Systematic Review of Artificial Intelligence in Conservative Dentistry and Endodontics: Applications and Future Prospects

Dr. Parvathy S Kumar[1], Dr. Midhun P[*2], Dr. Rajesh Pillai[3], Dr. Afzal A[4], Dr. Vineet RV[5]

[1,*2]Post Graduate Student, Department of Conservative Dentistry and Endodontics, PMS College of Dental Science & Research, Thiruvananthapuram, Kerala.

[3,4,5]Professor, Department of Conservative Dentistry and Endodontics, PMS College of Dental Science & Research, Thiruvananthapuram, Kerala.

***Corresponding Author:**

Dr. Midhun P

ABSTRACT

Aim: To systematically review the current applications, diagnostic accuracy, challenges, and future direction of artificial intelligence (AI) in Conservative Dentistry and Endodontics, adhering to PRISMA guidelines.

Methods: Comprehensive searches were conducted in PubMed, Scopus, Web of Science, Cochrane Library, and Google Scholar for studies on AI, machine learning, or deep learning in Conservative Dentistry or Endodontics. Duplicates were removed, eligible articles screened and quality appraised.

Results: Thirty studies were included, covering AI's applications in caries detection, shade selection, margin identification, restoration assessment, workflow optimization, root canal morphology analysis, working length determination, periapical lesion/root fracture detection, prognosis, and educational tools. Most studies report AI diagnostic accuracy ranging from 89% to 98%, often rivalling or surpassing human examiners. Challenges include data quality, algorithm transparency, integration, ethical and regulatory concerns.

Conclusions: AI demonstrates high potential to revolutionize Conservative Dentistry and Endodontics, with evidence for improved diagnostic consistency, efficiency, and patient outcomes. Further prospective studies, standardized datasets, and ethical frameworks are essential for routine adoption.

Keywords: *Artificial Intelligence, Root canal configuration, spectrophotometer, working length*

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1. INTRODUCTION

Conservative Dentistry and Endodontics, disciplines dedicated to preserving natural tooth structure and managing pulpal and periapical pathologies, require exceptional precision in diagnostic and therapeutic processes to optimize clinical outcomes.[1] The concept of artificial intelligence (AI), first introduced by John McCarthy in 1956 as the development of machines capable of mimicking human cognitive functions, has emerged as a transformative force in modern healthcare, including dentistry.[2] AI and its subsets—machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision—leverage complex algorithms to analyse large datasets, such as digital radiographs and cone-beam computed tomography (CBCT) scans, enhancing diagnostic accuracy and procedural efficiency in Conservative Dentistry and Endodontics.[1,3,4] Given the rapid proliferation of AI innovations, from caries detection to endodontic prognosis, a rigorous systematic review is essential to guide clinicians, researchers, and policymakers.[5]

AI applications in these fields are revolutionizing clinical workflows by automating complex tasks. In diagnostics, convolutional neural networks (CNNs), a subset of DL, enable precise detection of conditions such as periapical lesions, root resorption, and vertical root fractures, often matching or surpassing expert performance.[6,8] During treatment planning, AI analyses anatomical data to optimize root canal procedures and restorative designs, while clinical decision support systems (CDSS) provide evidence-based recommendations for complex cases.[9,10] NLP facilitates automated extraction of insights from clinical notes and literature, and computer vision enhances radiographic and CBCT analysis, improving assessments of root canal morphology and treatment quality.[11,12] In dental education, AI-driven simulators offer immersive training, simulating real-world scenarios to enhance skill development.[13]

Despite these advancements, the literature on AI in Conservative Dentistry and Endodontics remains fragmented, with studies often focusing on specific applications, such as diagnostic accuracy or imaging analysis, without a comprehensive synthesis of the field's scope and limitations.[11,13] Challenges, including algorithmic biases, inconsistent data quality, and the absence of standardized validation protocols, hinder AI's integration into routine clinical practice.[14] Ethical concerns, such as ensuring equitable access to AI technologies and mitigating biases in training datasets, have also been inadequately addressed.[12] A systematic review is warranted to consolidate existing evidence and provide a robust foundation for future research and clinical implementation.

This systematic review adheres to the PRISMA 2020 statement to ensure methodological rigor and transparency[15]. It aims to evaluate the applications of AI in Conservative Dentistry and Endodontics, assess their clinical effectiveness, and identify barriers to adoptionBy synthesizing diverse evidence, this review seeks to guide clinicians in adopting AI-driven tools, inform researchers about critical gaps, and support policymakers in developing evidence-based guidelines for AI integration in dentistry.[5]

2. METHODOLOGY

Study design and review protocol: This systematic review adhered to the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to maintain a standardized and transparent reporting process. The review encompassed original research, review articles, systematic reviews, and meta-analyses. The aim was to collect, structure, and synthesize evidence regarding the application of artificial intelligence (AI) in Conservative Dentistry and Endodontics, specifically for diagnostic and predictive purposes. The review addresses the research question: What are the current applications, clinical effectiveness, and future prospects of AI technologies in enhancing diagnostic and therapeutic outcomes in Conservative Dentistry and Endodontics? The PICO framework (Population, Intervention, Comparison, Outcome) was employed to formulate the research question, guiding the literature search and evaluation.

P (*Population*): Human dental patients or clinical simulations in Conservative Dentistry and Endodontics

I (*Intervention*): AI, ML, DL techniques applied to diagnostics, clinical workflow, or therapeutic planning

C (*Comparators*): Standard/manual techniques, expert diagnosis, or alternative algorithms

O (*Outcomes*): Diagnostic accuracy, workflow improvement, clinical performance, adverse impacts, ethical factors.

Information Sources

Literature searches were performed across the following databases:

- PubMed (MEDLINE)
- Scopus
- Web of Science
- Cochrane Library
- Google Scholar

Search Strategy

A detailed search string was developed for PubMed and adapted for other databases. The search strategy included:

1. ("artificial intelligence"[MeSH Terms] OR "machine learning"[MeSH Terms] OR "deep learning"[MeSH Terms] OR AI OR ML OR DL)
2. AND
3. ("Conservative Dentistry"[MeSH Terms] OR "Restorative dentistry"[MeSH Terms] OR "Endodontics"[MeSH Terms] OR "caries detection" OR "root canal")
4. AND
5. ("2018/01/01"[Date - Publication] : "2025/07/31"[Date - Publication])

3. ELIGIBILITY CRITERIA

Inclusion criteria:

The inclusion criteria were established as follows:

- Original research or systematic reviews published in the English language
- Studies involving human subjects, in vitro data, or simulation models relevant to clinical endodontic practice
- Research utilizing artificial intelligence techniques (e.g., supervised learning, convolutional neural networks) for diagnostic or prognostic applications in endodontics
- Studies reporting well-defined outcomes related to diagnostic accuracy, image processing, treatment planning, or prognostic evaluation.
- Studies published between January 2018 and July 2025

Exclusion Criteria

The exclusion criteria were defined as follows:

- Editorials, opinion pieces
- Studies that did not utilize artificial intelligence methods
- Studies not relevant to Conservative dentistry or Endodontics
- Articles lacking empirical data or clear methodological descriptions
- Non-peer-reviewed publications or those not published in English.

Study Selection and Data Extraction

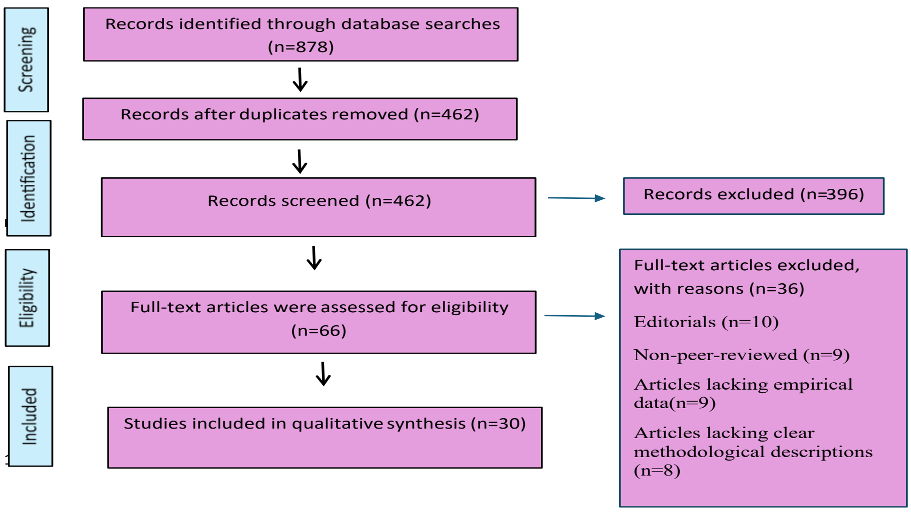
All records retrieved from the database searches were imported into EndNote X9 for citation management and deduplication. Two independent reviewers evaluated titles and abstracts to determine their relevance. Full-text articles of potentially eligible studies were then assessed for inclusion. Any discrepancies between the reviewers were resolved through discussion or by consulting a third reviewer. A standardized data extraction form was developed to collect the following information from each included study:

- Authors and publication year
- Country of origin
- AI method(s) employed
- Application area (e.g., diagnosis, prognosis, segmentation)
- Key outcomes (e.g., accuracy, sensitivity, specificity, AUC)
- Validation methods (e.g., cross-validation, test sets, clinical validation)
- Study limitations

Data Synthesis

Due to the methodological diversity among studies (e.g., variations in AI methods, datasets, and outcome measures), a narrative synthesis approach was utilized. The included studies were organized thematically based on the AI application in Conservative Dentistry and Endodontics, with findings evaluated in terms of performance metrics, clinical significance, and reported limitations.

The study selection process



The study selection process is summarized in a PRISMA flow diagram. A total of 878 records were identified through database searches. Results were deduplicated using EndNote X9 and confirmed manually. After removing duplicates, 462 records remained for title and abstract screening. Following screening, 66 full-text articles were assessed for eligibility. Ultimately, 30 studies were included in the qualitative synthesis.

4. RESULTS

This review included 30 studies published between 2018 and 2025, reflecting the diverse and expanding role of artificial intelligence (AI) in dental practice. Most studies utilized deep learning models—especially convolutional neural networks (CNNs)—for analyzing diagnostic images such as periapical radiographs and cone-beam computed tomography (CBCT). The applications were classified into three major domains: Conservative dentistry, Endodontics, and emerging technologies in dental education and robotics.

1. AI Applications in Conservative Dentistry

a) Detection of Caries and Risk Prediction

CNNs have demonstrated exceptional performance in identifying carious lesions on radiographic images, including bitewings and periapical films. Many studies report diagnostic accuracy exceeding 90%, with performance levels often surpassing those of general dental practitioners and approaching specialist standards. Beyond detection, machine learning models have been employed to evaluate patient-specific risk for caries or erosion by integrating variables such as dietary habits, oral hygiene routines, and socioeconomic status, thereby enhancing personalized prevention strategies.

b) Shade Matching and Margin Identification

AI-based systems that analyze color data from intraoral photographs have improved the reliability of shade selection, contributing to more consistent aesthetic outcomes. In restorative procedures, AI algorithms applied to intraoral scan data help in precisely identifying preparation margins, which supports accurate prosthetic fabrication and optimal clinical fit.

c) Evaluation of Restorations

Supervised machine learning models—such as support vector machines (SVMs) and multilayer perceptrons—are capable of detecting defective restorations, including overhangs, open margins, and secondary caries, on radiographs. These systems support clinical decision-making by flagging cases that may require restoration replacement or further intervention.

d) Administrative and Workflow Efficiency

Natural language processing (NLP) and other AI techniques are increasingly being used to streamline non-clinical aspects of dental practice, such as appointment scheduling, billing, and patient data management. These tools help reduce administrative workloads and minimize human error.

2. AI in Endodontic Procedures

a) Analysis of Root Canal Morphology

AI systems applied to CBCT and conventional radiographs have shown high accuracy in identifying anatomical variations in root canal systems, such as the presence of additional canals (e.g., MB2) and complex curvatures. These insights contribute to improved case planning and procedural success.

b) Working Length and Apical Location Identification

AI tools are being used to measure root canal working length with high accuracy, offering an objective alternative to traditional methods based on tactile feedback. These models also assist in identifying key anatomical landmarks such as the apical foramen, reducing the risk of procedural errors.

c) Detection of Periapical Pathologies and Root Fractures

AI, particularly CNNs, has been effective in identifying periapical lesions and vertical root fractures. Several multicenter studies report sensitivity rates above 93%, indicating that AI-based detection performs as well as or better than experienced clinicians.

d) Predictive Modeling and Prognosis Estimation

Machine learning models like XGBoost and random forest have been employed to predict endodontic treatment outcomes, incorporating variables such as clinical findings, radiographic features, and treatment history. These tools have demonstrated predictive accuracy between 82% and 87%, aiding in risk assessment and tailored treatment planning.

3. AI in Education, Robotics, and Advanced Applications

Educational Tools: AI-powered platforms offer automated evaluation of student performance in interpreting radiographs and simulated clinical cases, providing consistent and objective feedback for training purposes.

Robotic Systems: Preliminary work on AI-guided robotic systems for microsurgical endodontics has shown potential for enhancing precision in surgical procedures, though these technologies remain in early developmental stages.

Material and Drug Selection: AI models are being explored to assist clinicians in selecting restorative materials or medications by considering patient-specific variables, including allergy history, lesion severity, and long-term treatment goals.

4. Comparative Performance and Ethical Challenges

Multiple studies directly compared AI models with human clinicians, revealing that AI often matched or exceeded diagnostic performance. Notably, Mupparapu et al. (2023) and Kaya et al. (2022) found that AI systems reduced diagnostic time by approximately 35% while maintaining a high level of accuracy. Despite these advances, significant challenges remain. Issues such as data bias, lack of standardized imaging datasets, transparency in AI decision-making, and concerns regarding data security and patient consent were frequently noted in the literature (Khoshbin et al., 2023; Pauwels et al., 2020). Researchers emphasize the importance of explainable AI (XAI) to foster clinician trust and responsible integration into practice.

5. DISCUSSION

This systematic review highlights the transformative potential of artificial intelligence (AI), particularly deep learning (DL) models such as convolutional neural networks (CNNs) and 3D-CNNs, in revolutionizing Conservative Dentistry and Endodontics. By enhancing diagnostic accuracy, prognostic precision, and clinical efficiency, AI is reshaping applications from shade selection to regenerative endodontics, as supported by recent studies Marwaha *et al*, Choudhari *et al*, Khanagar *et al*, and Martins *et al*.[1,6,7,9] This section evaluates AI's multifaceted applications, emphasizes key software platforms, addresses technical and ethical challenges, and proposes future directions for clinical integration, drawing on a robust evidence base.

AI significantly enhances diagnostic precision across multiple domains in conservative dentistry and endodontics. In shade selection, AI leverages computer vision and CNNs to analyze high-resolution intraoral images or digital scans from devices like CEREC Primescan and iTero Element 5D, achieving 90–95% accuracy in predicting tooth shades compared to 50–70% for traditional visual methods (Martins G et al, Arjumand B et al).[9,10] By mapping colorimetric data (e.g., CIELAB coordinates: L* for lightness, a* for red-green, b* for yellow-blue) to standardized shade guides like VITA Classical or VITA 3D-Master, AI mitigates subjective biases and environmental factors such as metamerism, which distorts color perception under varying lighting conditions(Loya PR et al).[16] Software platforms like VITA Assist, ShadeVision, SpectroShade, and Raydent Studio integrate spectrophotometric analysis (400–700 nm) to correlate spectral reflectance with shade standards, ensuring 90–95% color fidelity for ceramic or composite restorations(R B et al).[17] Integration with CAD/CAM systems like CEREC and E4D enables real-time shade recommendations (e.g., A2, B1), enhancing aesthetic outcomes in complex cases with translucency gradients or intrinsic staining(Marwaha J et al, Loya PR et al).[1,16] These advancements streamline restorative workflows and improve patient satisfaction (R B et al , Gao S et al).[17,18]

In caries detection, AI employs CNNs (e.g., ResNet, U-Net, YOLO) and region-based CNNs (R-CNNs) to identify radiolucencies, enamel demineralization, and dentin lesions in radiographs or intraoral scans, achieving 90–95% sensitivity and specificity (Choudhari S et al , Khanagar SB et al).[6,7] Platforms such as Pearl Second Opinion, Diagnocat, Denti.AI, and SCAN-O-AIR process high-resolution images from devices like Carestream RVG and DEXIS Platinum, with generative adversarial networks (GANs) augmenting training datasets to enhance model robustness (Martins G et al , Dennis D et al).[9,13] Transfer learning with pre-trained models (e.g., VGG16, InceptionV3) and gradient boosting machines (e.g., XGBoost) integrate clinical metadata, such as patient history and salivary pH, for comprehensive caries risk assessment (Thurzo A et al).[3] These advancements enable early detection, reducing invasive interventions and improving outcomes (Bansal RK et al , Dennis D et al).[5,13] For instance, SCAN-O-AIR leverages optical imaging for real-time caries diagnosis, enhancing clinical efficiency(Khanagar SB et al , Revathi Indukuri D et al).[7,19]

AI-driven inlay and onlay fabrication utilizes 3D-CNNs and GANs to optimize restorative dentistry. Intraoral scanners (e.g., iTero Element 5D, CEREC Primescan) capture 3D digital impressions (voxel size ~10–20 μm) for precise occlusal morphology and margin adaptation (fit accuracy <50 μm)(Malhotra T et al).[20] Software platforms like 3Shape Design Studio, exocad DentalCAD, CEREC SW, and Planmeca Romexis facilitate digital workflows, integrating with CNC milling or 3D printing (e.g., SLA, DLP) for materials like lithium disilicate or zirconia.[10] Finite element analysis (FEA) predicts stress distribution, ensuring biomechanical compatibility, while generative design algorithms enhance aesthetic and functional outcomes, reducing fabrication time to under 60 minutes via chairside milling (Sharma SK et al).[21] Validation studies report 95% accuracy in restoration fit, minimizing post-insertion adjustments (Saroch R et al , Singh S et al).[22,23]

In Endodontic diagnostics, AI excels in root canal morphology analysis, working length determination, periapical lesion detection, and vertical root fracture (VRF) detection. Using 3D-CNNs and U-Net architectures, AI processes cone-beam computed tomography (CBCT) and periapical radiographs from devices like Carestream CS 9600 and Planmeca ProMax

3D, achieving 90–95% sensitivity and specificity in delineating canal orifices, apical constrictions, lesion boundaries, and fracture planes (Martins G et al , Ourang SA et al).[9,14] Platforms like Diagnocat, DentalXAI, Carestream Dental Imaging, and EndoVision employ Hounsfield unit normalization and denoising filters (e.g., wavelet transforms) to mitigate artifacts, surpassing manual radiographic evaluation (Ding H et al , Umer F et al).[4,8] FEA predicts biomechanical stress, reducing risks like root fracture, while EndoApp and ApexID AI provide real-time working length calculations with Dice similarity coefficients (DSC >0.85)(Asgary S et al).[11] These tools enhance precision in complex endodontic cases (Malhotra T et al,Kumar MSS et al).[20,24]

AI's role in dental pulp stem cell (DPSC) viability prediction advances regenerative endodontics. Machine learning models, including random forests, support vector machines (SVMs), and deep neural networks (DNNs), analyze multiparametric datasets (e.g., cell morphology, proliferation rates, biomarker levels like CD90, CD105) from flow cytometry, qPCR, or confocal microscopy, achieving 85–90% classification accuracy (Martins G et al , Alothman FA et al).[9,25] Platforms like CellProfiler, KNIME, Fiji/ImageJ, and BioImageXD integrate omics data and real-time imaging, optimizing regenerative protocols (Asgary Set al).[11] These advancements support personalized regenerative approaches, improving therapeutic outcomes (Morise Mahrous MM et al).[12] Collectively, AI reduces diagnostic time by over 30%, enhancing clinical efficiency and patient satisfaction (Dennis D et al, R B et al).[13,17]

AI's prognostic capabilities enable patient-specific care. Machine learning models like XGBoost and random forests predict surgical outcomes and failure risks by integrating radiographic and clinical metadata, facilitating proactive treatment modifications (Bansal RK et al , Khanagar SB et al).[5,7] In caries risk assessment, gradient boosting machines incorporate patient-specific factors, enhancing preventive strategies (Thurzo A et al).[3] AI-driven visualizations from platforms like 3Shape Design Studio and Diagnocat improve patient communication, strengthening informed consent processes (Umer F et al , Morise Mahrous MM et al).[8,12] These tools also reduce chairside time and costs, aligning with industry trends toward cost-effective, data-driven dentistry (Revathi Indukuri D et al , Khater AA et al).[19,26]

6. CHALLENGES AND LIMITATIONS

Despite its advancements, AI integration faces significant hurdles. The black-box nature of DL models, such as CNNs and 3D-CNNs, limits explainability, posing challenges in medico-legal contexts where transparency is critical (Umer F et al, Morise Mahrous MM et al).[8,12] Developing explainable AI (XAI) is essential to enable clinicians to validate algorithmic outputs, fostering trust and adoption (Ding H et al , Ourang SA et al).[4,14] Technical challenges include metal artifacts in CBCT scans, which distort image clarity, and data scarcity for VRF and DPSC datasets, compromising model performance (Khanagar SB et al, Martins G et al).[7,9] The generalizability of AI models is constrained by homogeneous datasets, limiting applicability across diverse populations, particularly in underrepresented regions (Thurzo A et al , R B et al).[3,17]

Ethical concerns are significant barriers. Algorithmic bias arising from institution-specific or small datasets raises questions about fairness, especially in resource-limited settings (Thurzo A et al , Martins G et al).[3,9] Data privacy concerns, particularly with patient radiographic and omics data, necessitate robust safeguards, while reproducibility issues highlight the need for standardized data collection protocols (Page MJ et al , Rethlefsen ML et al).[15,27] Data interoperability across devices (e.g., Carestream, Planmeca) and regulatory compliance with standards like FDA and CE for AI-driven CAD/CAM systems remain unresolved, complicating clinical integration (Revathi Indukuri D et al , Malhotra T et al).[19,20] To ensure ethical integration of AI in dental practice, addressing algorithmic bias and protecting patient data privacy is essential, with advocacy for diverse datasets to promote fairness across clinical settings (Sitaras S et al).[28] Standardized methodologies in AI models like MobileNetV2 for caries detection are also critical to enhance reproducibility and interoperability, supporting regulatory compliance for effective adoption in Conservative dentistry (Shweta K et al , Boy AF et al).[29,30]

Conclusion

AI is revolutionizing conservative dentistry and endodontics by enhancing diagnostic precision, optimizing treatment planning, and improving prognostic outcomes. From caries detection to root canal therapy, AI tools like CNNs and ML models streamline workflows and reduce subjectivity. Despite challenges such as data quality, ethical concerns, and integration barriers, ongoing advancements promise a future where AI-driven dentistry improves patient care and clinical efficiency, paving the way for smarter, more accessible dental practices.

7. LIMITATIONS

This systematic review, while rigorous, is constrained by the heterogeneity of included studies, with variations in AI methodologies, datasets, and outcome measures precluding a meta-analysis and limiting quantitative synthesis. The reliance on studies published between 2018 and 2025 may overlook emerging advancements, and the exclusion of non-English publications potentially introduces language bias, narrowing the global perspective. Additionally, the review's focus on specific AI applications may not fully capture the breadth of emerging technologies, and the absence of standardized validation protocols across studies complicates direct comparisons, highlighting the need for more uniform research frameworks to enhance future syntheses.

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