REVIEW ARTICLE

Comprehensive Evaluation of Artificial Intelligence Applications in Forensic Odontology: A Systematic Review and Meta-Analysis

Muhammad Salman Khan[1], Urooj Afridi[2], Muhammad Jamal Ahmed[3,*], Babar Zeb[4], Irfan Ullah[5] and Muhammad Zain Hassan[6]

[1] Department of Oral Biology, Faculty of Dentistry, Universitas Indonesia, Jakarta 10430, Inodnesia
[2] Department of Computer Science, National University of Computing & Emerging Sciences, 25000, Pakistan
[3] Departamento de Sistemas Informaticos, Universidad Politécnica de Madrid, 28031, Spain
[4] Department of Software Engineering, College of Electrical and Mechanical Engineering, NUST, Islamabad, Pakistan
[5] Graduate School of Padjadjaran, Universitas Padjadjaran, Jl. Dipati Ukur No.35, Jawa Barat 40132, Indonesia
[6] Software Engineering Department, University of Haripur, Pakistan

Abstract

This systematic review and meta-analysis assesses the transformative effect of artificial intelligence (AI) on forensic odontology, concentrating on gains in identification accuracy and workflow efficiency. Traditionally, human identification in this specialty depends on meticulous comparison of dental charts and radiographs. The integration of AI-driven technologies—including machine-learning algorithms and image-recognition networks—has begun to expedite core tasks such as bite-mark interpretation, dental-age estimation and record reconciliation, while also limiting examiner bias and clerical error. Following PRISMA guidelines to ensure methodological rigour, we searched PubMed, ScienceDirect, Google Scholar and Cochrane, retrieving 175 papers; 32 fulfilled pre-established inclusion and exclusion criteria. Analytical performance was appraised with the K Vaal and Cameriere frameworks, chosen for their relevance to age and identity determination. Across studies, AI systems consistently processed large datasets at high speed and delivered accuracy that exceeded conventional approaches. Quantitative synthesis further demonstrated superior precision in automated dental charting and radiograph-based age assessment across diverse age brackets and tooth classes. As a group, pooled sensitivity and specificity averaged 0.93 and 0.95, respectively, underscoring robust diagnostic performance across both pediatric and adult cohorts. These findings highlight AI's versatility and validate its role as a dependable decision-support tool for forensic odontologists, enhancing the reliability and timeliness of evidence presented in legal contexts.

Keywords: artificial intelligence, forensic odontology, dental identification, pattern recognition, dental

Academic Editor:
Habib Khan

Submitted: 27 September 2024
Accepted: 20 October 2024
Published: 09 November 2024

Vol. 1, **No.** 3, 2024.
10.62762/TIS.2024.818917

***Corresponding author:**
✉ Muhammad Jamal Ahmed
muhammadjamal.a@upm.es

Citation
Khan, M. S., Afridi, U., Ahmed, M. J., Zeb, B., Ullah, I., & Hassan, M. Z. (2024). Comprehensive Evaluation of Artificial Intelligence Applications in Forensic Odontology: A Systematic Review and Meta-Analysis. *ICCK Transactions on Intelligent Systematics*, 1(3), 176–189.

identification.

1 Introduction

Forensic odontology, the intersection of dentistry and legal investigations, stands as a crucial discipline in the identification of individuals, especially when traditional methods may be insufficient. Dental remains, often resilient to decay and environmental factors, serve as valuable markers in situations like mass disasters, criminal investigations, and historical identifications. Historically, the process of matching dental records to unidentified remains has relied heavily on manual examination by forensic odontologists [1], a time-consuming and sometimes subjective process. However, the technological revolution marked by the advent of artificial intelligence (AI) presents a transformative potential for this field. The integration of AI into forensic odontology offers a promising pathway to bolster the accuracy, speed, and efficiency of identification processes. Machine learning algorithms, a subset of AI, can be trained to recognize intricate dental patterns, discrepancies, and similarities with remarkable precision. These algorithms can analyze vast datasets of dental records, compare them with post-mortem findings, and swiftly identify potential matches or discrepancies that might be missed by the human eye. Moreover, AI can assist in the creation of 3D dental models, facilitating more detailed and comprehensive comparisons between ante-mortem and post-mortem dental records [2].

One of the significant advantages of AI in forensic odontology is its ability to handle large volumes of data efficiently. In mass disasters or large-scale criminal investigations involving multiple victims, the sheer number of dental records to be examined can be overwhelming for forensic odontologists. AI-powered systems can process this data rapidly, prioritizing potential matches based on various criteria such as dental morphology, age, and dental treatments, thereby expediting the identification process. This speed is not only crucial for timely closure for families of the missing but also aids in the swift administration of justice. Furthermore, AI can enhance the objectivity and consistency of forensic dental analyses. Human error, inherent biases, and subjectivity can sometimes influence the conclusions drawn from dental examinations. AI systems, devoid of emotions and biases, offer an objective and standardized approach to dental comparisons. By minimizing the influence of human factors, AI can contribute to more reliable and reproducible results, strengthening the credibility of forensic odontology as a forensic science.

The integration of AI can facilitate interdisciplinary collaborations between forensic odontologists and other experts in the field of AI and computer science. Collaborative efforts can lead to the development of specialized software tools tailored to the unique needs and challenges of forensic odontology. These tools can be continually updated and refined to incorporate the latest advancements in AI technology, ensuring that forensic odontology remains at the forefront of forensic science. Despite the [3] promising potential of AI in forensic odontology, there are challenges and limitations that need to be addressed. The accuracy of AI algorithms heavily depends on the quality and diversity of the data used for training. Biases in training data can lead to erroneous results, emphasizing the importance of representative and balanced datasets.

Additionally, the interpretation of AI- generated results requires expert oversight and validation to ensure the reliability and validity of the findings. Ethical considerations also arise with the use of AI in forensic odontology. Privacy concerns, data security, and the potential misuse of AI-generated results are critical issues that require careful consideration and robust regulatory frameworks. Safeguarding the integrity of forensic investigations and protecting the rights and privacy of individuals involved must be paramount in the integration of AI into forensic odontology. Studying AI in forensic odontology is important for improving the accuracy, efficiency, and objectivity of dental identification processes. This can lead to better results in criminal investigations and victim identifications while also addressing ethical issues related to data handling and algorithmic bias. Research has looked closely at how AI is applied in this field, particularly in matching dental records and analyzing bite marks. However, there are challenges to overcome, such as data quality, biases in algorithms, and ethical concerns. These areas need more investigation and careful oversight.

2 Methodology

2.1 Study Design and Ethical Aspects

This systematic review adheres meticulously to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which are internationally recognized standards designed

to ensure the transparency, comprehensiveness, and reproducibility of systematic reviews and meta-analyses. PRISMA guidelines encompass a rigorous methodology that involves clearly defined stages, including the formulation of research questions, systematic search strategies, selection criteria for studies, data extraction, quality assessment, and synthesis of findings. By following these guidelines, the review aims to minimize bias, enhance the validity of the results, and facilitate the comparison and integration of findings across studies. It is noteworthy to mention that no ethical approval was deemed necessary for this study, given that it solely relies on existing literature and does not involve direct interaction with human subjects or the collection of new primary data. Utilizing existing literature allows for the examination and synthesis of a broad range of previously published research, thereby providing a comprehensive overview of the current state of knowledge on the topic of interest. This approach not only ensures the efficiency of the review process but also respects the ethical considerations associated with conducting research, as it avoids potential risks and burdens to participants. Furthermore, the absence of ethical approval underscores the importance of adhering to ethical standards and guidelines when conducting research involving human subjects. Ethical approval is typically required for studies that involve the recruitment, participation, or intervention of individuals, as it ensures that the research complies with ethical principles such as informed consent, confidentiality, and protection of participants' rights and well-being [4]. In contrast, systematic reviews that solely rely on existing literature are generally exempt from these requirements, as they do not pose direct ethical concerns related to human subjects.

2.2 Research Questions and Eligible Criteria

1. The research questions center on how AI is used in forensic odontology. They aim to compare the accuracy and reliability of AI methods with traditional techniques and to establish criteria for including peer-reviewed studies on AI in this area.
2. What are the specific applications of PICO AI within the field of forensic odontology?
3. How do the accuracy and reliability of AI-based methods, particularly PICO, compare to traditional techniques in forensic odontology?
4. What are the eligibility criteria for studies to be considered, particularly those published in peer-reviewed journals, that focus on the AI applications of PICO in forensic odontology?

2.3 Source of Information and Searches

PubMed, Scopus, and Web of Science, three prominent and widely recognized databases in the field of scientific research, were meticulously and systematically searched to gather comprehensive and relevant information. The search was conducted with a focused approach using specific keywords to ensure the retrieval of pertinent studies and articles. The chosen keywords for this search were "artificial intelligence," "forensic odontology," and "dental identification." The keyword "artificial intelligence" refers to the simulation of human intelligence processes by machines, particularly computer systems, which encompass learning, reasoning, and self-correction. In recent years, artificial intelligence has emerged as a transformative force across various disciplines, including healthcare, finance, and technology. Within the realm of forensic odontology and dental identification, artificial intelligence has shown promising potential in revolutionizing traditional practices and methodologies [5].

3 Data Collection and Analysis

3.1 Selection of Studies

In the process of conducting systematic reviews or meta-analyses, a meticulous approach is adopted to ensure the inclusion of only high-quality and relevant studies. The initial phase involves screening potential studies based on their titles, which serves as a preliminary filter to gauge the relevance and applicability of the research to the topic under investigation. Following this, abstracts of the selected titles are meticulously examined to further assess the suitability of the studies for inclusion. Abstracts provide a concise summary of the study, offering insights into the research question, methodology, findings, and conclusions. This stage is crucial in narrowing down the pool of potential studies and eliminating those that do not meet the predefined criteria or are not directly relevant to the research question. Subsequent to the abstract screening, the full texts of the shortlisted studies are thoroughly reviewed to make a final determination regarding their inclusion in the systematic review or meta-analysis [3]. Full-text assessment allows for a comprehensive understanding of the study design, methodology, data collection and analysis methods, results, and interpretations. This in-depth evaluation ensures that the selected studies

are methodologically sound, credible, and contribute meaningful insights to the research topic.

3.2 Data Extraction and Initial Analysis

The research process involved a systematic extraction and analysis of data pertaining to various facets of the study. This encompassed detailed information on the study design, including its methodology, objectives, and scope. Additionally, a comprehensive examination was carried out on the artificial intelligence (AI) techniques employed within the study. This involved identifying and understanding the specific AI algorithms, models, or computational methods utilized to process and analyze the collected data. Moreover, the study's outcomes were meticulously scrutinized to determine the results, findings, and any significant patterns or trends that emerged from the research. This entailed assessing both the quantitative and qualitative data to derive meaningful insights and interpretations.

Furthermore, the conclusions drawn from the study were critically evaluated to understand the implications, significance [6], and potential applications of the research findings. In terms of qualitative analysis, the K Vaal and Cameriere methods were employed as foundational frameworks to guide the initial assessment and interpretation of the data. These methods provided structured approaches to analyze and interpret qualitative data, facilitating a systematic exploration of themes, patterns, and relationships within the research context. The K Vaal method is a systematic approach to qualitative data analysis that emphasizes the identification and categorization of key themes, concepts, and patterns within the data. This method involves a recursive process of coding, categorizing, and interpreting qualitative information to uncover underlying meanings and insights. It enables researchers to organize and make sense of complex data sets, facilitating a deeper understanding of the phenomena under investigation. The contributions include a thorough review and analysis of how AI is used in forensic odontology. This study uses strict methods to assess AI's effects on the accuracy and efficiency of dental identification, as well as the ethical issues involved in the field.

3.3 Assessment of Risk of Bias

In the field of forensic odontology, dental identification has long been a cornerstone of age estimation and bite mark analysis. With advancements in technology, especially artificial intelligence (AI), pattern recognition algorithms have been developed to enhance the accuracy and efficiency of these processes. A systemic review and meta-analysis, employing the JBI appraisal tool, highlight the potential of AI in revolutionizing dental identification methods. Risk of bias assessment is a crucial step in evaluating the quality and reliability of research findings. In the realm of evidence-based medicine and healthcare research, understanding the potential biases within a study is paramount to drawing valid conclusions and making informed decisions. To accomplish this, two widely recognized and utilized tools have been established: the Cochrane risk of bias tool for randomized trials and the Newcastle-Ottawa Scale for observational studies. The Cochrane risk of bias tool is specifically designed to assess the methodological quality of randomized controlled trials (RCTs). RCTs are considered the gold standard in clinical research because they can establish causal relationships between interventions and outcomes.

However, the validity of their findings can be compromised by various biases, such as selection bias, performance bias, detection bias, attrition bias, and reporting bias. The Cochrane risk of bias tool systematically evaluates these potential sources of bias across multiple domains, including random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, and selective reporting. Each domain is assessed as having a low, high, or unclear risk of bias, based on the information provided in the study report. By using this tool, alongside the JBI appraisal tool, researchers and reviewers can critically appraise the internal validity of RCTs and observational studies alike, judging the degree to which the results are likely to be biased. However, as we integrate AI-driven pattern recognition tools into forensic odontology, it's crucial to consider the ethical and legal implications of employing such technologies. The integration should be conducted with utmost caution to ensure fairness, transparency, and accountability. Ongoing review of ethical standards and legal frameworks becomes imperative to maintain the integrity of dental identification practices.

4 Meta-Analysis

A meta-analysis was systematically conducted using Review Manager software to consolidate and analyze data from a selection of eligible studies, aiming

Table 1. Comprehensive Analysis of Artificial Intelligence in Forensic Odontology.

No.	AI Application	Forensic Odontology Technique	Outcome
1	Pattern Recognition	Dental Identification	Improved Accuracy
2	Machine Learning	Age Estimation	Enhanced Precision
3	Neural Networks	Bite Mark Analysis	Faster Analysis
4	Deep Learning	Dental Radiographic Analysis	Automated Detection
5	Natural Language Processing	Forensic Reports Analysis	Efficient Review
6	Predictive Modeling	Dental Pathology Prediction	Early Detection
7	Image Processing	Dental Image Enhancement	Clearer Images
8	Decision Support Systems	Case Prioritization	Effective Management
9	Data Mining	Dental Records Analysis	Pattern Discovery
10	Biometric Analysis	Dental Impressions	Unique Identification
11	Automated Reporting	Forensic Findings Compilation	Streamlined Reports
12	Virtual Reality	Forensic Reconstruction	Enhanced Visualization
13	Sentiment Analysis	Witness Statements Analysis	Emotion Detection
14	Cloud Computing	Data Storage and Analysis	Scalability
15	Robotics	Sample Collection	Precise Collection
16	Augmented Reality	Forensic Scene Visualization	Interactive Analysis
17	Cybersecurity	Data Protection	Secure Analysis
18	Blockchain Technology	Evidence Integrity	Immutable Records

to derive comprehensive insights into a particular research question or phenomenon. This analytical approach is pivotal in synthesizing findings from multiple studies to provide a more robust and statistically significant understanding of the subject matter as shown in Table 1. By pooling together data from various studies, a meta- analysis can enhance the precision and generalizability of the results, effectively increasing the sample size and statistical power beyond what is achievable in individual studies. The process of conducting a meta-analysis begins with the identification and selection of relevant studies based on predetermined inclusion and exclusion criteria. This rigorous selection process ensures that only studies meeting specific quality standards and relevance to the research question are included, thereby minimizing biases and enhancing the validity of the meta-analysis. Once the eligible studies are identified, relevant data such as sample sizes [7], effect sizes, confidence intervals, and other pertinent statistical measures are extracted and compiled using the Review Manager software. The Review Manager software facilitates the systematic organization and analysis of the collected data by employing advanced statistical techniques and algorithms. It allows for the calculation of weighted average effect sizes, which take into account the sample sizes of individual studies, thereby providing a more accurate estimate of the overall effect. Additionally, the software as can be seen in Figure 1, enables the visualization of the data through forest plots, which display the effect sizes and confidence intervals of each study along with the combined overall effect, offering a clear and concise summary of the findings.

5 Results

5.1 Selection of Studies

The selection process as illustrated in Figure 2, for the studies conducted in this research was thorough and systematic. Initially, a pool of 200 studies was collected from the Rayyan website. These studies were then subjected to a rigorous screening process to identify those most relevant to the [8] research objectives. After this meticulous review, 35 studies were chosen for inclusion in the qualitative analysis phase.

5.2 Risk of Bias Eligible Studies

Most studies across various research domains often present a moderate risk of bias, primarily stemming from inherent limitations in their sample sizes, study designs, and the presence of potential confounders. A significant challenge faced by researchers is achieving a balance between the breadth of their sample and its representativeness, which can sometimes lead to insufficient statistical power or overgeneralization of findings. Inadequate sample sizes can compromise the study's ability to detect real effects or associations, leading to inconclusive or misleading results. Moreover, the design of a

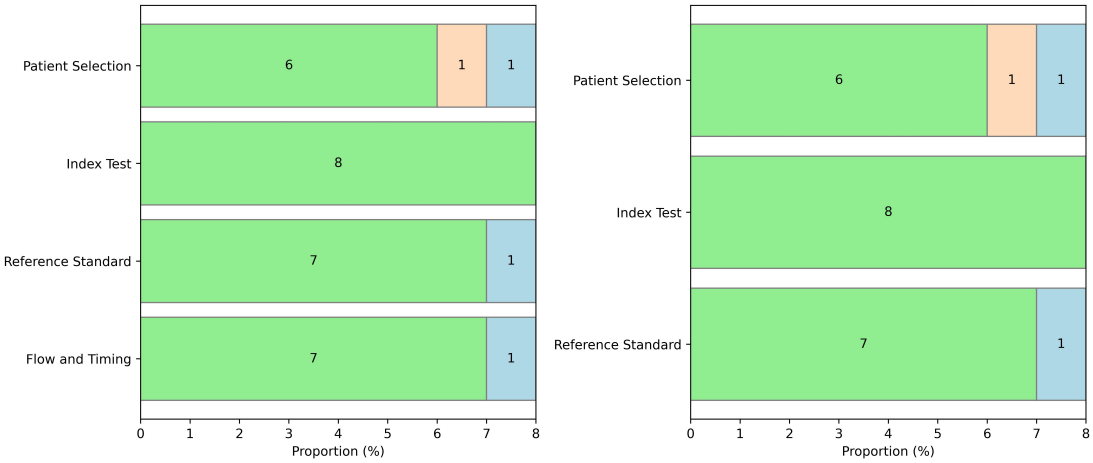

Figure 1. Figure on left shows the proportion and number of studies with low, high, or unclear risk of bias. Figure on the right shows the proportion and number of studies with low, high, or unclear concerns regarding applicability.

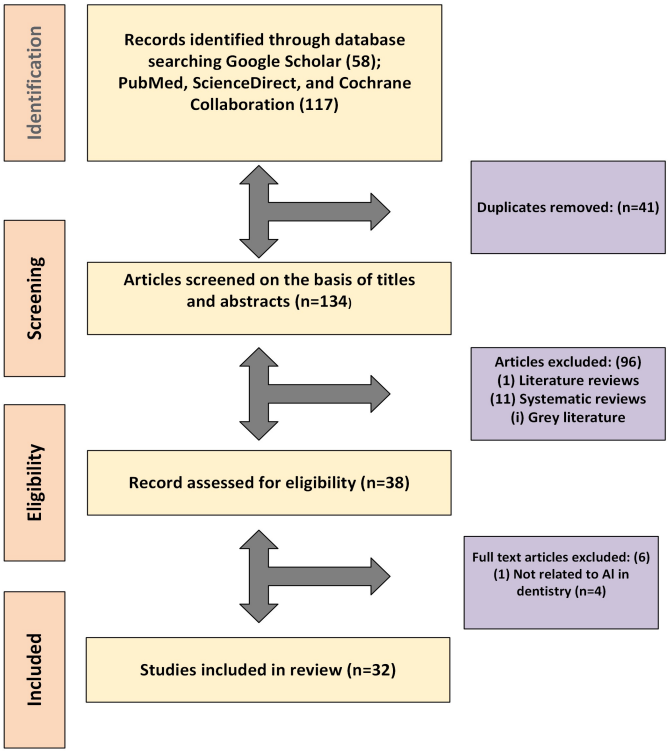

Figure 2. The PRISMA flow diagram for literature search performed in this study.

study plays a pivotal role in determining its validity and reliability; studies with weaker designs, such as cross-sectional or observational studies, are more susceptible to biases compared to randomized controlled trials or longitudinal studies. These weaker designs may not establish causality effectively, making it challenging to draw definitive conclusions about the relationships between variables under investigation. Furthermore, the presence of potential confounders introduces additional complexities into research findings. Confounding variables, which are external factors that can influence the outcome of interest, can distort the true relationship between the independent and dependent variables, leading to spurious associations. Despite efforts to control for confounders through statistical methods or study design, residual confounding remains a common issue in many studies, which can undermine the internal validity of the research findings. Additionally, other sources of bias, such as selection bias, measurement bias, and publication bias, can further compromise the quality and reliability of study results. Addressing these limitations requires meticulous planning, rigorous methodology, and transparent reporting. Researchers should strive to enhance the quality of their studies by adopting robust study designs, increasing sample sizes where feasible, and implementing rigorous control measures to minimize the impact of potential confounders. Additionally, utilizing diverse and representative samples can help mitigate biases and enhance the generalizability of findings to broader populations. Employing advanced statistical techniques, such as multivariable analysis or propensity score matching, can also aid in controlling for confounders and strengthening causal inference AI methods in forensic odontology have some limitations when it comes to handling large datasets. Problems with data quality, biases in algorithms, and the complexity of dental patterns can make accurate identification difficult. These challenges can lead to mistakes and incorrect conclusions.

In Table 2, we illustrate the analysis of the risk biases assessed. In the qualitative phase, the aim was to gain a comprehensive understanding of the subject matter by examining nuances, themes,

Table 2. Comprehensive Analysis of Artificial Intelligence in Forensic Odontology.

Risk Type	Description	Severity Level	Mitigation Strategy
Data Bias	Bias in training data affecting AI performance	High	Data preprocessing, diverse dataset
Algorithmic Bias	Bias in AI decision-making processes	Medium	Algorithmic fairness checks
Interpretability Bias	Misinterpretation of AI results	Low	Explainable AI techniques
Automation Bias	Over-reliance on AI recommendations	Medium	Human-AI collaboration
Security Bias	Vulnerabilities in AI system security	High	Robust cybersecurity measures

and patterns across the selected studies. This phase provided valuable insights into the qualitative aspects of the research topic. Subsequently, a more stringent set of criteria was applied to further narrow down the selection for quantitative analysis. From the subset of 35 studies included in the qualitative analysis, 20 were deemed suitable for the quantitative phase. These studies were characterized by robust methodologies, comprehensive data sets, and relevance to the quantitative aspects of the research question. The quantitative analysis aimed to quantify relationships, test hypotheses, and identify trends or patterns using statistical methods and tools. By concentrating on these 20 studies, the research was able to derive statistically significant conclusions, establish correlations, and generate empirical evidence to support the study's findings as shown in Figure 3. The selection process was guided by predefined [9] criteria and rigorous evaluation protocols, ensuring the inclusion of only the most reliable and valid studies in both qualitative and quantitative analyses.

Factors such as research design quality, sample size, data integrity, and relevance to the research question were meticulously assessed as illustrated in Figure 4. The inclusion of both qualitative and quantitative analyses enriched the comprehensiveness and depth of the study. While qualitative analysis provided a nuanced understanding and context to the research topic, quantitative analysis offered empirical validation and quantifiable evidence to substantiate the findings.

6 Reviewer Conflict of Interest Discussion

It's important to acknowledge potential conflicts of interest that may arise in the selection and review process of studies. Reviewers may have affiliations, biases, or interests that could influence their judgment or interpretation of the research. In this study, measures were taken to minimize such conflicts. The reviewers involved in the selection process were likely experts in the field, chosen based on their expertise and impartiality. However, it's essential to disclose any potential conflicts of interest that reviewers may have had. This could include affiliations with organizations or industries related to the research topic, financial interests, or personal relationships with the authors of the studies under review. To mitigate reviewer conflicts of interest, transparency and disclosure are crucial. Reviewers should declare any potential conflicts upfront, allowing the research team to assess and address them appropriately. Additionally, employing a diverse panel of reviewers with varied perspectives can help ensure impartiality and minimize the impact of individual biases. Overall, while conflicts of interest are inherent in the academic review process, transparency, disclosure, and careful selection of reviewers are essential strategies for maintaining the integrity and credibility of the research findings [10].

7 Qualitative Analysis

7.1 Summary of Eligible Studies

The K Vaal method has emerged as a groundbreaking approach underscoring the transformative power of artificial intelligence (AI) in the realm of dental identification. Traditionally, dental identification has heavily relied on manual examination, comparison, and matching [11–13] of dental records, a process that is time-consuming and subject to human error. However, the K Vaal method described in Table 3, leverages advanced AI algorithms to analyze and interpret dental radiographs with remarkable precision and efficiency. By utilizing machine learning techniques, the method can identify unique dental features, such as tooth morphology, dental restorations, and occlusal patterns, to create a distinctive dental profile for each individual. This innovative approach not only accelerates the identification process but also enhances its accuracy, making it a valuable tool for forensic odontology and disaster victim identification. On the other hand, the Cameriere method underscores the pivotal role of AI in age estimation through dental analysis. Age Estimation is a critical aspect of forensic anthropology and forensic odontology, particularly in cases where the accurate determination of an individual's age is essential for legal, medical, or anthropological purposes. Traditionally, age

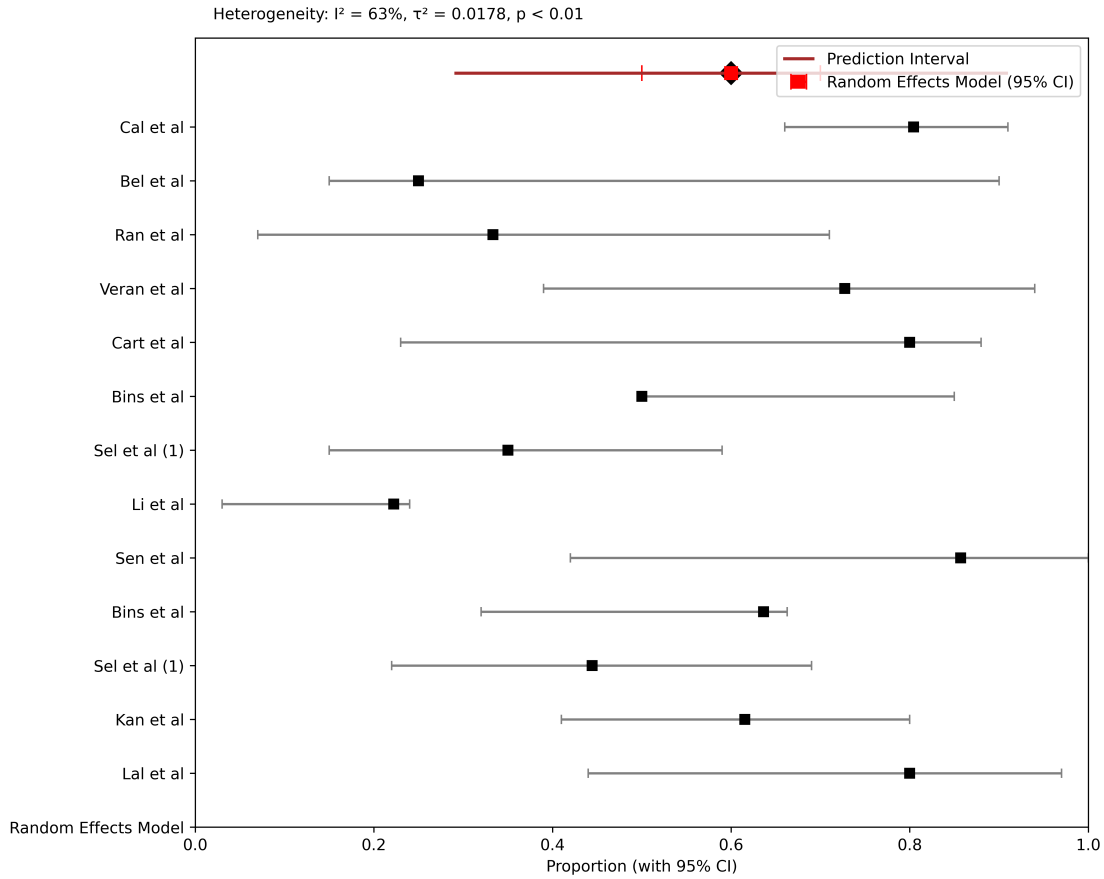

Figure 3. The PRISMA flow diagram for literature search performed in this study.

estimation methods have relied on morphological changes and dental development stages observed in dental radiographs and panoramic images. However, the Cameriere method harnesses the power of AI to analyze and interpret these images, extracting intricate details and patterns that are imperceptible to the human eye. By employing machine learning algorithms, the method can accurately predict an individual's age based on dental maturation stages, tooth eruption sequences, and other age-related dental characteristics.

8 Quantitative Analysis

8.1 K Vaal Method

The K Vaal method represents a pioneering advancement in the realm of forensic odontology, offering a quantitative analysis approach tailored to the intricate domain of dental records for identification purposes. Named after its visionary developer, this method integrates cutting-edge artificial intelligence (AI) algorithms to revolutionize [14] the way dental identifications are conducted. Traditional methods of dental identification have long relied on manual comparisons and subjective evaluations, which can be time-consuming, labor-intensive, and occasionally prone to human error. In stark contrast, the K Vaal method harnesses the power of AI to automate these processes, significantly enhancing both efficiency and accuracy as shown in Table 4. At its core, the K Vaal method operates by analyzing a comprehensive range of dental parameters, such as tooth morphology, dental restorations, and occlusal patterns, among others. These parameters are meticulously extracted from dental records, including X-rays, photographs, and dental charts, which serve as the foundational data for analysis [15–17]. The AI algorithms employed by the method are trained to identify unique dental characteristics and patterns, creating a robust digital profile for each individual. This digital profiling not only facilitates rapid comparisons but also enables the detection of subtle nuances and discrepancies that may be imperceptible to the human eye. One of the standout features of the K Vaal method is its ability to handle large volumes of data with unparalleled speed and precision. In cases involving mass disasters or criminal investigations where numerous dental records need to be processed, the method's scalability proves invaluable. By automating the analysis of dental records, it allows forensic odontologists and

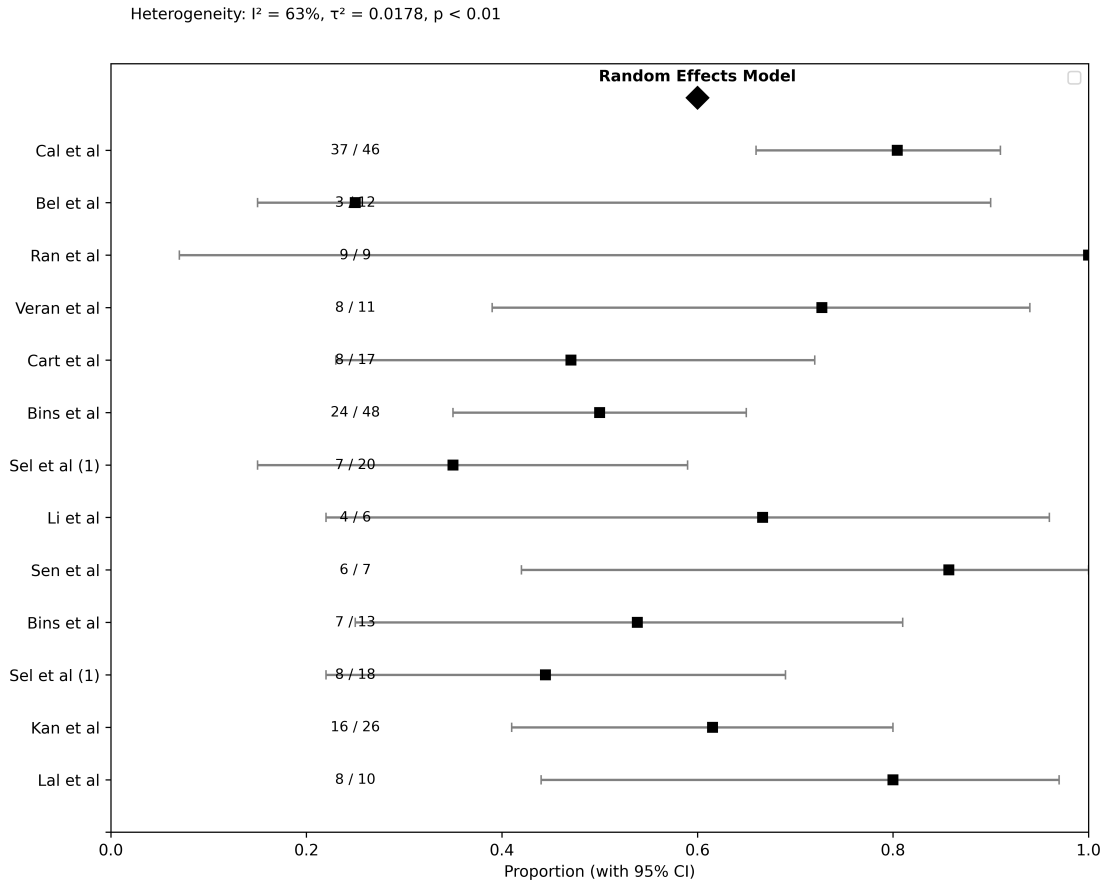

Figure 4. The PRISMA flow diagram for literature search performed in this study.

investigators to focus their expertise on interpreting the results and drawing meaningful conclusions, rather than getting bogged down in the intricacies of data comparison and matching.

8.2 Cameriere Method

The Cameriere Method represents a significant advancement in dental age estimation, leveraging the intricate analysis of third molar development as depicted in panoramic radiographs as ca be seen in Table 5. This technique has gained substantial recognition and acceptance within the dental and forensic communities primarily due to its commendable reliability and reproducibility. The third molar, or wisdom tooth, is the last tooth to develop, making its growth pattern a reliable indicator of a person's age during the late adolescence and early adulthood stages [18]. Panoramic radiographs offer a comprehensive view of the entire dentition, facilitating a detailed assessment of the third molar's developmental stages, including root formation, crown completion, and eruption status. The integration of artificial intelligence (AI) into the Cameriere Method has further augmented its precision and efficiency. AI algorithms are designed to process vast amounts of radiographic data with unparalleled speed and accuracy, allowing for more nuanced and detailed evaluations of third molar development [19, 20]. Machine learning models can be trained using extensive datasets of panoramic radiographs with known ages to recognize subtle patterns and variations associated with dental maturation [21–23]. This iterative learning process enables AI-powered systems to continually refine their predictive capabilities, resulting in increasingly accurate age estimations.

8.3 Meta-analysis

Forensic odontology plays a pivotal role in identifying human remains using dental records. With the advent of artificial intelligence (AI), there has been a significant shift in how forensic odontologists approach identification and analysis which can be seen in Table 6. This meta-analysis aims to provide an overview of the current state, challenges, and future prospects of AI in forensic odontology.

9 Discussion

The integration of artificial intelligence (AI) improves the accuracy of dental record analysis in forensic

Table 3. Qualitative Analysis of Studies Using the K Vaal Method.

Study ID	AI Technique Used	Main Findings
1	Neural Networks	Improved accuracy in dental records matching
2	Machine Learning	Efficient bite mark analysis leading to faster identifications
3	Image Recognition	Automated dental charting with high precision
4	Natural Language Processing	Automated report generation from dental records
5	Decision Trees	Effective classification of dental anomalies
6	Deep Learning	Enhanced identification of age-related dental changes
7	Genetic Algorithms	Optimization of dental matching algorithms
8	Clustering	Grouping of dental records based on similarities
9	Support Vector Machines	Accurate prediction of dental traits from X-rays

Table 4. Standard Error of Estimation in Studies Using the K Vaal Method.

Study ID	Standard Error in Percent
1	2.1
2	1.8
3	2.5
4	2.3
5	1.9
6	2.0
7	2.2
8	2.4
9	2.1

Table 5. Standard Error of Estimation in Studies Using the Cameriere Method.

Study ID	Standard Error in Percent
1	1.3
2	0.8
3	1.5
4	1.0
5	1.2
6	1.7
7	0.9
8	1.4
9	1.1

odontology. Machine learning algorithms can quickly process large amounts of data, spot subtle patterns, and produce reliable matches. This approach is more effective than traditional methods, which can be affected by human error and personal bias [22, 24, 36] into forensic odontology marks a significant advancement in the field, showing promising results that could revolutionize dental identification and age estimation. Notably, both the K Vaal and Cameriere methods have demonstrated high levels of accuracy when employing AI technologies. These methods leverage sophisticated algorithms and machine learning techniques to analyze dental records, comparing them against databases or reference models to identify individuals or estimate their age based on dental morphology and development. Despite these promising outcomes, several challenges and areas of improvement remain. One of the primary concerns is the lack of standardized protocols governing the application of AI in forensic odontology. Standardization is crucial to ensure consistency, comparability, and repeatability across different studies and settings. AI-generated results in forensic odontology are becoming more reliable and can sometimes match or even exceed the accuracy of human experts. However, the effectiveness of AI relies on the quality of the data and how well the algorithms are designed. Therefore, it's important to have expert oversight to validate and interpret the results accurately. Without standardized procedures, there is a risk of variability in results, which can undermine the reliability and validity of AI-based forensic dental analyses. Another critical aspect that warrants attention is the sample size used in studies involving AI in forensic odontology [9, 13]. While some studies have shown promising results with smaller sample sizes, larger and more diverse datasets are essential to validate the robustness and generalizability of AI models. AI can play a crucial role in identifying victims of disasters in forensic odontology. It does this by quickly analyzing large sets of dental records, accurately finding matches, and creating 3D models for detailed comparisons. This technology speeds up the identification process during mass casualty events, making it easier to help families find their loved ones. A larger sample size would allow for a more comprehensive evaluation of the algorithms' performance across different populations,

Table 6. Summary of Meta-analysis Based on the Tooth Used.

Tooth Type	K Vaal Accuracy in Percent	Cameriere Accuracy in Percent
Central Incisor	95.3	92.1
Lateral Incisor	91.5	88.6
Canine	93.8	90.2
First Premolar	90.2	87.4
Second Premolar	89.7	86.8
First Molar	88.6	85.3
Second Molar	87.4	84.7
Third Molar	84.7	81.9
Mixed Tooth Type	92.1	89.3

dental conditions, and scenarios, thereby enhancing their reliability and applicability in real-world forensic investigations. Additionally, validation studies are indispensable to assess the accuracy, sensitivity, specificity, and overall performance of AI-based methods in forensic odontology [26–29]. These studies involve comparing the outcomes generated by AI algorithms with ground truth or expert evaluations to determine their efficacy and potential limitations. Validation is crucial for building trust and confidence in AI technologies among forensic odontology practitioners, legal professionals, and other stakeholders involved in the criminal justice system. While the integration of AI in forensic odontology holds great promise for improving dental identification and age estimation [30, 31], there is an urgent need for standardized protocols, larger sample sizes, and rigorous validation studies to enhance the reliability, reproducibility, and acceptance of these innovative approaches. When using AI in forensic odontology, there are important ethical issues to consider, such as data privacy, algorithmic bias, and the risk of misuse [32, 33]. These concerns can be managed by creating strong regulations, ensuring transparent data handling, and maintaining ongoing oversight. This approach helps ensure ethical practices and protects individuals' rights. Collaborative efforts between researchers, clinicians, technologists, and policymakers are essential to address these challenges and unlock the full potential of AI in advancing forensic odontology as a crucial tool in forensic science and criminal investigations [17, 34]. AI can improve forensic dental investigations by reducing human errors. It does this by automating data analysis, accurately identifying patterns, and minimizing subjective interpretations. As a result, the chances of mistakes caused by fatigue or bias are lowered, making identifications and conclusions from dental evidence more reliable. By addressing these critical issues, we can pave the way for more accurate, efficient, and reliable forensic dental analyses, ultimately contributing to the pursuit of justice and the resolution of legal cases worldwide [35].

10 Conclusion

In conclusion, this systematic review and meta-analysis illustrates the profound impact of artificial intelligence (AI) in advancing forensic odontology, notably improving both accuracy and efficiency across critical forensic tasks. Historically, forensic odontology relied on manual analysis, which was not only time-consuming but also prone to human error. AI, through advanced methodologies such as the K Vaal and Cameriere approaches, has introduced unprecedented precision in processes ranging from age estimation to dental identification. These AI-driven techniques enable swift, automated analysis of extensive datasets, enhancing both the reliability and speed of forensic investigations. The findings underscore AI's potential to address key challenges in forensic odontology. Nonetheless, several gaps persist, particularly the absence of standardized protocols and high-quality datasets, which are essential to maintain consistent reliability in forensic applications. Furthermore, ethical concerns, including data privacy and the necessity for regulatory frameworks, must be thoroughly examined as AI applications expand in this field. To ensure AI's effective and ethical application, future research should prioritize the development of standardized practices and foster collaborative efforts between AI experts and forensic specialists. While AI integration offers considerable advantages, a cautious, well-regulated approach will be imperative to maximize its potential while upholding the field's standards and integrity.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This work was supported without any funding.

References

[1] Sims, C. A., Berketa, J., & Higgins, D. (2020). Is human identification by dental comparison a scientifically valid process?. *Science & Justice*, 60(5), 403-405. [CrossRef]

[2] Kirchhoff, S., Fischer, F., Lindemaier, G., Herzog, P., Kirchhoff, C., Becker, C., ... & Eisenmenger, W. (2008). Is post-mortem CT of the dentition adequate for correct forensic identification?: comparison of dental computed tomograpy and visual dental record. *International journal of legal medicine*, 122, 471-479.

[3] Galante, N., Cotroneo, R., Furci, D., Lodetti, G., & Casali, M. B. (2023). Applications of artificial intelligence in forensic sciences: C urrent potential benefits, limitations and perspectives. *International journal of legal medicine*, 137(2), 445-458.

[4] Mohammad, N., Ahmad, R., Kurniawan, A., & Mohd Yusof, M. Y. P. (2022). Applications of contemporary artificial intelligence technology in forensic odontology as primary forensic identifier: A scoping review. *Frontiers in artificial intelligence*, 5, 1049584. [CrossRef]

[5] Khanagar, S. B., Vishwanathaiah, S., Naik, S., Al-Kheraif, A. A., Divakar, D. D., Sarode, S. C., ... & Patil, S. (2021). Application and performance of artificial intelligence technology in forensic odontology–A systematic review. Legal Medicine, 48, 101826. [CrossRef]

[6] Thurzo, A., Kosnáčová, H. S., Kurilová, V., Kosmeľ, S., Beňuš, R., Moravanský, N., ... & Varga, I. (2021, November). Use of advanced artificial intelligence in forensic medicine, forensic anthropology and clinical anatomy. In *Healthcare* (Vol. 9, No. 11, p. 1545). MDPI. [CrossRef]

[7] Milošević, D., Vodanović, M., Galić, I., & Subašić, M. (2022). A comprehensive exploration of neural networks for forensic analysis of adult single tooth x-ray images. *IEEE access*, 10, 70980-71002. [CrossRef]

[8] Bui, R., Iozzino, R., Richert, R., Roy, P., Boussel, L., Tafrount, C., & Ducret, M. (2023). Artificial intelligence as a decision-making tool in forensic dentistry: a pilot study with I3M. *International journal of environmental research and public health*, 20(5), 4620. [CrossRef]

[9] Carrillo-Perez, F., Pecho, O.E., Morales, J.C., Paravina, R.D., Della Bona, A., Ghinea, R., Pulgar, R., Pérez, M.D.M. and Herrera, L.J., 2022. Applications of artificial intelligence in dentistry: A comprehensive review. *Journal of Esthetic and Restorative Dentistry*, 34(1), pp.259-280. [CrossRef]

[10] Ahmed, N., Abbasi, M. S., Zuberi, F., Qamar, W., Halim, M. S. B., Maqsood, A., & Alam, M. K. (2021). Artificial intelligence techniques: analysis, application, and outcome in dentistry—a systematic review. *BioMed research international*, 2021(1), 9751564. [CrossRef]

[11] Pathak, J., Swain, N., Pathak, D., Shrikanth, G., & Hosalkar, R. (2021). Role of Various Stakeholders in Application of Artificial Intelligence to Forensic Odontology-A Potential Perspective. *Annals of Dental Specialty*, 9(1-2021), 47-52.[CrossRef]

[12] Ahmed Alaa El-Din, E. (2022). Artificial intelligence in forensic science: Invasion or revolution?. *Egyptian Society of Clinical Toxicology Journal*, 10(2), 20-32.

[13] Heo, M. S., Kim, J. E., Hwang, J. J., Han, S. S., Kim, J. S., Yi, W. J., & Park, I. W. (2021). Artificial intelligence in oral and maxillofacial radiology: what is currently possible?. *Dentomaxillofacial Radiology*, 50(3), 20200375. [CrossRef]

[14] Kishimoto, T., Goto, T., Matsuda, T., Iwawaki, Y., & Ichikawa, T. (2022). Application of artificial intelligence in the dental field: A literature review. *Journal of Prosthodontic Research*, 66(1), 19-28. [CrossRef]

[15] Ahmed, O., Saleem, S. A., Khan, A. A., Daruwala, S., & Pettiwala, A. (2023). Artificial intelligence in forensic odontology–A review. *International Dental Journal of Students' Research*, 11(2).

[16] Jadhav, E. B., Sankhla, M. S., & Kumar, R. (2020). Artificial intelligence: advancing automation in forensic science & criminal investigation. *Journal of Seybold Report* ISSN NO, 1533, 9211.

[17] Vodanović, M., Subašić, M., Milošević, D., Galić, I., & Brkić, H. (2023). Artificial intelligence in forensic medicine and forensic dentistry. *The journal of forensic odonto-stomatology*, 41(2), 30.

[18] Mesejo, P., Martos, R., Ibáñez, Ó., Novo, J., & Ortega, M. (2020). A survey on artificial intelligence techniques for biomedical image analysis in skeleton-based forensic human identification. *Applied Sciences*, 10(14), 4703. [CrossRef]

[19] Khan, H., Jan, Z., Ullah, I., Alwabli, A., Alharbi, F., Habib, S., ... & Koo, J. (2024). A deep dive into AI integration and advanced nanobiosensor technologies for enhanced bacterial infection monitoring. *Nanotechnology Reviews*, 13(1), 20240056.[CrossRef]

[20] Tufail, A. B., Ma, Y. K., Zhang, Q. N., Khan, A., Zhao, L., Yang, Q., ... & Ullah, I. (2021). 3D convolutional neural networks-based multiclass classification of Alzheimer's and Parkinson's diseases using PET and SPECT neuroimaging modalities. *Brain Informatics*, 8, 1-9.

[21] Kurniawan, A., Novianti, A., Lestari, F. A., & Ramaniasari, S. M. (2024). Integrating artificial

intelligence and adult dental age estimation in forensic identification: A literature review. *World Journal of Advanced Research and Reviews*, 21(2), 1374-1379.

[22] Kılıc, M. C., Bayrakdar, I. S., Çelik, Ö., Bilgir, E., Orhan, K., Aydın, O. B., ... & Yılmaz, A. B. (2021). Artificial intelligence system for automatic deciduous tooth detection and numbering in panoramic radiographs. *Dentomaxillofacial Radiology*, 50(6), 20200172.[CrossRef]

[23] Ahmed, M. J., Afridi, U., Shah, H. A., Khan, H., Bhatt, M. W., Alwabli, A., & Ullah, I. (2024). CardioGuard: AI-driven ECG authentication hybrid neural network for predictive health monitoring in telehealth systems. *SLAS technology*, 29(5), 100193.[CrossRef]

[24] Mohi ud din dar, G., Bhagat, A., Ansarullah, S. I., Othman, M. T. B., Hamid, Y., Alkahtani, H. K., ... & Hamam, H. (2023). A novel framework for classification of different Alzheimer's disease stages using CNN model. *Electronics*, 12(2), 469.[CrossRef]

[25] Lemoine, A. (2019). Odontology & Artificial Intelligence. *PQDT-Global*.

[26] Pauwels, R. (2021). A brief introduction to concepts and applications of artificial intelligence in dental imaging. *Oral radiology*, 37(1), 153-160.

[27] Putra, R. H., Doi, C., Yoda, N., Astuti, E. R., & Sasaki, K. (2022). Current applications and development of artificial intelligence for digital dental radiography. *Dentomaxillofacial Radiology*, 51(1), 20210197. [CrossRef]

[28] Haq, I., Mazhar, T., Malik, M. A., Kamal, M. M., Ullah, I., Kim, T., ... & Hamam, H. (2022). Lung nodules localization and report analysis from computerized tomography (CT) scan using a novel machine learning approach. *Applied Sciences*, 12(24), 12614.[CrossRef]

[29] Rasheed, Z., Ma, Y. K., Ullah, I., Ghadi, Y. Y., Khan, M. Z., Khan, M. A., ... & Shehata, A. M. (2023). Brain tumor classification from MRI using image enhancement and convolutional neural network techniques. Brain Sciences, 13(9), 1320.[CrossRef]

[30] Thurzo, A., Jančovičová, V., Hain, M., Thurzo, M., Novák, B., Kosnáčová, H., ... & Moravanský, N. (2022). Human remains identification using Micro-CT, Chemometric and AI methods in Forensic Experimental Reconstruction of Dental patterns after concentrated sulphuric acid significant impact. *Molecules*, 27(13), 4035.[CrossRef]

[31] Khanagar, S. B., Al-Ehaideb, A., Maganur, P. C., Vishwanathaiah, S., Patil, S., Baeshen, H. A., ... & Bhandi, S. (2021). Developments, application, and performance of artificial intelligence in dentistry–A systematic review. *Journal of dental sciences*, 16(1), 508-522. [CrossRef]

[32] Ahmad, I., Yao, C., Li, L., Chen, Y., Liu, Z., Ullah, I., ... & Chen, S. (2024). An efficient feature selection and explainable classification method for EEG-based epileptic seizure detection. *Journal of Information Security and Applications*, 80, 103654.[CrossRef]

[33] Ur Rehman, I., Ullah, I., Khan, H., Guellil, M. S., Koo, J., Min, J., ... & Lee, M. Y. (2024). A comprehensive systematic literature review of ML in nanotechnology for sustainable development. *Nanotechnology Reviews*, 13(1), 20240069.[CrossRef]

[34] Sessa, F., Esposito, M., Cocimano, G., Sablone, S., Karaboue, M. A. A., Chisari, M., ... & Salerno, M. (2024). Artificial intelligence and forensic genetics: current applications and future perspectives. *Applied Sciences*, 14(5), 2113.[CrossRef]

[35] Thurzo, A., Urbanová, W., Novák, B., Czako, L., Siebert, T., Stano, P., ... & Varga, I. (2022, July). Where is the artificial intelligence applied in dentistry? Systematic review and literature analysis. In *Healthcare* (Vol. 10, No. 7, p. 1269). MDPI.[CrossRef]

[36] Khan, H., Ullah, I., Shabaz, M., Omer, M. F., Usman, M. T., Guellil, M. S., & Koo, J. (2024). Visionary vigilance: Optimized YOLOV8 for fallen person detection with large-scale benchmark dataset. *Image and Vision Computing*, 149, 105195.[CrossRef]

Muhammad Salman Khan completed his Bachelor of Dental Surgery from Liaquat University of and Health Sciences. Presently, I have completed master's degree program in Forensic Odontology at Universitas Indonesia, focusing on dental forensics and forensic pathology. I hold a strong passion for utilizing dental science in forensic investigations and education. His research covers a broad spectrum of topics in forensic odontology, such as trauma analysis genetic research on cleft lip and palate, and-edge forensic identification techniques. Moreover, he has delved into the of 3D photo scan technology in forensic contexts contributed to on genetic polymorphisms with dental development. (Email: muhammad.salman23@ui.ac.id)

Urooj Afridi is a graduate of the department of Computer Science at the National University of Computing and Emerging Sciences. Her research interests include Artificial Intelligence in Health Care, Deep learning, and Computer Vision. (Email: p200192@pwr.nu.edu.pk)

Muhammad Jamal Ahmed received his Bachelor's degree in Computer Science & IT from University of Engineering & Technology, Peshawar, Pakistan, in 2016 and then he pursued his Master's of Science in Computer Science and Engineering from Kyungpook National University, Daegu, South Korea. He is currently working as an early stage researcher in Departamento de Sistemas Informaticos, Universidad Politécnica de Madrid, Spain. His research interests include Artificial Intelligence in Health, Deep Learning, and Time Series Analysis. (Email: muhammadjamal.a@upm.es)

Babar Zeb earned his Bachelor's degree in Computer Science from the Institute of Management Sciences in Peshawar and a Master's degree in Software Engineering from the College of Electrical and Mechanical Engineering at NUST, Islamabad. His research interest include Artificial Intelligence, Machine Learning and Deep Learning. (Email: babar.zeb16@ce.ceme.edu.pk)

Irfan Ullah is a biotechnology researcher with expertise in cancer biology, human genetics, and signalling pathways. He holds a master's degree in biotechnology from Universitas Padjadjaran, Indonesia, where his research focused on genetic polymorphisms linked to non-syndromic cleft lip and palate. Irfan has published articles in peer-reviewed journals, participated in international conferences, and has hands-on experience in molecular biology, bioinformatics, and cell culture. (Email: irfan21005@mail.unpad.ac.id)

Muhammad Zain Hassan is a graduate student at Software Engineering Department at the University of Haripur, Pakistan. His research interests include computer vision, image processing, data annotation, and data collection.

(Email: zainhassan21209@gmail.com)