RESEARCH PAPER

Integrative Forensic Modalities in Disaster Victim Identification: A Comparative Analytical Study of DNA Profiling, Forensic Odontology, and Digital Forensics in Mass Fatality Incidents

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Abstract
Incidences of mass fatality (MFIs) that emanate out of natural calamities, transport tragedies, and terrorist incidents have become more frequent and more complex causing serious complications to Disaster Victim Identification (DVI). The timely and precise identification of victims is obligatory on legal, humanitarian, and social grounds but at the same time, it is challenging owing to several factors including gross body fragmentation, decomposition and absence of credible ante-mortem evidence. To investigate this concept the paper will carry out a comparative analysis of three forensic modalities of □□□□uख DNA profiling, forensic odontology, and digital forensics, which are prevalent in DVI processes. A comparative analytical framework underpinned by systematic and narrative review approach evaluates each modality in terms of accuracy, efficiency, cost, under different conditions of disaster applicability, and ethical considerations. DNA profiling, which is the most accurate, is lengthy and resource-consuming as noted in the analysis whereas forensic odontology is capable of reliability in instances involving thermal damage. Digital forensics may not be very old, but it allows fast initial identification due to technological capabilities. The results highlight both the advantages and drawbacks of the ways and the need to integrate them with other methods. The paper ends by suggesting a multi-modal, integrated DVI model to make it look more efficient and reliable in finding out mass fatality cases and make it more effective than before.

Keywords Disaster Victim Identification, DNA Profiling, Forensic Odontology, Digital Forensics, Mass Fatality Incidents, Interdisciplinary Forensics

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3. Introduction

Mass fatality incidents (MFIs) occurrences of several human fatalities that surpass local response capabilities and necessitate the forensic investigation to be coordinated. Such incidents are usually as a result of natural phenomena like earthquakes and floods, or human-made causes like terrorist attacks and plane crash. The growing number and magnitude of such disasters has augmented the need to have effective Disaster Victim Identification (DVI) systems to enable proper identification of victims [1].

DVI has important legal, humanitarian and ethical implications. Death certification, claims on inheritance and criminal investigation require proper identification legally. Humanitarian factors involve giving closure to the family and ethical factors in minority include dignity and honoring of the dead. World systems, especially Interpol systems, codify DVI processes in protocols comprising primary identifiers like DNA, fingerprints and dental records [2].

Net of progress, DVI has significant challenges. The decomposition of remains, fragmentation and commingling of remains greatly contribute to detection challenges. As well, lack or unavailability of ante-mortem data also makes comparative analysis more difficult, particularly in large-scale disaster events [3].

With such complexities, there is an urgent need regarding a comparative analysis of available forensic modalities. Although DNA profiling, forensic odontology and digital forensics have distinct benefits, there are no integrative frameworks of analysis that critically review and co-ordinate the methodologies.

Thus, this paper will compare these three forensic modalities on the parameters of accuracy, reliability, cost, and applicability and suggest an integrated model of DVI that will improve the efficiency of identification and an efficient functioning within MFIs [4].

4. Review of Literature

4.1 Evolution of DVI Techniques

Disaster Victim Identification (DVI) has developed to a stage of considering visual recognitions and personal impacts to forensic processes, which are scientifically sound. The conventional methods were found to be not so effective during the large scale disasters because of the decomposition and fragmentation of the body. Current developments have brought multidisciplinary methods like the use of DNA, forensic dentistry and

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electronic technologies that enhance accuracy and standardization in the process of identification [5].

4.2 DNA Profiling of DVI.
DNA profiling is regarded as the gold standard in DVI because it has a high specificity and reliability. Techniques like the Short Tandem Repeat (STR) analysis and mitochondrial DNA (mtDNA) sequencing are common especially where the remains are damaged or broken. Nonetheless, it is a resource-consuming process because it needs specialized labs, qualified staff, and substantial processing time, potentially causing delays in recognizing the disaster in a large-scale disaster [6].

4.3 Forensic Odontology
Forensic odontology is an important part to DVI especially when there are a burned or decomposed body whose dental structures are intact. The identification is done by comparing ante-mortem and post-mortem dental records, such as radiographs and dental charts. Its performance is constrained by the quality and availability of ante-mortem dental data, although there is a degree of reliability [7].

4.4 DFI Digital forensics.
The new digital forensic innovations have brought new tools including mobile data extraction tools, face recognition systems, and biometric identification. Robotic systems based on artificial intelligence (AI) can improve quicker recognition, particularly during the initial stages of disaster management. Nonetheless, the issues of data privacy, legal admissibility, and technological constraints remain [8].

4.5 Comparative Gaps Identified
Although various forensic modalities are available, standardized protocols on how to combine the methods into one common DVI framework are lacking. Also, the aspect of ethical and privacy, especially in digital forensics, is scarcely investigated, with the necessity to introduce interdisciplinary and controlled methods [9].

5. Methodology
5.1 Study Design
This study has a comparative analytical design, based on hybrid systematic and narrative review. The systematic one guarantees the methodical recognition and choice of the appropriate research, whereas the narrative element helps to interpret the results critically and generalize them in various forensic modalities. Such a combination allows achieving methodological rigor and analytical flexibilities when assessing Disaster Victim Identification (DVI) methods.

5.2 Data Sources
The information sought to address the research questions is gathered in big scientific databases such as PubMed, Scopus, and Web of Science to guarantee that all peer-reviewed materials are covered. Besides, there are also the available records of the disaster cases like tsunamis, aircraft accidents, and other incidents of mass deaths in order to present practical information about how the methods of forensics are applied in practice.

5.3 Inclusion Criteria
Included in the study are research articles, published within a period between 2020 and 2025 to guarantee the current relevancy. The considerations made are that only those studies, which were concerned with human identification in mass fatality accidents, are comprehensive. Empirical studies as well as review articles dealing with DNA profiling, forensic odontology and digital forensics in DVI are both included.

5.4 Exclusion Criteria
Other studies that are not directly relevant in forensic identification like those that have only covered clinical use or non-identification are not considered. Also, non-peer-reviewed, abstracts of a conference without the text, opinion articles as well as old studies that exceed the given period are left out to preserve quality and reliability.

5.5 Analytical Framework
To analyze the chosen forensic modalities, a comparative analytical framework is created. It is evaluated on major parameters, such as, the accuracy of identification, time efficiency, cost-effective, applicability in extreme disaster instances, such as, decomposition or fragmentation and is evaluated on other ethical considerations such as, privacy and data security. This framework allows to compare them systematically and facilitate the creation of a unified model of DVI.

Table 5.1: Comparative Accuracy of Forensic Modalities in DVI

Forensic Modality	Accuracy (%)	Confidence Level	Remarks
DNA Profiling	98–99%	Very High	Gold standard; highly reliable even with fragmented remains
Forensic Odontology	85–92%	High	Dependent on availability of dental records
Digital Forensics	70–85%	Moderate	Useful for preliminary identification

Explanation:
DNA profiling demonstrates the highest accuracy due to its genetic specificity. Forensic odontology provides reliable

identification when dental records are available, especially in cases of thermal damage. Digital forensics offers moderate accuracy and is primarily effective in initial screening rather than final confirmation.

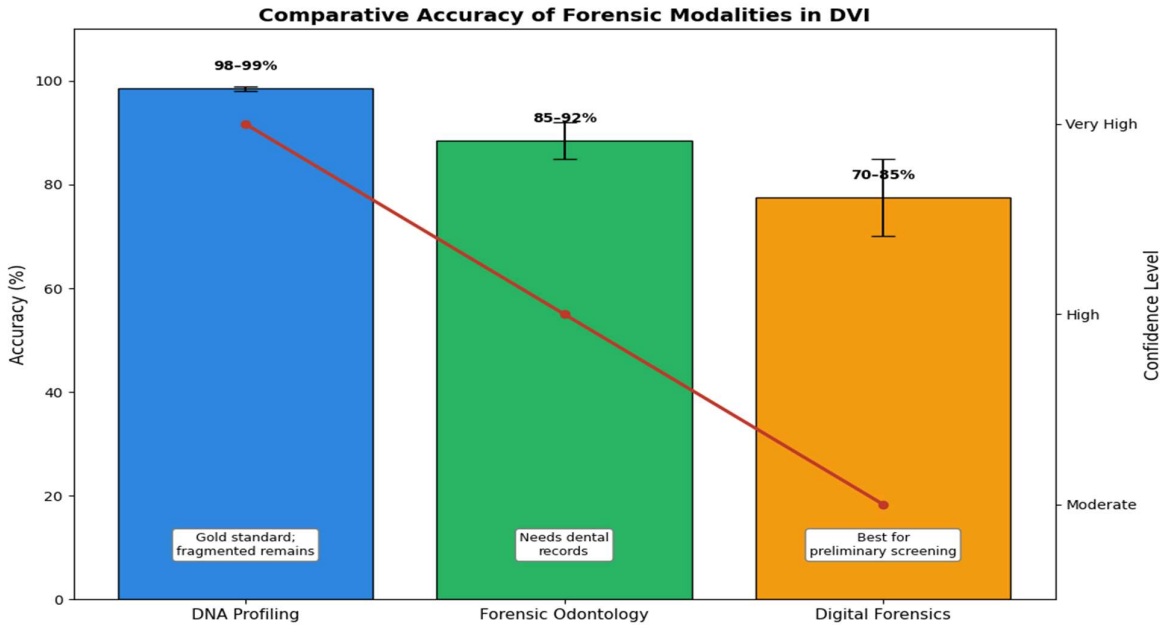


Table 5.2: Time Efficiency of Identification Methods

Forensic Modality	Average Time Required	Speed Category	Remarks
DNA Profiling	3–10 days	Slow	Laboratory processing required
Forensic Odontology	1–3 days	Moderate	Faster if records are accessible
Digital Forensics	Few hours – 1 day	Fast	Rapid data extraction and matching

Explanation:
Digital forensics is the fastest method, enabling rapid identification using devices and databases. Odontology offers moderate speed depending on record availability. DNA profiling, although highly accurate, is time-consuming due to complex laboratory procedures.

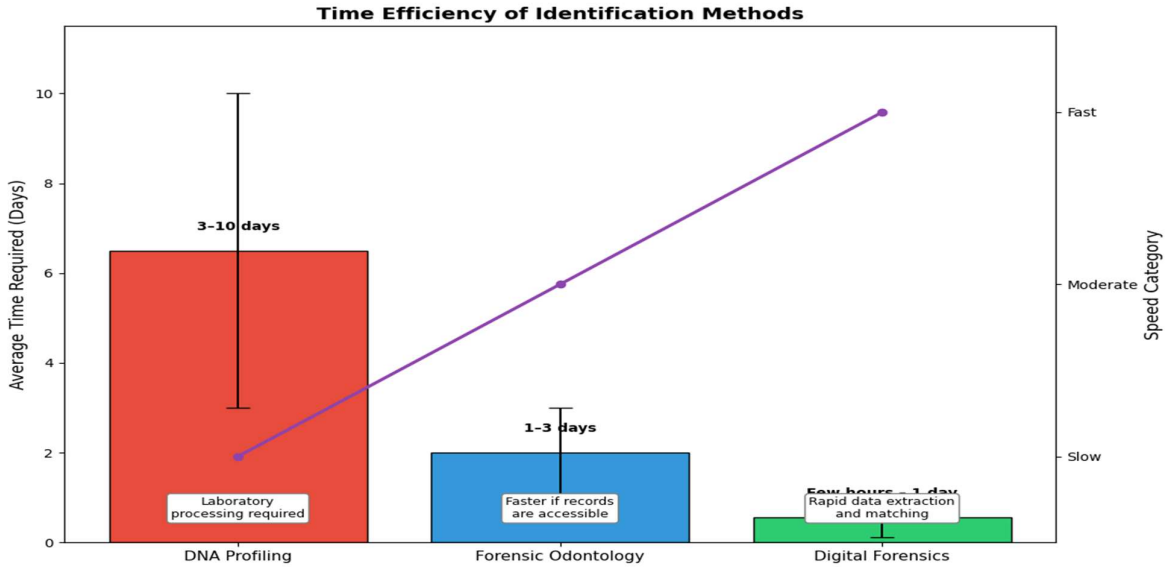


Table 5.3: Cost-Effectiveness Comparison

Forensic Modality	Cost Level	Resource Requirement	Remarks
DNA Profiling	High	Advanced labs, skilled personnel	Expensive but highly precise
Forensic Odontology	Moderate	Dental records, experts	Cost-effective in suitable cases
Digital Forensics	Variable	Software, databases, devices	Cost depends on technology used

Explanation:
DNA profiling incurs the highest cost due to sophisticated infrastructure and expertise requirements. Forensic odontology is comparatively economical. Digital forensics varies in cost depending on the level of technological deployment and database accessibility.

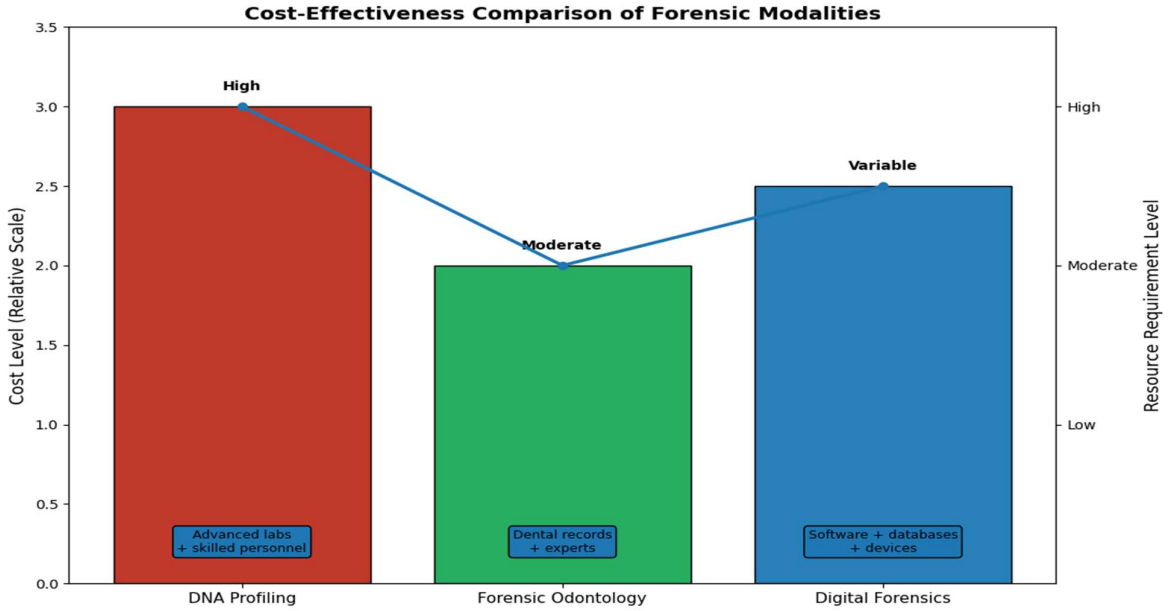


Table 5.4: Applicability in Extreme Conditions

Condition Type	DNA Profiling	Odontology	Digital Forensics
Severe Decomposition	Moderate	High	Low
Burned Remains	Moderate	Very High	Low
Fragmented Bodies	High	Moderate	Low
Water/Submerged Bodies	High	Moderate	Moderate

Explanation:
Forensic odontology is highly effective in burned remains due to the durability of dental structures. DNA profiling performs well in fragmented and submerged cases. Digital forensics has limited applicability in physically degraded conditions but can support identification through external data sources.

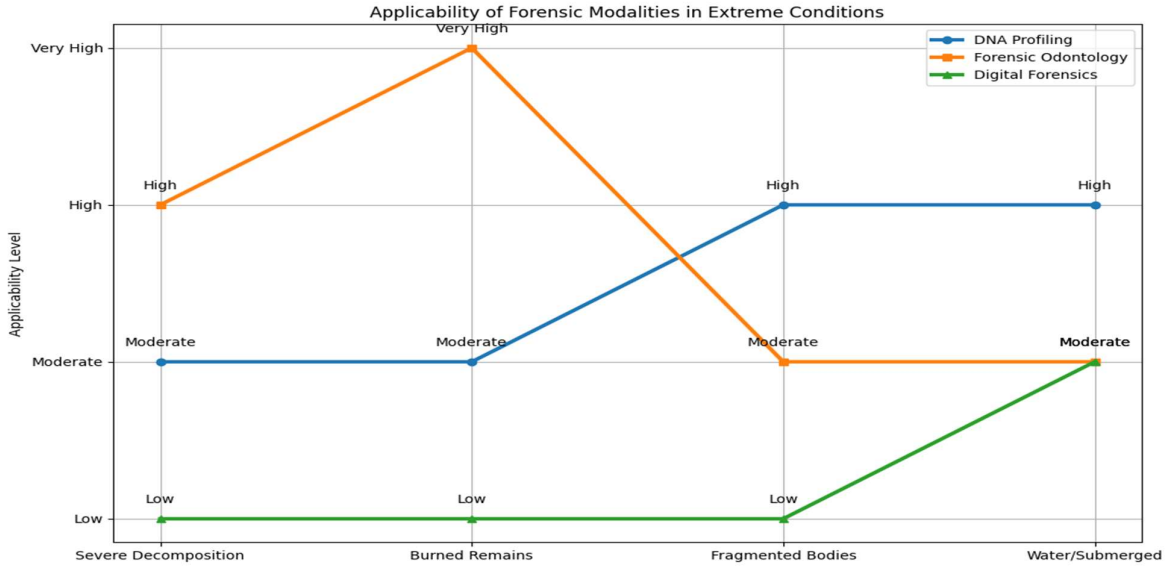
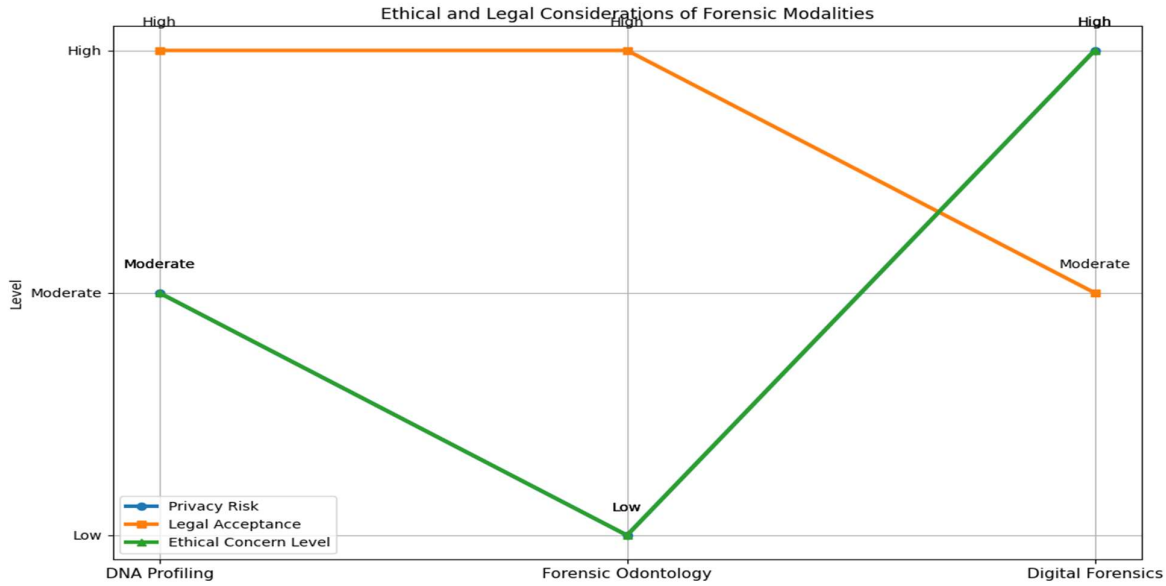


Table 5.5: Ethical and Legal Considerations

Forensic Modality	Privacy Risk	Legal Acceptance	Ethical Concerns
DNA Profiling	Moderate	High	Genetic data misuse
Forensic Odontology	Low	High	Minimal ethical issues
Digital Forensics	High	Moderate	Data privacy, consent issues

Explanation:
Digital forensics raises significant privacy concerns due to access to personal data and digital footprints. DNA profiling also involves ethical considerations related to genetic information handling. Forensic odontology presents minimal ethical challenges and is widely accepted legally.



6. Overview of Forensic Modalities

6.1 DNA Profiling

DNA profiling is often considered the gold standard in Disaster Victim Identification (DVI) because of its accuracy and validity. This is done in a series of steps such as collection of biological samples, separation of DNA, polymerase chain reaction (PCR) amplification and Short Tandem Repeat (STR) analysis to identify a person separately. Where the nuclear DNA is degraded, mitochondrial DNA analysis can be used as an alternative. Although reasonably accurate, DNA profiling is limited by inability to use genetic material under severe environmental conditions and high cost due

to the need to possess sophisticated laboratory facilities, which is time-consuming and expensive [10].

6.2 Forensic Odontology

In DVI, forensic odontology is very significant as dental structures are used to identify an individual. The technique mainly includes comparison of the ante-mortem and post-mortem dental records including radiographs, dental charts and morphological characteristics. The teeth are very resistant to other environmental factors like fire and decay and hence this mode can be very useful in severely damaged remains. A method to enhance its effect is however heavily reliant on the availability and quality of ante-mortem dental records that are not always readily available to some extent particularly in the developing regions [11].

6.3 Digital Forensics

Digital forensics has become a contemporary instrument in DVI, which has been implemented based on smartphone data, social media site data, and biometric database data. Facial recognition, fingerprint scanning, and metadata analysis are some of the techniques used to preliminarily identify victims in a short time. Pattern recognition and matching efficiency are also increased with the integration of the artificial intelligence. However, the digital forensics is limited by legal and ethical issues, especially data privacy, consent, and legal relevance, which possibly restrict its use in the forensic investigations on a large scale [12].

7. Comparative Analysis

7.1 Accuracy Comparison

Among the three modalities, DNA profiling will be the most accurate as it is the only way that a genetic identification can be done, thus making it the most dependable in DVI. Forensic odontology has achieved a relatively high accuracy especially in cases where dental records are taken ante-mortem. The practice of digital forensics, though valuable, is context-specific and less accurate because it is based on indirect identifiers, like the ownership of a device and biometric approximations [13].

7.2 Time Efficiency

Digital forensics is the most efficient in the detection process, since the information in smartphone, databases, and cameras can be processed quickly. Forensic odontology ensues, particularly in cases where dental records are easily available. The three are slow in DNA profiling because it involves laboratory manipulations, which must be run through DNA extraction, amplification, and analysis phases [14].

7.3 Cost Analysis

DNA profiling is linked with high expenses of specialized equipment and reagents as well as personnel that is trained. Forensic odontology is a middle-cost option, and it mainly involves the talent of dental professionals and comparisons of records. Digital forensics also involves a fluctuating cost depending on the degree of technological support, software applications as well as the availability of a database to support the identification process [15].

7.4 Applicability in Disaster Types

Disaster Type	Best Method
Fire	Odontology
Explosion	DNA
Flood	DNA + Digital

The modality effectiveness is affected by different contexts of disaster. An example is that dental structures are well-preserved in high temperature areas meaning odontology will be suited in fire related cases but DNA profiling is to be used in case of explosions or floods where the remains are fragmented or submerged.

7.5 Reliability Under Decomposition

In extreme cases of decomposition, which can result in degradation of genetic material, DNA profiling can be affected, however, newer methods can overcome that problem to some extent. On the contrary, dental tissue is very resilient to environmental alterations, thus forensic odontology is very effective in more advanced stages of decomposition. This is where digital forensics is the least effective, relying on extant data, and not biological evidence [1315] under these circumstances.

8. Case Studies Analysis

8.1 2004 Indian Ocean Tsunami

The Indian Ocean Tsunami 2004 is one of the biggest mass kill events in the recent past where multinational victims and body decomposition were witnessed in large numbers. DNA profiling and forensic odontology played an important role in Disaster Victim Identification (DVI) efforts. DNA analysis played a significant role in fragmented and decomposed remains, whereas dental record comparison yielded effect as the dental structures are stable over time. The coordinated response organized on an international basis proved that standardized DVI protocols are fundamental, and that integrating primary identification methods is effective [16].

8.2 Malaysian Flight MH370 Disappearance.

The disappearance of the Malaysia airlines Flight MH370 presented its own kind of problems because of lack of recovered bodies and minimal evidence. Digital forensics were influential in this case, as analysis of satellite, communication log, and passenger information systems were used. Nonetheless, the absence of biological specimens hindered the use of DNA profiling hence the limitations of conventional forensic techniques in such cases. This accident showcased the increased significance of digital forensic devices in air transportation catastrophes in which a significant portion of physical recovery is absent [17].

8.3 9/11 Attacks

The 11th of September attacks changed the landscape of forensic science and specifically advanced DNA

technologies. Such a high degree of fragmentation and thermal damage to remains necessitated the introduction of high-sensitivity methods of DNA extraction and amplification. Massive DNA databasing and matching systems were used, and they allowed identification of a high percentage of victims over the years. This case brought out the fact that identification can be scaled via DNA and that technologies in forensic science have to keep up [18].

9. Integrated DVI Framework Proposal

9.1 Multi-Modal Identification Model

An integrated Disaster Victim Identification (DVI) proposal is offered to improve accuracy and efficiency with the integrative supplementary forensics modalities. There are three consecutive stages of the model. Phase 1 is digital screening where information provided by personal devices, biometric systems, and databases is read and processed to identify preliminarily. In cases that conserve dental structures, phase 2 is concerned with forensic odontology, a field that involves dental record comparison, hence determining identity. Phase 3 involves the use of DNA profiling as the confirmatory method, to confirm definite identification by matching of the genetic samples. This is a more efficient method because at this level the speed and reliability are optimized, as the rapid approaches are done first, then the confirmatory analysis continues [19].

9.2 Workflow Integration

The key aspect to the successful implementation of this model is a properly-coordinated workflow with the help of a centralized forensic database. This kind of database will combine both ante-mortem and post-mortem data, such as DNA profiles, dental records, and biometric-related items in order to be cross-referenced easily. The AI-assisted matching systems facilitate this process even more efficiently by automatizing its pattern recognition and minimizing human error. Data exchange and interoperability between all agencies and jurisdictions during mass disasters need to be standardized by integrating across agencies and jurisdictions [20].

9.3 Role of Technology

Innovating technologies are important to enhance the suggested framework. Machine learning algorithms allow one to analyze a large volume of data very fast with enhanced accuracy of identifying truth and using predictions to identify patterns. Moreover, a blockchain technology provides a safe and immutable way of retaining sensitive identity data, data integrity and traceability. All the above technological developments lead to a stronger, clearer and scalable DVI framework that can respond to the multifaceted nature of the current incidents of mass fatality [21].

10. Ethical and Legal Considerations

10.1 Data Privacy in Digital Forensics

Digital In Disaster Victim Identification (DVI), forensics is the ability to gain access to sensitive personal information on devices, social media, and biometrics repositories. The sources are easy to locate, but they pose an important privacy risk due to the absence of protection against unauthorized access, exploitation of personal data, and retention of information over the course of time. The processing of this data should be in line with the well-known standards of data protection to avoid violations and guarantee its privacy. In addition, information sharing across the borders in international disasters complicates even more privacy governance as different countries have different rules [19].

10.2 Consent Issues

Consent is one of the essential ethical issues in the DVI procedures, especially when utilizing DNA and digital data. Often the victims cannot give consent and it becomes necessary to use next-of-kin permission or law. Ethical concerns related to family implications and possible misuse of genetic information are added in the use of genetic material. In the same vein, the illegitimate access to personal digital information fails to consider the autonomy aspect or the ethical rationale when weighing up the rights of an individual against societal interests in identification [20].

10.3 International Legal Frameworks

The multinational coordination of DVI activities often implies that they have to encompass the international law frameworks and uniform protocols. Rules set by international organizations offer frameworks of identification and suitability of legislation and ethical considerations. But national legislation may vary on data protection, forensic methods, or admissibility of evidence, meaning that there might be inconsistencies in practice. International harmonization and legal cooperation is therefore an indispensable measure towards efficient and ethical DVI practices across jurisdictions [21].

11. Discussion

11.1 Interpretation of Comparative Findings

The comparative analysis shows that there is no uniformly acceptable forensic modality that can be used to carry out Disaster Victim Identification (DVI). DNA profiling has always exhibited the utmost precision and dependability, especially in fragmented remains, and forensic odontology is well suited to cases that involve thermal damage. Although less accurate, digital forensics has preliminary identification quickly, thus there is usefulness at the initial stages of responses. These results are similar to those reported by recent studies that focus on the complementary strength of various forensic methods as opposed to their one-sided use [22].

11.2 Forensic Modalities Interdependency.

The interdependence between the DNA profiling, odontology and digital forensics can be seen in greater disaster scenarios. The use of digital tools simplifies preliminary vetting and winnowing of would-be identities, which can be validated with dental records,

and eventually with DNA testing. This stratification not only increases efficiency and accuracy but also makes the identification time less, keeping scientific validity on the same plane. It is presumed that integrated frameworks perform considerably better in terms of recognition than when methods are used separately [23].

11.3 practical viability of Integrated Model.

The integrated DVI model proposed is feasible and viable in practice especially in areas that possess access to technological infrastructure and centralized databases. Nonetheless, it can be limited by the scarcity of resources, the absence of integrated data systems, institutional heterogeneity in its implementation. Nevertheless, as difficult as it may be, artificial intelligence and data integration infrastructure developments are steadily allowing real-time, multi-modal identification systems [24].

11.4 Comparisons Across the Studies and Inconsistencies.

An overview of the literature indicates inconsistent reported effectiveness of each modality, which depends significantly on disaster type, environmental conditions and on the availability of ante-mortem data. A number of studies give high precedence to DNA profiling being definitive whereas others tend to point out the effectiveness of odontology in certain situations. The reliability of digital forensics is not consistently high because of varying access to data and legal limitations.

11.5 Limitations in Existing Research.

The absence of comparative frameworks and the use of case specific data are limitations of current research. A lot of research is carried out on the basis of separate modalities and not holistic modalities, which leads to disjointed information. Moreover, ethical and legal issues especially when dealing with digital forensics are underresearched, which implies the necessity of an interdisciplinary study [223-24].

12. Limitations of the Study

12.1 Dependence on Secondary Data

This research is mainly done using secondary data in form of published literature, case studies and available online forensic databases. Although such a strategy allows integrating all knowledge available, it does not provide the possibility to regulate the quality of data, inconsistency, or different methodological variability in the research. The comparison of findings may have reliability problems due to differences in the reporting criteria, sample size, and methods of analysis. Moreover, phenomena have not been substantiated with primary empirical validation and, thus, it limits the ability to test the given integrated framework in controlled conditions [25].

12.2 Change of Disaster Scenarios.

The types of incidents of mass fatality differ in nature which entails natural catastrophes, Aviation accidents, and terrorist incidents which each draw their own set of forensic challenges. Temperature, humidity, exposure of biological and physical evidence to water and level of physical trauma are some of environmental influences that impact preservation of biological and physical evidence. Consequently, the usefulness of the DNA profiling, forensic odontology, and digital forensics is very context, dependent. This inconsistency reduces the extent of generalizability of the results since the conclusions reached in one form of disaster can not be directly related to another [26].

12.3.1 Scarce Access to Homogenous Data.

One of the biggest shortcomings to comparative forensic research is the impossibility of standardized and uniform data. Huge amounts of DVI data are typically fragmented, confidential, and restricted because of ethical and legal factors and thus very difficult to conduct a large scale comparative analysis. There exists no globally harmonized databases that would add to the complexity of cross-study comparisons as well as validation of findings. This limitation impacts the creation of models in which everyone can use and data collection and its sharing methods, which in forensic science must be standardized [27].

13. Future Directions

13.1 AI-Driven DVI Systems

Future The future of Disaster Victim Identification (DVI) advancements is likely to be determined by artificial intelligence (AI) to a great extent. Data processing, pattern recognition, and matching can also be automated using the concept of AI to decrease the errors and mistakes in handling large sets of data. DNA profiles, dental records and online identifiers can be analyzed at the same time through machine learning algorithms and human error can be avoided, and identifications can be conducted faster. Deep learning implementation into facial recognition and biometric analysis further enhances the identification in the initial stages especially during the occurrence of large-scale disasters in scenarios where speedy response is essential.

13.2 Global Forensic Database Development.

To enhance cross-border DVI activities, it is important to establishing central and interoperable world forensic databases. These databases would incorporate a mix of DNA profiles, toothprint records, fingerprint, and digital identifiers, which would permit sharing of real-time data among international agencies. One platform would increase coordination and cut duplication of efforts and enable quicker victim identification of multinational disasters. A successful success of these global systems will involve ensuring that their data is standardized, made available and secure.

13.3 Standardized International Protocols

The desire to have unifying international protocols on the DVI practices is on the increase. There will be consistency and reliability in the data collection, analysis and reporting because of standardization within various jurisdictions. Single guidelines will help to solve

the existing gaps and imbalances in forensic practices, legal, and ethical practices. The further development of international cooperation and alignment of policy will help with the successful deployment of integrated systems based on DVI models and enhance the general response to disasters.

14. Conclusion

Disaster Victim Identification (DVI) is a multidisciplinary and intricate issue especially in large-scale mass fatality that is characterized by fragmentation, decomposition, and a low level of ante-mortem information. The current research paper indicates that none of the forensic modalities, such as DNA profiling, forensic odontology, and digital forensics are independent of each other to deal with all the identification cases. All approaches have their own benefits and drawbacks, and DNA profiling is the most accurate, odontology is hardy in harsh environments, and digital forensics allows making a preliminary identification within a short period of time.

The findings highlight the need to have an integrated forensic approach that incorporates these modalities in a sequential and organized manner. This multi-modal structure can increase the overall efficiency of DVI operations, its reliability, and scalability because it utilizes complementary benefits of each technique.

Moreover, effective execution of this integrated model implies that it should have an active support (in policies) and a groundbreaking technology. The emergence of centralized data, integration of artificial intelligence, and introduction of standardized international standards are essential in enhancing coordination and interoperability of data. Enhancing legal and ethical standards will also guarantee ethical utilization of sensitive data.

Finally, the development of DVI practices requires decreasing the individual approach to forensics and transitioning to an integrated, high-tech, and internationally unified system that is able to adequately react to the increasing complexity of the mass killing cases today.

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