

Review Article

Applications of Generative Artificial Intelligence in Dental and Orthodontic Education: A Systematic Review of Opportunities, Challenges, and Future Perspectives

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Generative artificial intelligence (AI) has rapidly been introduced in medical and dental education, creating opportunities for students in how to learn and engage with educational content. Through its ability to generate educational content, deliver immediate feedback, simulate clinical situations, and support individual learning, generative AI has the potential to reshape conventional approaches to dental and orthodontic education.

This systematic review aimed to examine the applications of generative AI in dental and orthodontic education and to evaluate its educational opportunities, challenges, and outcomes, with particular emphasis on learning and knowledge retention, clinical decision-making, practical skills, educational assessment, and feedback. A systematic review was conducted using the PICO framework and in accordance with PRISMA guidelines. Major scientific databases, including PubMed, Cochrane Library, ERIC, CINAHL, IEEE Xplore, ISI, ISC, and Magiran, were systematically searched for studies published between 2010 and 2024. After screening and eligibility assessment, 17 studies were included in the qualitative synthesis. Risk of bias and certainty of evidence were evaluated using appropriate methodological assessment tools.

The review studies mentioned that AI-based educational tools may enhance student engagement, learning, and selected clinical competencies through personalized learning, immediate feedback, educational chatbots, and simulated learning environments. AI tools also excelled at answering specialized dental and orthodontic questions and supporting students in making clinical decisions. However, the evidence also highlights important concerns regarding the accuracy and reliability of AI-generated outputs, data privacy, algorithmic transparency, excessive reliance on AI, faculty preparedness, and limitations in technical infrastructure.

Generative AI can generate a textbook orthodontic treatment plan in seconds, but it cannot teach a student how to calm a terrified patient sitting in the dental chair. We have to explicitly protect time for chairside manner, active listening, and human connection.

1. Introduction

Generative artificial intelligence (AI) refers to a group of technologies that can create new content, including text, images, code, and other forms of digital output, by learning patterns from existing data (Gupta et al., 2024; Haase & Hanel, 2023). The development of large language models and applications such as ChatGPT has broadened the use of AI beyond conventional analytical and diagnostic functions toward education, content generation, human-computer interaction, and decision-making support (Gupta et al., 2024; Sridharan & Sequeira, 2024; Dixon, 2021). In medical education, these developments have created new ways to interact and allow students to engage with content.

In medical education, generative AI models can be used to develop and reorganize learning materials, respond to students'

questions, develop clinical scenarios, provide feedback, and support various forms of assessment (Dixon, 2021; Reddy, 2024). Current evidence indicates that AI has the potential to change traditional teaching and learning processes; however, its educational effectiveness is strongly influenced by teaching design, human supervision, data quality, and the AI literacy of users (Cook, 2024; Yim et al., 2024; Dixon, 2021; Reddy, 2024). The key issue is not therefore whether learners have access to advanced technologies, but how these technologies are deliberately incorporated into the educational process.

This issue is particularly relevant in dental education, where students must acquire theoretical knowledge, clinical reasoning, practical competencies, and decision-making in complex clinical contexts.

Orthodontic education adds further demands, because students must acquire theoretical knowledge while developing competencies in diagnostic data interpretation, cephalometric analysis, treatment planning, and evaluation of clinical outcomes. Accordingly, technologies capable of creating interactive learning environments, clinical scenarios, developing digital educational resources, and providing adaptive feedback based on learner performance may offer valuable opportunities to supplement traditional educational approaches (Karabacak et al., 2023; Ye et al., 2024; Giordano et al., 2021).

In recent years, the use of AI applications in orthodontics has expanded across several domains, including cephalometric analysis, diagnosis, treatment planning, digital education, and simulated learning environments (Karabacak et al., 2023; Giordano et al., 2021; Bragazzi & Garbarino, 2024). At the same time, generative AI tools such as ChatGPT have emerged as novel educational interfaces. Studies assessing the performance of large language models in responding to dental and orthodontic questions have reported that these systems can generate acceptable responses in many situations; however, the quality and accuracy of their outputs may vary depending on the nature of the question, the area of specialization, and the clinical context (Lin et al., 2023; Mengi et al., 2024). Consequently, the incorporation of generative AI into dental education should be accompanied by critical appraisal, scientific verification, and appropriate expert supervision.

A particularly important feature of generative AI in education is its potential to facilitate the personalisation of learning. Intelligent systems can adapt the content and learning pathways to the current knowledge, performance, and individual needs of learners. Through continuous interaction, these systems can also provide additional training and feedback opportunities (Yim et al., 2024; Dixon, 2021). In dental education, training these skills can support the explanation of complex concepts, clinical scenario testing, self-directed learning, and the provision of continuous training support (Daraqel et al., 2024; Gandedkar et al., 2021). However, a distinction must be made between generating answers and achieving meaningful learning. If students rely excessively on readily available AI-generated answers, their active engagement, critical thinking, and independent problem-solving skills may be weakened (Higgins et al., 2022).

Despite these training opportunities, the integration of generative AI also raises a number of important concerns. Privacy and data security are among the most important concerns, especially when information relating to patients is entered into AI systems (Pedersen, 2023; Ye et al., 2024). In addition, the complexity and, in some cases, limited transparency of AI models may make it difficult to understand the processes that underlie specific answers or recommendations (Wells et al., 2024; Cochrane Training, 2024). Another challenge that requires careful consideration both in the education and clinical setting is the potential to produce inaccurate or misleading information, reproduce biases in training data, and encourage over-reliance on AI-generated outcomes (Higgins et al., 2022; Duggal & Tripathi, 2024; Schwendicke et al., 2020).

The successful integration of AI into education also depends on factors that go beyond the technical capabilities of the systems themselves. Faculty and student preparedness, AI literacy, access to the relevant technological infrastructure, and developing clear educational and ethical policies are key factors of successful implementation. Research on medical education in the era of AI has highlighted the need to reconsider existing curricula and to prepare future health workers to work effectively in an AI-enabled clinical setting (Yadalam et al., 2024; Miramadi et al., 2024). In this context, AI literacy should go beyond basic knowledge of AI technologies and include knowledge of their limitations, critical assessment of the output of AI, data ethics, protection of privacy, and professional accountability (Miramadi et al., 2024).

At the level of the education system, the challenges of implementing generative AI go beyond technical considerations. Infrastructure constraints, implementation costs, insufficient governance frameworks, lack of adequately trained staff, and resistance to technological change can all hinder the sustainable and efficient adoption of these technologies. Multidisciplinary perspectives on generative AI stressed the importance of considering opportunities, challenges, and wider impacts in parallel in research, practice, and policymaking (Carroll & Borycz, 2024). Similarly, research examining the requirements for developing and implementing generative AI has highlighted the importance of infrastructure, governance, implementation capacity, and human resources development (Chan & Hu, 2023). These considerations are particularly relevant in the field of dental education, where technological innovation needs to be kept in line with educational standards, professional ethics, and requirements for protecting health-related data.

Despite the growing interest in generative AI, evidence on its real educational effectiveness in dental and orthodontic education is still limited and evolving. Several studies reported potential benefits in areas such as learning, learning to work, responses to specialised questions, and support for clinical skills, while others identified concerns about accuracy, reliability, user acceptance, ethical considerations, and infrastructure readiness (Daraqel et al., 2024; Chau et al., 2024; Gandedkar et al., 2021; Lin et al., 2023; Mengi et al., 2024; Duggal & Tripathi, 2024; Schwendicke et al., 2020; Schwendicke et al., 2023). Moreover, the considerable heterogeneity of study designs, interventions in the AI field, outcome measures, and characteristics of participants makes direct comparison and generalization of the findings difficult.

Therefore, a systematic review to synthesise and critically evaluate the available evidence on the use of generative artificial intelligence in dental and orthodontic education is justified. The aim of this review was to examine the educational applications of generative AI and to evaluate its related opportunities, challenges, and outcomes. Particular attention was given to four main areas: learning outcomes and knowledge retention; clinical decision-making and practical skills; educational assessment and feedback of training; and user acceptance and training readiness. In addition, ethical, technological, and implementation issues related to the integration of generative AI into dental and orthodontic education were examined.

2. Methods

2.1. Study Design

This study was carried out as a systematic review to identify, assess, and synthesise the available evidence on the use of generative artificial intelligence (GAI) in the field of dentistry and orthodontics. The review looked at the educational applications of generative artificial intelligence and their reported effects on learning and retention, clinical decision-making, practical and clinical skills, learning outcomes and feedback, as well as the acceptance and readiness of users for the use of AI technologies.

The review process has been structured in line with the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA) Guideline. The identification and selection process included the search of databases, initial screening, a title and abstract search, a full-text assessment, and the final inclusion of eligible studies in the qualitative synthesis.

As the studies included differed significantly in terms of research design, study population, artificial intelligence technologies, intervention approaches, and outcome measures, statistical aggregation of findings was not considered appropriate. The evidence has therefore been synthesised in a qualitative and thematic way. The studies included were grouped under common themes, and the findings, differences between studies, methodological limitations, and gaps in the existing evidence were reviewed.

2.2. Research Question and PICO Framework

The main research question was: How has generative artificial intelligence, including tools such as ChatGPT and other generative language models, been used in dental education, especially orthodontics, and what are the results in terms of learning, retention of knowledge, clinical decision-making, practical skills, and learning experience?

The PICO framework has been used to structure the research question and to define the scope of the literature search and the criteria for eligibility.

Population: The population included dental and orthodontic students, students undergoing clinical dental training, faculty members and instructors, and other persons involved in the dental and orthodontic education process.

Intervention: The intervention of interest was the teaching use of generative artificial intelligence and related technologies, including large language models (LLMs), chatbots, educational chatbots, and other generative systems, used to create or deliver educational content, facilitate learning interactions, answer questions, create learning scenarios, provide feedback, or support learning activities. The conceptual distinction between generative artificial intelligence and other forms of artificial intelligence has been maintained. Technologies such as cephalometric analysis, artificial intelligence-based diagnosis, virtual reality, and augmented reality have not been automatically categorised as generative artificial intelligence. Their findings were considered only if they were directly relevant to the educational objectives of the review as such.

Comparator: When a comparator group or condition was available, the results of AI-based learning were compared with

conventional learning methods, face-to-face instruction, lectures, traditional learning resources, standard clinical education, or other relevant learning approaches. In studies without a comparator group, evidence on user experience, performance, attitudes, and perceptions of the use of artificial intelligence was considered in the qualitative synthesis.

Outcomes: The main outcomes included learning and retention, educational performance, clinical decision-making, practical and clinical skills, performance in examinations, and quality and timeliness of feedback from training. Secondary outcomes included learner engagement, learning experience, attitudes towards and acceptance of artificial intelligence, educational preparedness, AI literacy, privacy, reliability, ethical concerns, and barriers to implementation.

2.3. Search Strategy

A systematic literature search was carried out using the databases and information sources provided in the protocol of the study. This included the databases PubMed, Cochrane Library, ERIC, CINAHL, IEEE Xplore, ISI, ISC, and Magiran. These databases have been selected to provide a wide range of medical and dental sciences, education, educational technologies, and research in the field of artificial intelligence.

In order to enhance the sensitivity of the search, the names of some commonly used generative artificial intelligence tools have been included, where appropriate. In addition to the electronic search of the database, the reference lists of relevant studies were checked manually in order to identify potentially eligible studies which could not be obtained by the database search.

The survey covered studies published from 2010 to 2024. Language restrictions were applied in accordance with a predefined search strategy and eligibility criteria.

2.4. Inclusion and Exclusion Criteria

The following criteria were used: Studies included those that addressed the use of AI, and specifically generative AI, in dental education, orthodontic education, or educational processes related to dental sciences; employed or assessed a generative AI-based tool or system, such as LLMs, ChatGPT, educational chatbots, or similar generative systems, in an educational setting; involved dental or orthodontic students, learners, instructors, faculty members, or other participants in dental education; examined at least one educational outcome, such as learning, educational performance, knowledge retention, clinical decision-making, practical skills, feedback, engagement, or attitudes towards AI; contained a comparator or comparison condition where appropriate.

Studies were excluded if they met any of the following criteria: Related solely to AI applications in settings outside of education or outside of dentistry and orthodontics; considered AI in the context of diagnosis, prediction, or treatment without a clear educational component; were opinion articles, editorials, letters, or theoretical papers that lacked evaluable empirical findings; did not provide full text; did not provide adequate methodological information or results for evaluation and data extraction; or included populations, interventions, or outcomes that fell outside the scope defined by the research question and PICO framework.

2.5. Study Screening and Selection

The selection of the studies was carried out in a sequential manner. Initially, all records identified by means of a database search were reviewed, and those deemed irrelevant during the pre-screening procedure were deleted. Subsequently, the titles and abstracts of the remaining records were screened against predefined exclusion and inclusion criteria. At this stage, studies which did not demonstrate sufficient relevance to the research question were excluded.

In a second phase, the full text of potentially eligible studies was collected and evaluated against the pre-defined eligibility criteria. Reasons for exclusion at the full-text stage have been noted. Finally, the qualitative summary included studies that met all eligibility criteria. In total, 500 records were identified in the initial search. After the initial screening process, 51 records were still available for further examination. Subsequently, 35 studies were sourced and fully peer-reviewed for eligibility, of which 17 studies met the pre-defined criteria and were included in the qualitative synthesis.

As the included studies showed significant methodological and clinical variability, the final synthesis of evidence was done in a qualitative rather than a statistical meta-analysis.

2.6. Data Extraction and Synthesis

After selecting the final studies, a predetermined framework was employed to extract pertinent information. The primary findings, assessed outcomes, educational domain, comparator or comparison method, participant characteristics, type and application of the AI technology, publication year, study design, and bibliographic characteristics were all included in the extracted data.

The findings were organized into the following major thematic areas:

- Applications of generative AI in dental and orthodontic education;
- Effects on learning and knowledge retention;
- Effects on clinical decision-making and practical and clinical skills;
- Role of generative AI in educational assessment and feedback;
- Acceptance, attitudes, and educational readiness;
- Technological, ethical, and implementation challenges; and
- Requirements for integrating AI into educational curricula.

Given the diversity of the studies included in terms of design of the study, population, artificial intelligence technology, intervention approach, and outcome measures, the findings were synthesised primarily by qualitative and thematic analysis. Studies were compared on common themes, with particular attention being paid to consistency of findings, conflicting evidence, methodological limitations, and gaps in the existing literature.

A conceptual distinction was made between evidence directly related to generative AI and evidence related to broader

2.7. Risk of Bias Assessment and Certainty of Evidence

The risk of bias and the reliability of the evidence was assessed in the light of the design and methodological characteristics of the studies included. As the studies differed significantly in their design, population, intervention, implementation procedures, and outcome measures, the quality of the studies was assessed by the characteristics of each study rather than by using a single assessment tool for all studies.

Assessment of potential sources of bias was conducted using the Cochrane Risk of Bias 2 (RoB 2) framework for randomized controlled trials, and the Newcastle–Ottawa Scale (NOS) for non-randomized and observational studies, where the study design aligned with the structure of the instrument (Higgins et al., 2022; Wells et al., 2024).

The methodological characteristics of each study included were examined, including the design of the study, the sampling procedures, the allocation or composition of the groups, the intervention and comparator characteristics, the methods for measuring the results, and the completeness of the reported data. If the information required for the assessment of a particular methodological area was not sufficiently reported, this uncertainty was taken into account in the interpretation of the methodological quality. No conclusions have been drawn beyond the information provided in the original studies.

The overall certainty of evidence for the primary outcomes was assessed with the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework (Cochrane Training, 2024), which takes into account risk of bias, inconsistency, indirectness, imprecision, and potential publication bias. However, due to the high degree of heterogeneity in the study designs, interventions, populations, and outcome measures, the certainty of evidence was not assumed to be consistent across all outcomes and was interpreted in the context of the nature of the available evidence, as this was a qualitative and thematic synthesis rather than a quantitative meta-analysis.

Another separation was made between generative and non-generative AI. Studies of technologies like cephalometric analysis, AI-based diagnosis, virtual reality, or augmented reality were included only if their educational aims were related to the research question, and their results were not extrapolated to generative AI unless the characteristics of the underlying technology were taken into account (Nordblom et al., 2024; Liu et al., 2023; Gandedkar et al., 2021; Schwendicke et al., 2020). However, the results of the quality and certainty assessments were interpreted with caution due to the small number of studies included, substantial methodological heterogeneity, and differences in interventions and outcome measures.

4. Results

4.1. Study Identification and Selection Process

A systematic search of predefined databases turned up 500 alerts in total. After the initial screening, which included the deletion of duplicate records and records clearly not relevant to the review, 51 records were retained for the purpose of a title and abstract examination. These records were then assessed against predefined inclusion and exclusion criteria. Following the title and abstract screening, 35 articles were selected for a full-text evaluation. The full text was assessed for its relevance to dental and orthodontic education, the study population, the interventions, and the results reported.

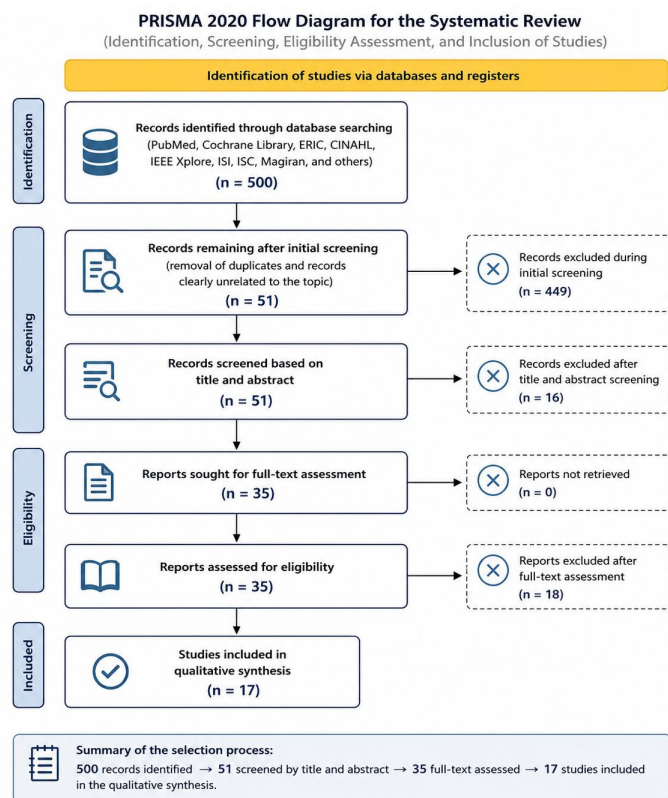


Figure 1. PRISMA 2020 flow diagram showing the identification, screening, eligibility assessment, and inclusion of studies in the systematic review.

Thus, of the 500 records identified through the initial search, 51 (10.2%) proceeded to title and abstract screening, 35 (7.0%) underwent full-text assessment, and 17 (3.4%) were ultimately included in the qualitative synthesis.

4.2. General Characteristics of the Included Studies

A total of 17 studies met the eligibility criteria and were included in the qualitative synthesis. The included studies demonstrated substantial heterogeneity in terms of research objectives, study designs, participant characteristics, types of artificial intelligence technologies, educational settings, and outcome measures. This heterogeneity reflected differences in the technologies investigated, the characteristics of learners and professionals, the educational contexts in which AI was applied, and the methods used to evaluate its effects.

Of the 17 included studies, 10 were cross-sectional or survey studies, 3 were review studies, 2 were experimental studies, and 2 were qualitative studies.

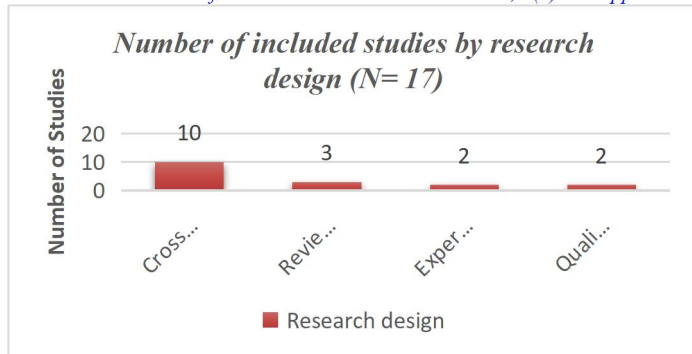


Figure 2. Distribution of the included studies according to study design.

The study population included dental and orthodontic students, postgraduate students, faculty members, orthodontic practitioners, and other professions involved in the field of education and health care. Some studies have directly explored the use of chatbots and language models as teaching tools (Fang et al., 2025; Ghorashi et al., 2023), while others have explored the knowledge, experience, attitudes, and readiness of participants in the use of artificial intelligence in dentistry and orthodontics (Lin et al., 2023; Mengi et al., 2024).

The technologies studied in the cohort were diverse, including large-scale language-based models, generative chatbots, intelligent learning systems, digital learning technologies, virtual and augmented reality, as well as selected applications of artificial intelligence for clinical analysis and decision-making (Karanth et al., 2024; Fang et al., 2025; Ghorashi et al., 2023; Gandedkar et al., 2021). Among the studies specifically testing generative AI, some looked at the performance of ChatGPT and Google Bard in answering orthodontic questions (Daraqel et al., 2024), and another looked at the performance of generative AI in dental licensing exams (Chau et al., 2024).

These findings were later categorized into the following major thematic domains: applications of generative AI in dental and orthodontic education, effects on learning and knowledge retention, clinical decision-making and clinical skills, educational assessment and feedback, acceptance, attitudes, and educational readiness, and ethical, technological, and implementation-related challenges. Due to the high level of heterogeneity between the included studies in terms of study design, intervention characteristics, populations, measurement instruments, and outcome variables, statistical pooling was not deemed appropriate, and the findings were synthesized qualitatively and thematically.

4.3. Applications of Generative Artificial Intelligence in Dental and Orthodontic Education

The findings showed that generative artificial intelligence has the potential to support dental and orthodontic education in a variety of educational roles. The main applications identified were the creation and explanation of educational content, interactive answers to learners' questions, support for self-directed learning, the creation of educational and clinical scenarios, feedback, assessment support, and teaching and pedagogical support.

One of the most frequently discussed applications was the use of artificial intelligence-powered chatbots as interactive tools to

support learning. Fang and colleagues examined the use of artificial intelligence chatbots in clinical dental education and reported on their potential to facilitate interaction and teaching (Fang et al., 2025). Similarly, Ghorashi and others examined the potential applications of artificial intelligence-powered chatbots in medical education, in particular their ability to answer questions interactively and support learning (Ghorashi et al., 2023).

Orthodontic education has also explored large language models, with Daraqel et al. comparing ChatGPT and Google Bard for responding to general orthodontic questions and finding that both models were able to generate useful responses for some specialized questions, but not consistently across topics (Daraqel et al., 2024), indicating that generative AI may be a useful supplementary educational resource for reviewing specialized content, but the outputs should be critically assessed and verified against reliable scientific sources and, where necessary, expert judgment.

Other studies reviewed digital technologies, virtual reality, and augmented reality in orthodontic education (Karanth et al., 2024; Gandedkar et al., 2021), which may offer the potential for simulation, repeated practice, and exposure to educational or clinical procedures; however, these technologies were not considered direct evidence of the effectiveness of generative AI and were therefore interpreted in the present review as complementary components of the digital transformation of dental education.

Overall, the findings suggest that generative artificial intelligence can extend its educational role beyond mere information retrieval by facilitating interactive learning, self-directed learning, scenario-generating, feedback, and selected assessment and reasoning activities. However, the educational value of these applications seems to depend on the quality of the artificial intelligence system, the pedagogical design, the way the technology is integrated into learning activities, and the degree of appropriate human oversight.

4.4. Effects on Learning and Knowledge Retention

One of the main themes identified across the studies was the promotion of learning. Available evidence suggests that interactive artificial intelligence tools can facilitate self-directed learning by providing fast access to information, explaining concepts, answering questions, and enabling learners to engage in repeated interaction and practice (Fang et al., 2025; Ghorashi et al., 2023).

The ability of intelligent systems to provide explanations that can be adapted to different levels of learner knowledge and individual learning needs is a potential mechanism for these benefits (Karabacak et al., 2023; Xu et al., 2024). This ability may be particularly important in the context of dental and orthodontic teaching, where students have to combine theoretical concepts with clinical applications. Immediate access to answers can also facilitate independent learning. During the course of the study, students can formulate questions and use interactive artificial intelligence tools to clarify concepts or to address areas of uncertainty (Fang et al., 2025; Ghorashi et al., 2023). Such interaction can increase exposure to educational material and provide additional training opportunities.

The evidence, however, is not sufficient to show a definitive effect of generative AI on long-term knowledge retention, as most of the studies included examined short-term outcomes such as response quality, examination performance, learning experiences, or learner engagement, and the evidence is not sufficient to show that generative AI consistently results in sustained improvements in long-term knowledge retention. In addition, allowing ready-made answers without any limit may decrease active processing and critical thinking if AI is being used inappropriately. Therefore, the educational value of generative AI is not only a function of its ability to generate answers but also how learning activities are designed and the level of engagement.

4.5. Effects on Decision-Making and Clinical Skills

Another important topic was the potential role of artificial intelligence and intelligent technologies in supporting clinical decision-making and developing clinical skills. AI-based tools can provide information, create training scenarios, answer clinical questions, and allow learners to interact with hypothetical cases, thus providing additional opportunities to practice aspects of clinical decision-making (Fang et al., 2025; Xu et al., 2024).

In orthodontic education, digital and simulated environments can provide opportunities for the practice of complex procedures, without relying solely on direct patient interaction (Karanth et al., 2024; Gandedkar et al., 2021). Such an environment can facilitate repetition of exercises and help students to develop stronger links between theoretical knowledge and clinical application.

Generative language models could also be employed to aid reasoning through clinical scenarios, question-and-answer exercises, and educational content analysis. However, there is some evidence of their performance on orthodontic questions showing that the quality of responses is not always high and that it could depend on the nature, complexity, and subject-specific content of the question (Daraqel et al., 2024).

Therefore, the data support the use of AI in a complementary role for education rather than as a replacement for clinical education or professional judgment, and this distinction is particularly relevant to dentistry and orthodontics, in which practical competence develops through real clinical experience or appropriately validated simulation, direct observation of performance, and expert feedback.

In the field of cephalometric analysis, there was also a relatively positive attitude towards applications with artificial intelligence support, although concerns remain about reliability, accuracy, and implications of AI for the future of the profession (Lin et al., 2023). Therefore, AI-supported training should be carried out in a context where clinical judgement, professional judgement, and clinician accountability are at the centre of decision-making.

4.6. Role in Educational Assessment and Feedback

Generative AI has also shown potential in the area of learning outcomes. One of the studies included assessed the performance of generic artificial intelligence models in dental licensing tests and found that they could answer a certain number of specialised questions, although performance varied

depending on the type of questions and the content area (Chau et al., 2024). This finding shows both the capacity of language models to process specialised learning issues and the challenges they pose to traditional assessment approaches. As students increasingly have access to tools that can generate answers, assessments based primarily on reproducing factual information may be less effective in distinguishing between memorized and recalled facts.

The findings therefore support a stronger focus on evaluation approaches that assess reasoning, problem-solving, knowledge application, clinical case analysis, and practice. Within these approaches, artificial intelligence can act as both an evaluation subject and a complementary tool to support evaluation activities.

Artificial intelligence can also contribute to providing rapid and interactive feedback in education. Chatbots powered by artificial intelligence can answer students' questions and provide instant explanations (Fang et al., 2025; Ghorashi et al., 2023). However, feedback generated by artificial intelligence should be seen as a complement to, rather than a substitute for, feedback provided by qualified instructors. The possibility of inaccurate, incomplete, or mis-contextual responses makes human supervision of learning assessment and feedback processes of particular importance (Xu et al., 2024; Schwendicke et al., 2023).

4.7. Acceptance, Attitudes, and Educational Readiness

The studies included showed that acceptance of artificial intelligence is not uniform among dentists and orthodontists. Although participants generally acknowledged the potential benefits of artificial intelligence in training and in professional practice, concerns were also raised about accuracy, reliability, professional implications, and over-reliance on technology (Lin et al., 2023; Mengi et al., 2024). Lin et al. in their study on cephalometric analysis with AI, report familiarity with and relatively positive attitude towards AI among orthodontists and students. However, concerns have been raised about the reliability of this technology and its possible implications for the future role of orthodontists (Lin et al., 2023). Similarly, Mengi et al. reported differences in knowledge, attitudes, and levels of AI use among members of the orthodontic community (Mengi et al., 2024).

These findings indicate that AI readiness is about more than just access to technological tools; factors including AI literacy, prior experience, trust in the technology, faculty preparedness, awareness of the technological limits, and having clear frameworks for responsible use may all affect acceptance and readiness, and readiness should encompass the ability to evaluate generated outputs for errors or misinformation, compare AI-generated information with trusted scientific sources, and recognize the ethical implications of AI use (Xu et al., 2024; Schwendicke et al., 2023).

4.8. Challenges and Ethical Considerations

In addition to the potential educational benefits, the studies included identified a number of ethical, technological, and implementation challenges. The most important concerns were privacy and data security, the accuracy and reliability of the output produced, transparency, algorithmic bias, over-reliance on artificial intelligence, and professional liability (Chen &

Protecting patient information is of particular importance when artificial intelligence is used in an educational or clinical setting. Use of clinical data or personally identifiable information without appropriate safeguards may increase the risk of improper disclosure and misuse. Therefore, the introduction of artificial intelligence in training should be accompanied by clear policies on data management, confidentiality, access, and the protection of health information (Chen & Esmaeilzadeh, 2024; Ye et al., 2024; Duggal & Tripathi, 2024).

Another important challenge is the reliability of the outputs generated by artificial intelligence. Generative models may produce answers that appear consistent and authoritative, but contain incorrect, incomplete, or misleading information. This is particularly important in the context of dental and orthodontic education, where the uncritical acceptance of incorrect information may contribute to the development of faulty knowledge or inappropriate clinical judgement (Daraqel et al., 2024; Schwendicke et al., 2020).

Another concern is the over-reliance on generative artificial intelligence. Unstructured or inappropriate use can reduce the opportunities for independent thinking, problem-solving, and critical involvement. Training activities should therefore encourage students to analyse AI-generated information, challenge its validity, compare it to authoritative sources, verify the underlying claims, and critically assess the output produced (Larson et al., 2024).

At the institutional level, limited technical infrastructure, lack of clear policies, lack of training of faculty, and lack of human capacity may also be a barrier to sustainable implementation (Xu et al., 2024; Schwendicke et al., 2020; Schwendicke et al., 2023). The integration of generative artificial intelligence in dental and orthodontic education should therefore be seen not only as a technological intervention but also as a wider educational, ethical, organisational, and professional process.

4.9. Quality and Certainty of the Evidence

Given that the included studies were heterogeneous with respect to their study designs and the nature of the evidence that they generated, the methodological quality of the included studies was considered on a study-by-study basis, and a single approach to methodological assessment was not deemed appropriate for all studies. Note, however, that we cannot report definitively on the precise distribution of randomized and non-randomized studies, or the exact risk-of-bias ratings and quality scores, because we did not extract and evaluate the methodological characteristics of all 17 included articles.

For randomised controlled trials, the Cochrane Risk of Bias 2 (RoB 2) tool is suitable for assessing areas such as the randomisation process, the deviation from the intended intervention, the missing outcome data, the measurement of the results, and the reported outcome (Higgins et al., 2022). In observational or other non-randomised studies, the Newcastle-Ottawa Scale (NOS) may be used if the design of the study complies with the assessment framework of the study (Wells et al., 2024).

The reliability of the evidence should also be taken into account in relation to the specific results and the body of evidence contributing to each result. The GRADE framework considers in its assessment of certainty factors such as the risk of bias, inconsistency, indirectness, inaccuracies, and possible bias in the publication (Cochrane Training, 2024). Therefore, given the significant variability between the studies included, it cannot be assumed that the reliability is consistent across all results.

Overall, the results must be carefully interpreted because of the variety of study designs, participant populations, AI technologies, intervention approaches, and outcome measures. There is some evidence that generative AI has some promising educational applications and potential benefits, but it is not yet clear that it is truly effective or superior to traditional educational methods. For example, to determine how generative AI affects learning and knowledge retention, clinical skills, and clinical decision-making, future studies with more rigorous designs, adequate sample sizes, validated outcome measures, longer follow-up periods, and transparent methodological reporting are needed.

5. Discussion

5.1. Educational Potential of Generative Artificial Intelligence in Dental and Orthodontic Education

The results of this systematic review indicate that generative artificial intelligence (AI) and selected complementary AI-based and digital technologies have significant potential to support and transform several aspects of dental and orthodontic education. The main applications identified in the studies included were the creation and explanation of educational content, interactive responses to learners, support for self-directed and individualised learning, feedback, development of educational and clinical scenarios, and assistance in selected assessment and decision-making activities (Fang et al., 2025; Xu et al., 2024; Ghorashi et al., 2023).

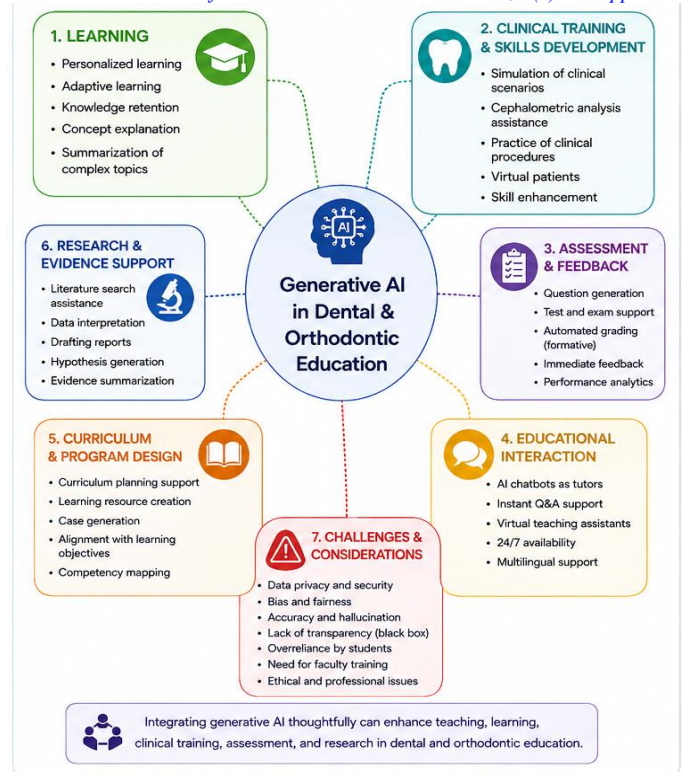


Figure 3. Applications of Generative Artificial Intelligence in Dental and Orthodontic Education.

However, the educational value of generative AI goes beyond text generation or quick answers. Its ability to facilitate interactive and flexible learning environments in which students can ask questions, explore alternative explanations, engage with educational content repeatedly, and receive immediate responses is its greater potential. In dental and orthodontic education, where students are required to integrate theoretical knowledge with clinical reasoning and practical application, these characteristics could prove to be highly valuable.

The studies included show that AI-based tools can provide additional support for understanding theoretical concepts, answering questions from learners, clinical scenarios, and facilitating self-directed learning (Fang et al., 2025; Ghorashi et al., 2023). In the field of orthodontic education, the integration of artificial intelligence, virtual reality, and augmented reality in the digital learning environment can further enhance the possibilities for simulation, repetition, and practice of selected procedures (Gandedkar et al., 2021). These observations are broadly in line with previous research highlighting the potential of artificial intelligence to contribute to changes in the educational environment of medicine and dentistry (Karabacak et al., 2023; Sridharan & Sequeira, 2024; Yadalam et al., 2024; Schwendicke et al., 2020).

However, the results do not suggest that AI should replace traditional educational processes; a clear distinction should be kept between applying AI to enhance education and handing over education to AI, and generative AI can enhance information access and content generation, facilitate educational interaction, but cannot supplant instructor oversight, professional judgment, human interaction, or real clinical experience (Pedersen, 2023; Yu & Guo, 2023; Karabacak et al.,

2023; Miramadi et al., 2024). Thus, the educational model that seems to fit best is one in which AI is used as an adjunct to a human-focused educational paradigm.

5.2. Personalization and Adaptive Learning

Personalisation is one of the most important learning opportunities in artificial intelligence. Conventional learning approaches often provide students with similar content and learning activities, despite differences in prior knowledge, learning rates, and individual learning needs. Intelligent systems can partly address these differences by providing explanations, supplemental materials, and learning activities that answer students' questions and perform well (Yu & Guo, 2023; Sridharan & Sequeira, 2024).

This ability may be particularly important in orthodontic education, where students must integrate theoretical principles with diagnostic information interpretation and clinical decision-making. Areas such as dental and skeletal malocclusion diagnosis, cephalometric analysis, treatment planning, and interpretation of clinical data require students to move constantly from theoretical understanding to clinical application. Digital and smart learning environments can offer further opportunities for repetition, practice, and individualised explanations in these fields (Karanth et al., 2024; Gandedkar et al., 2021).

Another potential advantage is the speed of interaction. Students can ask questions during independent study and get quick answers, which could increase exposure to learning material and promote self-directed learning (Fang et al., 2025; Ghorashi et al., 2023). Personalisation should not, however, be construed as proof of fully automatic or independently effective learning. Generative language models can produce inaccurate, incomplete, or oversimplified information, which makes the involvement of instructors crucial in setting learning goals, choosing reliable sources, guiding learning activities, and evaluating AI-generated content (Larson et al., 2024; Bragazzi & Garbarino, 2024; Miramadi et al., 2024).

The educational value of personalisation therefore depends not only on the technical ability of artificial intelligence systems to adapt their responses, but also on the quality of the learning framework in which they are used.

5.3. Simulation and Clinical Skills Education

One of the most challenging aspects of dental and orthodontic education is the development of practical and clinical skills, as clinical competence needs repetition of practice, observation, feedback, technical performance, and exposure to clinical situations, which is impossible to do for theoretical knowledge. Digital technologies, simulation, virtual reality, augmented reality, and some AI-based applications can offer students controlled environments in which to practice some procedures and diagnostic activities before or in addition to clinical exposure (Karanth et al., 2024; Gandedkar et al., 2021).

In these environments, learners can repeat procedures, make mistakes, and become accustomed to clinical processes without relying solely on actual patients. There is also existing evidence that digital and simulated environments can support practical-skills education and enhance learner readiness for

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clinical environments (Karanth et al., 2024; Fang et al., 2025; Gandedkar et al., 2021).

These applications may be especially applicable to cephalometric analysis, image interpretation, malocclusion diagnosis, and treatment planning in orthodontic education. The relatively positive attitudes reported by some orthodontic professionals and students toward AI-assisted cephalometric analysis may also suggest an initial level of acceptance of AI-supported technologies in orthodontic education and practice (Lin et al., 2023).

However, simulation is not a good substitute for authentic clinical experience. Dental and orthodontic practice is not just about technical knowledge or procedural competence. Clinical performance also includes appropriate responses to human and contextual factors, fine motor skills, communication with patients, professional judgment, and appropriate responses to human and contextual factors. Thus, simulated environments should be considered as complementary educational tools that complement, rather than replace, supervised clinical training.

5.4. Impact on Clinical Decision-Making

Another area where AI can provide training support is in developing clinical decision-making skills. Students of dentistry and orthodontics need to learn to collect and interpret patient information, integrate diagnostic findings, consider alternative treatment options, and justify clinical decisions based on scientific evidence. In the educational context, artificial intelligence systems can facilitate the practice of these processes by organising information, creating hypothetical clinical scenarios, presenting alternatives, and supporting structured reasoning (Giordano et al., 2021; Bragazzi & Garbarino, 2024).

Studies evaluating language models in the context of dentistry and orthodontics have shown that these systems can provide acceptable answers to some specific questions, but their performance is not consistent across topics and types of questions (Daraqel et al., 2024; Chau et al., 2024). This variability is important, as a linguistically conclusive answer cannot necessarily be equated to a scientifically or clinically correct one.

The educational value of generative artificial intelligence in clinical decision-making may therefore lie less in providing a final answer and more in facilitating the clinical decision-making process. For example, students can use artificial intelligence to create hypothetical cases, formulate analytical questions, compare diagnostic and therapeutic options, and explore alternative paradigms. The resulting results can then be compared to scientific literature and to expert advice, enabling students to critically assess the accuracy and limitations of the information generated by artificial intelligence (Larson et al., 2024).

On the other hand, uncritical dependence on AI-generated responses may encourage cognitive dependence on automated systems and reduce opportunities for independent reasoning. Hence, dental students in AI-enabled educational environments should consider the competency of verifying, evaluating, and critically assessing AI-generated information as a crucial competency (Larson et al., 2024; Miramadi et al., 2024).

5.5. Educational Assessment and Feedback

These results also show that generative AI may be used for assessment and feedback in educational settings, as language models can answer exam questions, generate education scenarios, and, under certain conditions, provide initial feedback to learners (Ghorashi et al., 2023; Chau et al., 2024). Chau et al. tested generative AI models on dental licensing examinations and showed that these systems could answer a significant proportion of specialized questions, but performance was affected by question type and examination conditions (Chau et al., 2024). Generative AI may be particularly useful for formative feedback because it can provide rapid responses.

On the other hand, the application of generative AI to formal assessment poses concerns, because model performance varies, there is a risk of the model being wrong, there is a risk of bias, and it is uncertain whether AI-generated outputs are valid and reliable (Bragazzi & Garbarino, 2024; Chau et al., 2024). Therefore, AI should be considered at this time to be primarily a supportive aspect of assessment and feedback, and final determinations of student achievement and competence should be the responsibility of trained human evaluators.

The advent of generative artificial intelligence also has implications for the design of evaluation itself. If students have access to systems that are able to produce complex answers, assessments based mainly on memorization of information may be less informative about real understanding. Therefore, greater emphasis can be put on reasoning, problem-solving, knowledge transfer, clinical case analysis, and demonstration of practical competence.

5.6. Ethical and Technological Challenges

But major issues with ethics, technology, and organization will need to be solved for this integration of generative AI and related technology in dental or other educational settings (Chen & Esmailzadeh, 2024; Ye et al., 2024; Duggal & Tripathi, 2024; Schwendicke et al., 2020; Schwendicke et al., 2023; Thurzo et al., 2022; Surlari et al., 2023).

When AI systems are used in clinical or educational settings involving patient information, clinical images, treatment records, or other sensitive data, patient privacy is particularly important (Chen & Esmailzadeh, 2024; Ye et al., 2024; Duggal & Tripathi, 2024). Therefore, clear procedures governing data collection, storage, access, confidentiality, and protection of health information are necessary for AI to be properly implemented.

Another critical issue is the validity of the information that generative models generate: the responses that they produce can be linguistically fluent and even sound authoritative but can be factually incorrect, incomplete, or poorly contextualized (Daraqel et al., 2024; Schwendicke et al., 2020). Thus, in addition to scientific verification and expert oversight, responsible educational use of generative models also requires careful attention to the context in which the model is deployed.

Another concern is algorithmic bias. Artificial intelligence systems trained or evaluated using datasets that do not adequately represent different populations, clinical conditions,

Finally, lack of AI literacy among students and faculty can hamper efficient and responsible use of these technologies. Access to an artificial intelligence tool does not necessarily mean the ability to assess the accuracy or adequacy of its output. Therefore, users must understand the capabilities and limitations of artificial intelligence systems, identify potential errors, verify information with reliable sources, and understand the ethical implications of their use (Xu et al., 2024; Schwendicke et al., 2023; Miramadi et al., 2024).

5.7. The Role of Faculty and the Changing Position of Traditional Education

Integration of artificial intelligence into dental education should not be seen as a process which removes the role of teachers. Rather, it can help to gradually transform the educational role of teachers. As students gain more access to generative artificial intelligence, digital resources, and other information sources, the role of information transfer itself will become less central to the role of instructors. Instead, greater emphasis can be put on designing meaningful learning experiences, coaching students, assessing information, monitoring clinical performance, and developing critical thinking and judgement (Karabacak et al., 2023; Xu et al., 2024; Schwendicke et al., 2023).

This transformation may give more opportunities to devote greater educational attention to competencies like clinical reasoning, problem-solving, communication with patients, professional responsibility, and practical skills that cannot be adequately developed through automated information delivery. Nevertheless, a sufficient level of faculty preparedness is necessary for this transition. Uncertainty regarding the educational and professional implications of these technologies, a lack of knowledge about AI, and a lack of confidence in their use may hinder successful integration (Xu et al., 2024; Mengi et al., 2024; Schwendicke et al., 2023). Instead of being a mere activity that takes place after the introduction of AI technology, faculty development should be regarded as a crucial element of AI implementation.

The future role of the dental educator may consequently be characterized less by the exclusive transmission of information and more by facilitation, mentorship, critical evaluation, clinical supervision, and responsible integration of technology into learning.

5.8. Requirements for Integrating AI into the Curriculum

For dental and orthodontic education to be effective, the integration of AI tools into existing courses is not enough. In addition to educating students about how to use AI systems, educational programs should be designed to ensure that students are able to use AI in accordance with professional and ethical responsibilities, recognize their limitations, protect sensitive information, and critically evaluate their outputs (Xu et al., 2024; Schwendicke et al., 2023).

AI literacy may be considered a new dimension of competence to be integrated into dental and orthodontic education, and relevant educational content may include basic concepts of AI, generative models, responsible application of AI tools, validation of results, algorithmic bias, data privacy and security, ethics, and AI applications in educational and clinical settings (Xu et al., 2024; Schwendicke et al., 2023).

What is important is that AI literacy should not remain a theoretical exercise. Students should be able to interact with AI tools in a controlled learning environment, analyse their

responses, compare the generated information with reliable scientific sources, identify errors, and justify whether a particular AI-generated response is appropriate or not. These activities can help develop a critical AI literacy, combining technical competences with scientific judgement, critical thinking, and professional responsibility (Larson et al., 2024; Miramadi et al., 2024). A successful and sustainable implementation also depends on wider institutional conditions. Adequate technical infrastructure, reliable access to technical resources, clear data protection and responsible use policies, administrative support, and permanent faculty development.

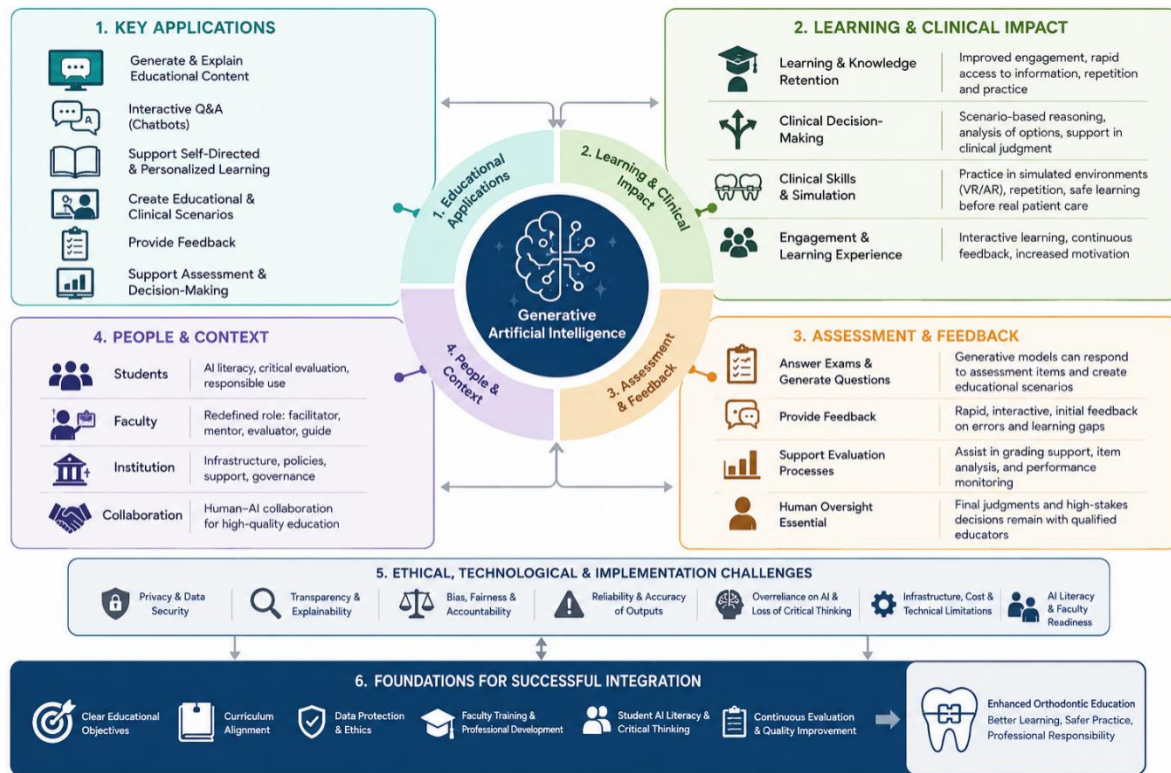


Figure 4. Conceptual Framework for Integrating Generative Artificial Intelligence into Dental and Orthodontic Education.

The findings suggest that the incorporation of generative AI into dental and orthodontic education is not merely a technological intervention but a more comprehensive educational transformation that necessitates convergence between curriculum design, faculty development, student AI literacy, ethical governance, data protection, technological infrastructure, and ongoing evaluation, under which conditions AI may be a beneficial adjunct to traditional education and continue to maintain the primacy of human expertise, clinical judgment, and professional accountability.

Overall Interpretation

In general, this systematic review showed that generative AI is a promising educational tool with potential applications in dental and orthodontic education, but it has not been shown to be superior to traditional education, and there are concerns about heterogeneity of evidence, reliability of AI, privacy, ethics, user readiness, and overreliance, with more research needed in well-designed comparative and longitudinal studies using measurable outcomes such as learning, knowledge

retention, clinical reasoning, practical competence, and long-term educational effectiveness.

6. Future Perspectives

Future use of generative artificial intelligence in dental and orthodontic education is likely to lead to the development of a more intelligent, interactive, personalised, and multimodal learning environment. In this environment, generative artificial intelligence can be integrated with e-learning platforms, clinical simulation, 3D learning resources, and data analysis tools to provide a more co-ordinated and flexible learning experience (Nordblom et al., 2024; Yadalam et al., 2024; Karanth et al., 2024).

One important future direction is the shift from mainly text-based systems to multimodal artificial intelligence systems capable of processing and generating a wide range of educational and clinical information. In orthodontic training, these skills may be particularly relevant in areas such as cephalometric analysis, image interpretation, diagnostic reasoning, and treatment planning (Nordblom et al., 2024; Liu et al., 2023; Lin et al., 2023).

Another important direction is the development of more reliable and, where possible, explainable AI systems. Greater

8. Conclusion

The evidence examined in this systematic review indicates that generative artificial intelligence has considerable potential to complement and strengthen dental and orthodontic education. The main potential applications identified include supporting personalized learning, providing rapid and interactive feedback, facilitating practice of clinical decision-making, generating educational content and scenarios, supporting certain assessment processes, and enhancing selected digital and simulation-based learning environments.

However, the available evidence remains insufficient to establish the definitive long-term effectiveness of generative AI on learning, knowledge retention, clinical skills, or clinical performance. The heterogeneity of the included studies, the limited number of experimental investigations, differences in outcome measures, and the rapid evolution of AI technologies require cautious interpretation of the findings. In addition, a clear distinction should be maintained between evidence concerning generative AI and evidence derived from other forms of artificial intelligence in dentistry and orthodontics to avoid inappropriate generalization.

The successful integration of generative AI into dental and orthodontic education should therefore not be based on replacing faculty members or eliminating conventional educational approaches. Rather, AI should be integrated as a complementary and human-centered educational technology. Achieving this goal requires the development of AI literacy among students and faculty members, appropriate faculty training, clear ethical and educational policies, protection of sensitive data, adequate technical infrastructure, and reliable mechanisms for evaluating and verifying AI-generated outputs (Xu et al., 2024; Schwendicke et al., 2023; Miramadi et al., 2024).

Accordingly, the future of dental and orthodontic education may be better understood not as a competition between humans and artificial intelligence, but as a purposeful collaboration between the two. In such a model, AI can enhance educational interaction, information processing, personalization, and analytical support, while educators and clinical professionals remain responsible for professional judgment, ethical decision-making, patient communication, and clinical supervision.

Future research should employ longitudinal, controlled, and multicenter designs with standardized and validated outcome measures to determine the effectiveness, safety, sustainability, and educational value of generative AI in real-world dental and orthodontic education. Such evidence will be essential for determining how generative AI can be integrated responsibly and effectively into future curricula.

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transparency in AI-generated results may help educators and students better understand, evaluate, and verify the information provided by these systems and assess its consistency with established scientific evidence (Bragazzi & Garbarino, 2024; Schwendicke et al., 2020).

Future research should move beyond predominantly descriptive and cross-sectional investigations toward longitudinal studies, controlled experimental designs, and multicenter research. Such studies should evaluate outcomes including knowledge retention, transfer of learning and skills to clinical settings, quality of clinical decision-making, educational performance, and, where appropriate, implications for patient safety.

From an educational and institutional perspective, the development of clear frameworks for the responsible use of AI will also be important. Such frameworks should clarify the appropriate boundaries of AI use, the responsibilities of students and faculty members, data-protection requirements, procedures for evaluating and citing AI-generated content, and expectations regarding the use of AI in educational assessment (Schwendicke et al., 2023; Miramadi et al., 2024; Taghizadeh & Khordmandnia, 2024).

Ultimately, the desirable future of generative AI in dental and orthodontic education is likely to depend on effective collaboration between humans and AI rather than the replacement of one by the other. Within such a model, AI can support content generation, information processing, personalized learning, and educational interaction, while instructors and clinical specialists remain responsible for professional judgment, ethical decision-making, human interaction, and clinical supervision.

7. Strengths and Limitations of the Study

The systematic review is strong because it focused on generative AI specifically in dental and orthodontic education, including learning, knowledge retention, clinical skills, decision-making, assessment, feedback, and user acceptance, utilized multiple databases and the PICO framework for a structured approach to evidence identification and synthesis, and differentiated generative AI from conventional AI applications such as cephalometric analysis, AI-assisted diagnosis, VR, and AR.

Several limitations must be noted, however. Generative AI in dental education is a nascent and rapidly evolving field with a relatively small number of studies, significant heterogeneity in methods, populations, technologies, and outcomes that precluded statistical pooling, and many included studies that were cross-sectional, survey-based, or non-experimental, which offer limited evidence about long-term effects on learning, clinical skills, or professional performance, and some that assessed attitudes and perceptions rather than true educational or clinical outcomes.

Finally, rapid changes in artificial intelligence models may reduce the reproducibility and universality of findings over time. Overall, therefore, the evidence should be interpreted with caution. Future research should take advantage of larger samples, standardised methods, validated results, longer follow-up, and direct comparison with conventional teaching approaches.

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Conflict of Interest

The authors declare that they have no conflict of interest related to this research.

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