

APPLYING FORENSIC TECHNOLOGY FOR CRIMES INVESTIGATIONS IN COLD CASES

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ABSTRACT

Advanced forensic technologies act as a key piece in solving cold cases. These are crimes that go unsolved usually because there is no one to hold accountable, the memories of close witnesses fade or the old means of gathering information do not meet today's standards. Recent advances in technology, particularly those related to DNA kitting, genotyping, digital forensics and AI analysis have transformed law enforcement's capacity to revisit and finally solve these cases that were once believed unsolvable. Problems faced in cold cases such as evidence deterioration or lack of preservation, and the difficulty involved in reopening old investigations. The article highlights the game-changing effects of contemporary techniques such as next-generation DNA sequencing, re-evaluations in forensic pathology, and the use of AI to assist with collating large data sets and improve accuracy—and speed—of investigations. It is expected that the future of cold case investigations will strongly depend on further innovations in AI, machine learning and bioinformatics to achieve a more sensitive and deeper analysis on small or decomposed samples. Concerns of ethical nature regarding genetic privacy and data safety are seen as necessary for responsible use of such a novel technology. Finally, it is contended that the assimilation of these multi-disciplinary forensic developments is certain to have a major impact on solve rates while providing long overdue justice to victims and their families, all within the context of moving forensic investigations from reactive strategies to proactive tactics in solving enduring criminal mysteries.

Keywords: Cold cases, DNA Genealogy, DNA Profiling, Digital Forensics.

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INTRODUCTION

Cold cases, often characterized by prolonged periods of inactivity due to lack of definitive leads, pose several challenges to law enforcement and justice approaches. Among the primary struggles faced by those attempting to solve cold cases is the rapid decay of evidence, fading memories of witnesses, and a lack of forensic techniques or actionable evidence at the time of the occurrence [1]. Nonetheless, recent advancements in technology and forensic science have encouraged inquiries and invigorated investigations in the numerous cold cases, providing new knowledge and understanding that was not previously available [2]. This work discusses the technological breakthroughs that have revolutionized cold case investigations, including the methodologies of DNA profiling, digital forensics, and AI-based approaches. In doing so, the paper shall also explore the role of forensics experts and the eventual direction of these technologies [3].

Collectively, these technologies provide tremendous advantages for the rendering of evidence, experiential forensic analysis, and response to questions and fears [3]. The advancement of the application is evident through artificial intelligence and large, complex patterns by massive parallel artworks that will further revolutionize the work of the Forensic scientists. The evolution of human identification has long passed from the late development of ISCF, loci discovered in microbiology and other techniques and strategies that have been used to identify human DNA and other methods, technologies such as massive parallel work that has made it easier to resolve the cases by correcting the cold cases. Additionally, in the United States, it is estimated that over 250,000 murders remain unsolved [4]. This provides the backbone of the hypothesis. This shows that cold cases can solve decades later, and this is why it is vital to prioritize

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developments in forensic science methodologies that will help achieve solving. The integration of dense single-nucleotide polymorphism testing and the use of STR has shed great light on the way forensic scientists work [5].

Understanding Cold Cases

Nevertheless, even with those technological leaps, many cases still remain unresolved due to the complexity of the issues and obstacles facing the investigators. The issues often stem from poor quality of evidence, the breaking of the chain of custody, and non-existent forensic procedures and tests at the respective time of the criminal activity, which make it problematic to reconsider the cases years or even decades after [6]. According to Allison, cold cases are those criminal cases that have remained unsolved for a long periods of time which could even be for years or decades after every bit of evidence at the particular time of the occurrence has been unearthed. The cases are known as cold given that there are no discoveries or leads that could be uncovered at the particular time, hence no active investigations could be successful in the absence of a new evidence or new forensic technology discoveries or invention [7]. On the other hand, given the nature on absence of immediate and critical discovery on the aspect of such cases, it calls for a re-evaluation in order to discover new leads using the latest discovery in forensic science which could not have been available at the time of the first discovery. This dormancy makes cold cases different from active ones which would otherwise be actively investigated with all available evidence unearthed [8]. Several factors explain why cases go cold, and cold environments such as icy conditions preserve DNA well. However, warmer environments characterized by humidity and other factors such as temperature and microbiological conditions degrade DNA extensively, thus limiting the investigation powers surrounding a cold case. The challenges in understanding cold cases call for multi-pronged methods, including evidence re-examination, as already demonstrated [9].

Reasons for Cases Remaining Unsolved

Several critical factors contribute to the protracted nature of cold cases. These include the limited nature of forensic technology at the time of the initial offenses, which often complicated the identification and preservation of valuable trace evidence, as well as the inherent difficulty in maintaining evidence integrity over time [10]. Paradoxically, the value of evidence wanes as trends, decay, and people die or forget. Moreover, a “cold case” per se medicine does not have a firm universal definition, and as a result, their categorization and prioritization may vary drastically from location to location. It includes varied conditions in which open offenses enter this category, lack of validated guidelines for inter-agency cooperation, and the courage of a large number of open murders that regularly stretch back

for years [11]. For example, 34% of murders in the U.S. were unsolved from 1965 to 2020, while 33% of British and Welsh individuals were unable to identify a suspect in arrests between April 2018 and March 2019. While statistics provide quantifiable proof of the societal burden of the enduring nature of hot cases, unreported bodies are more often sought long and undertakes than murders. This victim is amazed by the vicious implications of extrusion toward the stricken family member and the region for everyone included [12], [13]. As a result, the tactical target of advanced technology is essential to overcoming the challenges tied to liberating research. Reconnecting technology-based methods of analysis together with the surveillance of children’s viability provides a turbid focus on what was previously a shit object. This likelihood is crucial for reviving the justice organizations [14].

There are a number of important reasons why cold cases take so long to solve. For example, forensic technology was not very advanced at first, so it was often impossible to find and keep important trace evidence. Also, it is hard to keep evidence safe for long periods of time. This loss of evidentiary value is often made worse by witnesses' memories fading, key people not being available, or even the death of people who were involved [15]. The lack of a clear, universal definition for a "cold case" makes it even harder to sort and rank these investigations, since different jurisdictions may have different rules for deciding what counts as one. This lack of clarity can make it harder for agencies to work together and come up with standard procedures for reopening investigations that have stalled [16]. For instance, reports say that 34% of murders in the US between 1965 and 2020 are still unsolved, and 33% of murders in England and Wales between April 2018 and March 2019 did not have any suspects charged. These numbers show how deeply unsolved crimes affect society, as they can cause trauma to continue and make people lose faith in the justice system. Long-term missing person investigations and underreported violent crimes, such as sexual assault, also add to the total number of cold cases, making them harder to solve [17]. In addition to these statistical facts, the psychological effects on the families and communities of victims often last for decades, making it even more important to go back and solve these cases that seem impossible to solve. Consequently, the strategic implementation of advanced forensic technologies and methodologies is essential to surmount these persistent investigative challenges. This renewed investigative focus, coupled with enhanced technological capabilities, offers a crucial pathway toward achieving justice for victims and their families [18].

Challenges in Cold Case Investigations

In spite of the progression of forensic technologies, cold cases encounter an exceptional set of

insurmountable issues that distinguish them from ongoing inquiries. The primary obstacle is the measure of time that has transpired since the wrongdoing was committed and the negative effect it produced on forensic evidence and people's recall [3]. As a result, several of this evidence has deteriorated or been destroyed, and witness recall has died. In addition, certain people may be inaccessible or extra challenging to locate. These factors make it exceedingly difficult to obtain a clear, accurate, and dependable image of the past. Finally, even the most up-to-date modules of forensic science face minimal success when many law enforcement agencies are involved. Specifically, collaboration is disrupted when authorities from different territories are present [19, 20].

Degradation and Loss of Evidence

Long-term storage of forensic samples results in extensive degradation of biological materials, complicating and, at times, eliminating the potential of DNA extraction and profiling. It is worsened even more by the poor storage conditions, including exposure to light, heat, or moisture that accelerate the decay of the organic compounds necessary for forensic analysis [21, 22]. Besides, even if evidence is available, the integrity of its chain of custody is often questionable, raising issues regarding its admissibility in court and, therefore, explanatory relevance to the cold gap cases. DNA is a sufficiently delicate compound that can be erased even from single traces under the high impact of temperature, microbial factors, and moisture increasingly complicated in ancient samples. Forensic science is equally even more converging currently, meaning that the evidence collected in the yesteryears has undergone less preservation and human analytical rigors to meet the recent protocols [23]. For example, several governments and agencies have no standardized international storage and custody protocols in many cases. It leaves a vast space in enhancing the revaluation of the evidence and impact-based global reference criteria for the forensic staff [24].

Fading Witness Memory and Availability

As time passes, the precision and specificity of witness recollections deteriorate as the horrific specifics witnessed during the traumatic event no longer come to light from the horrifying overall. This feature has been attributed to natural memory degradation and interference but is exacerbated by the apparent unavailability of the original incident's several witnesses. Well-intentioned witnesses, for example, may have passed away, shut down mentally to avoid the memories, or even relocated, making re-interviewing for hidden corroboration difficult [25]. Additionally, human memory literally degrades over time, reducing its quality and availability and necessitating an increase in the use of more objective forensic evidence to fill the

perceived gaps. However, direct recall can be replaced by more effective interview strategies more time-expire. For example, several approaches and theories have demonstrated how contextual clues can aid a type of interview called cognitive interviewing, encouraging participants to produce information they did not even realize they had easy access to. In light of these findings and others, it is clear that effective psychology will benefit long-term investigations into cold cases [27]. Additionally, witnesses may have their memories blocked by either psychological process or lingering negative emotions tied to their original experiences [28].

Limitations of Historical Forensic Technology

Several decades ago, forensic analysis was sorted to be the opposite of the careful and sensitive path it has now become. With the analysis of evidence, scientist had eliminated too many chances to identify a suspect months or years before and close the case eventually [29]. This thesis can be supported with the following evidence: the development and introduction of new technologies and analysis methods can be concluded that as science knows more about the evidence and clues they can get from the existing volumes of evidence [30]. For example, the use of DNA profiling was not very popular at that time, which is why even known criminal cases used to go cold and left with insufficient evidence or incorrectly collected samples. As a result, without a proper chain of custody and preservation evidence collected, many further analysis cases were not possible. Fingerprint examination was also not as sensitive as today, with its reliance on a database and rapidly searched algorithm not available back then. Besides, the improper preservation of evidence, including most biological and trace evidence, further damaged the credibility and possibility of re-concluding the investigations [31]. Modern forensic scientists recommend using new analytical tools or techniques to gain new evidence from the existing one. Starting with the determination that additional information could be obtained using the samples and evidence collected before, researchers obtain new datasets and apply new methods. For instance, the advent of massively parallel sequencing methods changed the way carbon-dated samples of tissues from a crime scene could be investigated and enhanced the process of obtaining genetic profiles from biological evidence on a crime in carbon-dated materials [32].

Forensic Technologies Applied to Cold Cases

Modern forensic technologies have revolutionized the sphere of cold case investigations, enabling investigators to solve crimes that were seen as unresolvable due to the limitation of earlier scientific means [33]. New forensic possibilities open up unprecedented opportunities for re-examining evidence, developing new leads, and eventually bringing criminals to justice, providing

long-overdue closure to the victims' families. More particularly, the evolution of DNA identification, digital forensic achievements, and advanced imaging have made it possible to generate information from the previously unobservable or disregarded sources of evidence, reigniting long-stalled investigations [34]. Nowadays, joint databases, advanced forensic methods, and technological advances help exhume neglected evidence and drive new investigations. The fundamental change in approach does not only imply utilization of advanced scientific means but also entails a comprehensive and multidisciplinary re-examination of available evidence [35]. Very often, the "case rethinking" implies that investigators go through a thorough reconsideration of all evidence and existing theories about the case identifying biases and institutional thinking traps that may have prostrated earlier efforts [36]. Digital possibilities and the advent of sophisticated computational methods also enable a reconstitution of crime scenes and identification of offenders with previously unseen precision. Within the range of novel forensic methods, the identification of genetic code and genetic genealogy has emerged as the most powerful means, as new methods that do not require a large amount of tissue can effectively identify criminal's years after their crime [33]. This implies that the law enforcement can draw comprehensive genetic portraits and match them to existing databases or genetically link to relatives of the suspects. New forensic technologies have made a big difference in how cold case investigations are done. They have helped police solve crimes that were thought to be impossible to solve because older scientific methods were not sufficient. This change in thinking means using advanced scientific methods and looking at old evidence from a new angle that includes more than one field of study. This process often requires a thorough "case rethinking," in which investigators carefully review all the evidence and theories they have, directly addressing any cognitive biases or organizational problems that may have slowed progress in the past [37]. The combination of advanced computational tools and knowledge from many fields now makes it possible to reconstruct crime scenes and find criminals with a level of accuracy that was unthinkable in the past [23]. DNA profiling and genetic genealogy have emerged as particularly transformative innovations, providing robust methodologies for identifying individuals from even minute or degraded biological samples. These methods make it easier to create complete genetic profiles, which can then be used to match them against existing criminal databases or to trace family trees to find possible suspects [30].

DNA Profiling and Genetic Genealogy

The incredible power of DNA analysis to accurately match individuals unimaginably has revolutionized forensic science, facilitating the discovery of

intricate cases with unparalleled precision for law enforcement officials. Advanced forensic DNA analysis over the past three decades has advanced discrimination power, speed, and sensitivity, enabling difficult samples to be resolved and summarized the growing aggravated significance of the technique in forensic science [38]. The revolution in forensic DNA analysis has made DNA profiling a critical tool that allows the science of linking suspects to crime scenes or victims through biological evidence. This role is expected to equip the science with the capacity to help solve vicious series of crimes, including genocide cases that happened decades ago since DNA is a stable double helical structure that includes genetics. It offers a durable and easily preserved hereditary code that underpins its mainstream forensic science usage [39].

Digital Forensics in Cold Case Analysis

In addition, other forensic DNA analysis techniques, such as Y-chromosome analysis for male-specific identification and single nucleotide polymorphism analysis for degraded samples in forensic biology, have expanded the application of DNA as evidence in complex cold cases [6]. Moreover, the ability to undertake massively parallel sequencing has facilitated the analysis of highly degraded samples or low copy numbers of DNA samples, making the method more sensitive and accurate, hence obtaining more genetic information from even the smallest piece of evidence [40]. Apart from traditional DNA profiling, integration with genetic genealogy has transformed cold case solving by creating a picture of unknown offenders through their relations. For example, this model helped identify the Golden State Killer. By comparing the thousands of single nucleotide polymorphisms with databases of people's genetic material, one could determine a lot of information from distant relatives and close relatives [6]. As portrayed in the Golden State Killer case, forensic genealogy identifies distant cousins after comparing single nucleotide polymorphisms and comparing distant relatives to hypothesize their family tree. This helps reconstruct ancestors in a criminal genealogy tree, giving them the ethnicity and approximate location where the suspect would likely be. However, data protection laws and discrimination should be put in place as this technology continues growing in forensic biology to ensure a balance between crime-solving and human rights [41]. In this context, DNA methylation analysis and forensic DNA phenotypes will have a much greater discriminatory potential, capable of estimating the age of the sample and predicting some of the physical characteristics of a person [42].

Advanced DNA Databases and Linkages

DNA analysis capacities in assisting to resolve cold cases largely depend on the availability of sophisticated DNA databases, including comprehensive genetic profiles' repositories. The

latter allow law enforcement to compare DNA evidence collected from crime scenes to genetic profiles of known offenders or arrestees, generating new leads and direct matches that can remain undiscovered using regular investigative tools [42]. The US Combined DNA Index System cross-references DNA evidence retrieved from cold cases to convicted offender's profiles, considerably boosting chances of finding offenders years or even decades in the future. Moreover, international cooperation and the development of shared DNA database regulations, such as those coordinated by INTERPOL, expand the potential for cold hits internationally [43]. Such cooperation allows for comparing DNA evidence used in cold cases over-border, granting the opportunity to trace suspects that were previously identified committing cold offenses in other jurisdictions. Supported by continuous DNA databases' expansion and newly developed search algorithms, cold hits become more probable, transforming cases once characterized by inactivity and hopelessness into actionable intelligence sources [44].

Forensic Pathology and Re-Examination Techniques

The re-examination of forensic pathology evidence, including but not limited to modern imaging and analytical methods, is essential to gaining an accurate understanding of the cause and manner of death in cold cases. More often than not, the new evidence corrects the mistakes made during the original investigation or simply fills gaps that were overlooked initially [45]. For example, post-mortem examinations, virtual autopsies with resources like a CT scan, and MRI, as well as forensic anthropological examinations, have all been used to find new evidence or re-analyze the existing discoveries. It is usual for subsequent testing and studies to fill the void left by mistakes or misunderstanding in the initial autopsy, primarily whenever significant medical or other discoveries have occurred during the elapsed time period [46]. An excellent example to start with is virtual autopsies. It manages to create a permanent, non-destructible record of the state and can be re-examined dozens of years following the initial procedure when the original report is unavailable. At the same time, forensic anthropology works on cremation or defleshed remnants and, in turn, attempts to reconstruct crimes more generally, locating a scene based on the past's presented evidence [47]. The point is that these approaches pave the way for the identification of unknown substances and unfamiliar examination, making a significant contribution to every old case study. Investigative genetic genealogy, in its turn, helps establish a complete family through a combination and trace the victim from the families with ready DNA [33].

Surveillance Technology and AI-Driven Analysis

Cold case investigations have recently benefited from the revolutionary artificial intelligence and advanced surveillance technology, enabling unprecedented opportunities for analyzing vast amounts of data and extracting latent information. This includes algorithmic processing of old crime scene footages, digital forensics of cell phone and social media, and predictive modeling to detect particular patterns or anomalies that a human investigator can ignore [48]. For example, AI algorithms can help to enhance blurry images, recover fragmented video sequences, and through facial recognition data or matching with license plate recognition systems. In turn, AI-driven analysis may scan large datasets, such as historical crime report and geographical information systems, to determine spatial and temporal patterns that can indicate serial offender activities or previously unknown connections between cases [49]. Additionally, these computational techniques can be also employed to refer to extensive volumes of unstructured text, such as witness statements or archival documents, to extract key entities, relationships, and occasions that may produce potential leads and evidence or confirm an existing theory [50]. All these capabilities, when coupled with forensic archaeology and anthropology, contributed to a general increase in the accuracy and reliability of results, allowing for more thorough reconstructions of crime scene or events. Furthermore, it is important to reference that the constant development of digital forensics tools, powered by AI and machine learning technologies, simplifies and accelerates data retrieval and analysis from mobile devices and social media platforms, thus significantly reducing the quantity of manual work [3].

Impact of Modern Forensic Techniques on Solved Cases

The inverse of these cases shows how DNA typing advances, ranging from RFLP to modern techniques, have genuinely changed forensic science by democratizing the level of genetic information. One critical innovation, polymerase chain reaction, enabled the development of forensic genetics as a routine forensic investigative tool in the 1990s to analyze tiny amounts of highly damaged DNA samples [6]. This change led to the testing of previously unsolvable cold cases, particularly based on biological material that previous generations had declared too little or harmed. Depending on the technique used, subtler, more degraded, or highly compromised samples could generate data of investigative value. DNA proficiency testing accompanied by novel advancements like mtDNA or Y-chromosomal STR sequencing and forensic genetic ancestry developed the implementation possibilities further. Forensic genetic genealogy, which allows investigators to identify a perpetrator

or match a crime scene sample to a victim through distant relative genealogists' genetically reconstructed family trees after being stumped in other searches, 42 is an adaptation of these methods. The technique has been precarious in the absence of a "smoking gun" crime scene sample against which to equate against criminal databases [52, 53].

Role of Forensic Experts

In this case, a wide range of specialists, from forensic scientists to forensic pathologists, can be referred to as forensic experts. Independent specialist expertise in the field of forensic science is instrumental in reevaluating and solving cold cases, the technological trend is quickly becoming a key element in the leads due to forensic experts, as Hoobe goes on to say [3]. Their expertise allows them to conduct a thorough review of the material, which may have been collected in evidence for several years and even several decades, using modern knowledge, methodologies, and approaches that were not available during the original examination. This implies, in addition to being able to explain the most recent developments in DNA sequencing, digital forensics, and forensic pathology, having the appropriate experience to work effectively with highly degraded samples or samples [30]. Moreover, Forensic experts also have to explain difficult to understand analytical results, draw parallels and unlit and complete the whole jigsaw in a way that their professional judgment deserves sufficient reception in the courtroom [54]. However, working on such cases requires not only an analytical mindset but a profound set of skills to work with physical evidence, combine this knowledge with cutting-edge visualization and analysis techniques. In addition to providing expert consultation, forensic experts are often called upon to conduct expert reviews and testing expert reviews. Just as importantly, forensic experts are often given the responsibility of helping judges to make evidentially necessary decisions according to the state of the art on sciences [55].

Contributions of Forensic Scientists and Specialists

Taking this into perspective, forensic scientists get a chance to begin with reviewing the original case files. This includes police reports, autopsy findings, and the use of photographs to possibly identify evidence that would be suitable for re-analysis using new technology. In this case, forensic experts can locate the evidence most suitable for reanalysis with newer forensic technologies such as advanced DNA sequencing that might be used to recover out the evidence that might be missed during initial investigations hence quintessential for the legal process [56]. Further, forensic experts target trace evidence and compare the results from reanalysis with a comprehensive forensic database of evidence profiles termed Combined DNA Identification System to come up with conclusive results that they

can use in court during conviction or exonerations [57]. This step is essential in that it provides a systematic methodology to generate new evidence that is critical in the determination of the case outcome. In this regard, the evidence is produced, contrary to the legal definition, is beyond reasonable doubt since the process supports the scientific method of preventing bias from the investigator. The process is guided by the scientific collector that forbids anyone from sharing through negligence or abusing the concept [58]. Secondly, the forensic collectors offer assistance to law enforcement by conducting just a scientific inquiry which offers neutral conclusion and question discredits or eliminates bias from various sources. This is achieved by forensic scientists through comprehensive re-analysis of trace evidence revealed new biological material and previously inaccessible digital footprints that could link the case to potential perpetrators and/or suspects or to develop new lines of inquiry from the vast body of trace and toxicological evidence that bands passed [59].

Future of Cold Case Investigations

Forensic science and technology are continuously evolving and with current trends, will revolutionize cold case investigations by expanding the range of opportunities to revisit and solve decades-long puzzles. Artificial intelligence and machine learning will ultimately become more involved in forensic analysis, making large datasets automatable for pattern recognition and for predictive modeling in developing strategies for investigations [60]. Combining forensic databases with large language models such as ChatGPT may also simplify and speed up the process of data analysis and identification by exposing small patterns in digital evidence like text messages and social media posts [61].

Evolving Technologies and Their Impact

For example, AI-driven systems could sift through vast amounts of historical data in under a second, seeking connections or any novelties in the data such as anomalies that have never been discovered before but are relevant to solving an investigation. That said, it is reasonable to think that the advances in forensic DNA phenotyping were practically utilized to produce more detailed profiles of the phenotypes of unknown individuals with a narrower pool of potential suspects or used to help identify missing persons [62]. Prior next-generation sequencing technologies of advanced bioinformatics and genomics in forensic genetics, DNA samples of any type and size, including those severely degraded or minute, might be analyzed more accurately and sensitively than is currently possible. In analogy to currently employed CRISPR-Cas systems that promise to completely change the way we conduct DNA manipulation and analysis in the future, future developments of these systems might make more

accurate genetic profiling possible from difficult-to-analyze DNA samples [63]. However, such new opportunities also bring extraordinary ethical considerations, including genetic privacy and data security, and require comprehensive governance to ensure their responsible use for forensic purposes. Important aspects of such governance would cover potential unjust biases in the AI models trained on historical data, as such biases might reinforce societal inequalities but in a novel AI-regulated form along existing police lines [64].

Bringing Justice to Unsolved Crimes

In the end, the integration of these advanced forensic technologies, international cooperation and standardization and protocolization will eventually secure substantial increases in the solve rates of cold cases and provide closure to the victims and their family members [65]. What is more, further incorporation will create an opportunity for the re-evaluation of analyses and evidence that were previously considered infeasible due to the emergence of sophisticated computational and interdisciplinary scientific methods. In turn, such improvements in analytical reasoning will eventually narrow possible conclusions and further establish a level of certainty within the most complex cold cases [66]. The latter could include cases that lack physical evidence or cases that sensibly predefined DNA samples to determine the identities of culprits. For example, the ongoing development of such methods as Single-Cell DNA and epigenetic analyses further increase the success rates of even minute samples of DNA. Access to CRISPR-Cas systems will further consider a reduction in the cost of DNA sequencing and will enable with increased sensitivity DNA detection to such matters [30]. Genome Online's high-throughput DNA sequencers will in the same way evaluate a cost-effective up-to-date analysis of such low input samples. Further advances should also be

made with bioinformatics, which currently struggles with complex genetic samples. These advancements will allow the more effective interpretation of evidence, genealogical re-evaluation, and end more cold cases with adjudication and enhanced information knowledge [6].

CONCLUSION

Forensic application of nanotechnology in biosensors is also primed for opportunities, notably due to its unprecedented sensitivity to biological traces, providing the faculties needed in the analysis of available tiny samples, mostly vital in cold cases. These advances provide a platform on which previously challenging evidence yields crucial knowledge, increasing the chances of culprits' identification and, ultimately, cold case closure. Advanced DNA sequencing is, in turn, complimented by third-generation sequencing such as Nano pore and single-molecule real-time sequencing. These innovative tools present capabilities like long-read length and on-go analysis that are more advantageous in forensic applications, particularly when studying degraded and complex samples. Such innovations, incorporating next-generation sequencing and rapid DNA analysis, have essentially revolutionized the field, facilitating higher speeds and accuracy in DNA analyses, and broadening the forensic capacity in DNA application. This advance ensures that forensic specialists can handle evidence swiftly, analyze more complicated samples, and carry out real-time field investigations.

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