analysis and Next Generation Sequencing Techniques (NGS) are useful in resolving complicated mixed and degraded samples. DNA phenotyping and probabilistic genotyping software give more advanced means to interpretation (Haddrill, 2021; Alketbi, 2023).

b. Digital Forensics: Digital data is collected from smartphones and networks through specialized software capable of recovering deleted data and metadata (Ashwini & Dineja, 2025). Now, AI assists in behaviour and pattern recognition, increasing reliability and speed in analysis (Bokolo et al., 2023; Goyal et al., 2020).

c. Forensic Toxicology: Biological samples containing drugs and toxins are analysed using specialized techniques such as GC-MS and LC-MS/MS (Ahluwalia & Sharma, 2023; Rana, 2018). These techniques are important in cases of overdose and poisoning.

3. Interdisciplinary Collaboration

Every forensic team consists of a pathologist, a digital forensic analyst, and a legal professional to ensure every piece of evidence is analysed in context (Jonnalagadda et al., 2024). Interdisciplinary collaboration is also important in cases with multiple jurisdictions (Bhadra & Nair, 2021; Gadelrab & Ghorbani, 2020).

3. Applications of Modern Forensic Science

1. Criminal Justice

With the advent of new technologies DNA profiling is transforming the criminal investigation processes. The applications of NGS and forensic genealogy technologies not only solve cold cases but also exonerate the wrongly convicted individuals (Alketbi, 2023; Haddrill, 2021). (Ash & Dineja, 2025) and (Silde & Angelopoulou,2014) demonstrates the importance of digital forensics in retrieving communication histories and using AI to connect suspects to crimes.

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2. Disaster Victim Identification (DVI)

In the case of large-scale disasters, forensic science plays a pivotal role in the identification of the remains by using dental records and 3D imaging as well as mitochondrial DNA (Jonnalagadda et al., 2024; Vodanović & Brkić, 2012).

3. Cybercrime and Digital Evidence

The use of AI technology as well as metadata is proven useful in the investigation of online fraud, ransomware attacks and stalking (Fatima 2020; Yu, 2021; Warikoo 2014). The methodologies of cyber profiling are indispensable for the extraction and analysis of behavioural information from the digital traces and the data left behind (Spicer, 2019; Marrington, 2009).

4. Medical-Legal Investigations

CT and MRI scans are making post mortem procedures more efficient by allowing for virtual autopsies and other non-invasive techniques (Rana, 2018). The field of forensic toxicology is being strengthened by the field of pharmacogenomics, allowing for more thorough investigation in forensic pathology (Ahluwalia & Sharma, 2023; Chen, 2022). The innovative procedures are changing forensic pathology by making it objective and more comprehensive.

Additionally, forensic toxicology is used to detect poisons, overdoses, or drug interactions. Toxicological screenings are crucial in cases of suspicious deaths, workplace accidents, and allegations of medical malpractice. The integration of pharmacogenomics now allows forensic scientists to understand individual variations in drug metabolism, offering deeper insight into cause of death or impairment (Rana, 2018). Together, these innovations enhance the forensic pathologist's ability to produce objective, detailed findings that support justice.

4. Challenges and Limitations

While forensic science has advanced remarkably in the 21st century, it continues to face several persistent challenges and limitations. These range from technical and legal issues to ethical dilemmas and institutional shortcomings. Understanding these constraints is essential for ensuring that the application of forensic technologies remains reliable, equitable, and scientifically grounded.

1. Legal Admissibility And Standardization

Forensic science faces one of its greatest challenges in report variability of different standards from one jurisdiction to the other. Even with the advent of more sophisticated forensic techniques, the lack of consistency in accreditation, the forensic method's validation protocols, and its calling into question the admissibility of the evidence in court. A good example is the new emerging technology of probabilistic genotyping and forensic phenotyping which, in legal terms, do not have sufficient frameworks and these types of evaluative technologies are usually viewed either by the court or the jury owing to their lack of understanding of their science.

Failure to have accepted systems of forensic standards with the lack of systems for quality assurance as well as lack of forensic guideline criteria further complicates the forensic standardization issue. As pointed out by Jonnalagadda et al. (2024), the lack of forensic education and institutional infrastructure leads to over uneven capabilities of forensics in a given region especially in the developing parts of the globe, (Jonnalagadda et al. 2024).

2. Ethical Concerns and Privacy Issues

The use of DNA databases and facial recognition and AI-based surveillance systems have profoundly impacted data privacy, consent, and misuse. For example, forensic genetic genealogy has solved cold cases, but its use of public genealogy databases poses ethical dilemmas about the indirect involvement of individuals through the genetic data of their relatives.

In addition, AI-based profiling and risk assessment tools, if trained with biased data, may perpetuate discrimination through already existing prejudices. Alketbi (2023) reinforces the notion of having transparent policies and ethical principles regarding the collection, storage, sharing, and use of genetic and biometric data (Alketbi, 2023).

3. Issues With Technology Constraints and Bias in Interpretation

There are still problems with advanced technology tools. The accessibility and quality of forensic DNA evidence are still challenging in the areas of decomposition, contamination, and complex mixture interpretation. The application of probabilistic genotyping software in mixture analysis has brought some advances, but the results are not

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algorithm independent, and in some cases, they need an expert's interpretation.

Moreover, forensic studies in areas like bite mark analysis, handwriting analysis, and forensic anthropology are subjective in nature and may be influenced by human interpretation. These techniques could be proven with scientific but flawed due to absence of replication and statistical validation methods.

4. Resource Limitations and Case Backlogs

Forensic laboratories globally deal with understaffing and a growing backlog of cases. These bottlenecks are particularly pronounced in countries with under-resourced criminal justice systems as they impede both investigations and court processes. According to Ahluwalia and Sharma (2023), forensic labs are inadequate in terms of resources and are often overburdened, resulting in sub-optimal evidence analyses (Ahluwalia & Sharma, 2023).

The gap in forensics services in high income and low income countries is further worsened by the soaring prices of next generation tools such as virtual autopsy systems and AI platforms, and whole genome sequencing.

5. Training and Gaps in Specialization

With the evolution of new tools and techniques in forensic investigations, there is an increased need for continual education and training for forensic practitioners, legal professionals, and employees in law enforcement agencies. Unfortunately, training gaps exist. Insufficient training might lead to a lack of competence in interpreting intricate exhibits, or employing software tools in investigations or court proceedings (Jonnalagadda et al., 2024).

In addition, legal practitioners might find it difficult to comprehend the probabilistic evidential output or AI tools, which impacts the weight of such evidence during the litigation process.

5. Future Aspects of Forensic Science

The progress of forensic science is influenced by new technological developments, the integration of computing technologies, and the rise of transnational crime. New technologies and tools have the potential to enhance the speed, accuracy, and neutrality of forensic investigations and therefore, require the attention of ethicists and policymakers. These technologies and tools are bound to change forensic science fundamentally in the coming decades.

1.The Impact of Automation and AI Technology

The branching AI subsets technology, especially machine learning, are poised to change how forensic investigations are conducted in the future. AI can be trained to:

• Conduct predictive profiling through the application of biometrics and behavioural indicators.

• Achieve automated reconstructions of the crime scene through computer vision and 3D mapping.

• Real-time analysis of video streams enhances surveillance, facial recognition, and tracking of known associates

The integration of AI into these systems offers numerous advantages, especially in reducing human error and bias, which is common in subjective forensic fields like fingerprint comparison, gait analysis, and handwriting recognition. As an illustration, the comparison of data points done by automated algorithms helps in the comparison of thousands of data points in less than a minute which is far more precise than humans. Also, AI pattern recognition has successfully automated the process of linking digital evidence such as internet histories and communication metadata to certain actions of an individual in the system (Ashwini and Dineja, 2025). But as the systems advance, they must also include an evolving design bias that focuses on transparency and system explainability particularly in legal settings that require proof, public trust, and shreds of evidence to validate the claims made.

2. Microbiome Forensics

The human body is home to trillions of microorganisms which vary between individuals, body sites, and environments, and are known as the microbiome. Microbiome Forensics is a new branch of forensics that looks into how the patterns of microbes can:

• Help with identifying a person.

• Accurately estimate post-mortem interval (PMI) in comparison to traditional decomposition markers.

• Estimate where or in what environment a victim or suspect may be based on the transfer of microbes.

To illustrate, communities of microbes found within the skin or the gut are eliminated in a predictable manner post-

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mortem, creating new biological clocks for the estimation of time-of-death. Also, microbes found in soil may be transferred within the context of a crime which could indicate the geographic location of a sample. This is what makes microbiome analysis so powerful in human and environmental forensic investigations (Rana, 2018). With time, this field has the potential to change the way we solve complicated cases that lack or have very few biological markers to work with.

3.Virtual and Augmented Reality in Forensics

VR and AR technologies are now being adopted for both research and teaching purposes in forensic science. Possible future developments include:

• Fully immersive 3D environments for the examination of evidence in crime scene reconstructions.

• Training simulations for forensic and law enforcement personnel.

• Demonstrations in court for judges and juries depicting the spatial and temporal aspects of crime in 3D.

VR technologies offer reconstruction tools that maintain spatial, geometric, and contextual relationships in the crime scene. This is particularly important in intricate cases involving multiple victims or large-scale damages. Such reconstructions can aid jury comprehension, enhance transparency, and bolster expert testimony. With decreasing cost and improved availability, AR and VR technologies are anticipated to become standard tools in forensic pedagogy and litigation strategies.

4.Worldwide Harmonization and Development of Regulation

With the evolution of crimes like human trafficking, cybercrime, and terrorism into more transnational forms, the international collusion and integration of forensics systems is necessary. The existing gaps, in terms of the level of assurance and accreditation, databases, and varying forensic capabilities among countries, differ quite dramatically

Advancements in the future will rely on efforts directed toward:

• Standardizing procedures for evidence collection, storage, and custody tracking.

• Creating unified databases for DNA, digital forensics, and biometrics.

• Creating an international certification and forensic laboratory audit system.

Entities like INTERPOL, UNODC, and ISO are pursuing framework sponsors working toward global standards. However, as Jonnalagadda et al. (2024) pointed out, developing countries are still lacking in forensic infrastructure and education, which poses a considerable challenge (Jonnalagadda et al., 2024).

The development of uniform frameworks will improve the reliability of investigation results and facilitate the conduct of international investigations and legal collaboration.

5.Ethical and Legal Frameworks

Forensic tools that require increasingly more data, and those that become more automated and invasive, will necessitate the development of robust ethical and legal frameworks to protect the individual, and foster social trust. Following are key issues of concern:

• Privacy of data, and safe storage of biometric and genetic information.

• Privacy and consent of public and familial DNA for identification purposes.

• Responsibility of AI for profiling and forensic tools.

• Socioeconomic and geographic equity in the availability of forensic service.

Consider the example of forensic genetic genealogy. While powerful, it poses issues of informed consent and the potential criminal ramifications for innocent relatives whose DNA is housed in public ancestry databases. The equally concerning opaque AI tools poses the problem of scrutiny in legal processes, resulting in the risk of unreviewable or biased adjudicatory processes.

As emphasized by Alketbi (2023) concerning forensic practices, there is a need to have balancing legislation, ethical scrutiny, and public participation alongside technological advancements that informs us about.

6. Conclusion

Innovative collaborations and new technologies like molecular biology, digital technologies, artificial

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intelligence, and interdisciplinary collaboration have revolutionized forensic science. Advancements like digital forensics, virtual autopsies, DNA profiling, and microbiome-based identification have broadened, enhanced, and increased the precision and efficiency of forensic investigations. However ethical issues, privacy matters, inconsistent global standards, lack of privacy frameworks, and algorithmic biases pose enforceable challenges. Region based resource disparities, the absence of broadly accepted protocols add on obstacles toward reliable forensic science. Forensic practices are accessible, and uncompromised is still up for debate worldwide. The future of crime scene analysis and interpretation shall be dramatically reshaped by AI, microbiome forensics, and virtual reality. However, global standardization, robust frameworks and ongoing ethical supervision is required to these technologies. Innovations must be met with enforced policies to meet the justification of science and serve the world with transparency and balance.

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