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REVIEW ARTICLE

ARTIFICIAL INTELLIGENCE IN DENTAL IMPLANTOLOGY:A SCOPING REVIEW.

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Abstract

Background: Artificial intelligence (AI) is rapidly transforming dental implantology by introducing advanced approaches for diagnosis, treatment planning, surgical guidance, and outcome prediction. The integration of AI with cone-beam computed tomography (CBCT), intraoral scanning, digital workflows, and computer-assisted implant surgery has created new opportunities for personalized and precision-based implant treatment. However, the current evidence remains heterogeneous, and a comprehensive mapping of AI applications in implant dentistry is needed. **Objective:** This scoping review aimed to map the current evidence regarding the applications of artificial intelligence in dental implantology, with particular emphasis on diagnostic performance, digital implant planning, surgical assistance, prediction models, and future clinical perspectives.

Methods:A scoping review was conducted according to the methodological framework of the Joanna Briggs Institute (JBI) and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. A comprehensive literature search was performed in PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. Studies investigating AI-based technologies applied to dental implantology were considered eligible. Data were extracted regarding study characteristics, AI algorithms, clinical applications, imaging modalities, outcomes, and reported limitations.

Results: The available evidence indicates that AI applications in implant dentistry are primarily focused on automated radiographic analysis, anatomical structure recognition, implant position optimization, guided surgery, and prediction of clinical outcomes. Deep learning algorithms, particularly convolutional neural networks (CNNs), have demonstrated promising performance in CBCT-based anatomical identification and treatment planning. Emerging applications include AI-assisted prosthetic design, peri-implant disease prediction, and integration with three-dimensional digital workflows. Nevertheless, limitations related to dataset quality, external validation, standardization, and clinical implementation remain.

Conclusion: Artificial intelligence represents a promising technological advancement in dental implantology, supporting a transition toward personalized, data-driven, and precision-based implant treatment. Further prospective clinical studies and standardized validation protocols are required before widespread routine application of AI systems in implant practice.

Keywords: Artificial intelligence; dental implants; implant dentistry; deep learning; digital dentistry; CBCT; computer-assisted implant surgery; scoping review.

1.INTRODUCTION

Dental implantology has evolved considerably over the last several decades, transitioning from a primarily surgical discipline focused on

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osseointegration toward a digitally integrated, patient-centered, and precision-based field. The predictability of implant-supported rehabilitation has been enhanced through advances in implant surface technology, three-dimensional imaging, guided surgery, computer-aided design and manufacturing (CAD/CAM), and biomaterial development. Nevertheless, implant treatment remains a complex clinical process that requires accurate diagnosis, comprehensive anatomical evaluation, prosthetically driven planning, and individualized decision-making.

The long-term success of dental implants depends on multiple biological, anatomical, mechanical, and patient-related factors. Accurate assessment of available bone volume, identification of critical anatomical structures, evaluation of soft tissue conditions, and appropriate implant positioning are essential components of predictable treatment outcomes. Traditionally, implant planning has relied on clinician experience combined with two-dimensional radiography, clinical examination, and manual interpretation of three-dimensional imaging data. Although these approaches remain clinically effective, they may be influenced by operator variability and limitations associated with the analysis of complex diagnostic information.

The rapid development of digital dentistry has significantly changed contemporary implant workflows. Cone-beam computed tomography (CBCT), intraoral scanners, virtual implant planning platforms, and computer-guided surgical systems have enabled clinicians to evaluate anatomical structures in three dimensions and perform prosthetically driven implant placement. However, the increasing volume of digital diagnostic information has created new challenges regarding efficient data interpretation and clinical decision support. Artificial intelligence (AI) has emerged as a promising technology capable of addressing these challenges through automated analysis, pattern recognition, and predictive modelling.

Artificial intelligence refers to computational systems capable of performing tasks traditionally associated with human cognitive functions, including learning, classification, prediction, and decision-making. In dentistry, AI applications have expanded rapidly, particularly in diagnostic imaging, radiographic interpretation, treatment planning, and prediction of clinical outcomes [1]. Machine learning and deep learning approaches allow algorithms to identify complex relationships within large datasets, potentially improving diagnostic consistency and supporting personalized treatment strategies [2].

Within dental implantology, AI has gained increasing attention because implant treatment requires the integration of multiple data sources, including CBCT images, intraoral scans, clinical parameters, and prosthetic requirements. Unlike conventional software based on predefined rules, AI-driven systems can learn from large numbers of clinical examples and improve their performance through iterative training. Deep learning methods, particularly convolutional neural networks (CNNs), have demonstrated substantial potential for medical and dental image analysis due to their ability to automatically detect and classify anatomical structures within complex imaging datasets [3].

One of the most investigated applications of AI in implant dentistry is automated analysis of CBCT images. Accurate interpretation of CBCT data is fundamental for implant placement because clinicians must evaluate bone dimensions, density characteristics, alveolar ridge morphology, and anatomical limitations such as the mandibular canal and maxillary sinus. Recent studies have demonstrated that deep learning algorithms can assist in the segmentation and identification of anatomical structures, reducing manual workload and improving reproducibility of radiographic assessment [4,5]. These developments may be particularly valuable in complex implant cases involving severe bone deficiency or anatomically challenging regions.

AI-assisted implant planning represents another rapidly developing area. Conventional digital implant planning requires clinicians to manually determine implant position, angulation, diameter, and depth according to anatomical and prosthetic considerations. AI-based systems have the potential to automate several stages of this process by recognizing edentulous regions, analysing available bone, and generating optimized implant positioning recommendations. Current evidence suggests that AI-based planning systems may demonstrate promising technical accuracy; however, differences in datasets, validation protocols, and clinical scenarios presently limit direct comparison between studies [6].

The integration of artificial intelligence with digital implant workflows may contribute to the development of personalized implant dentistry. Contemporary treatment concepts increasingly emphasize individualized planning based on patient-specific anatomical characteristics rather than standardized approaches. By combining radiographic information, intraoral scanning data, and clinical variables, AI systems may support customized treatment strategies that consider both surgical and prosthetic objectives [7]. This approach corresponds with the broader movement toward precision dentistry, where clinical decisions are supported by patient-specific biological and digital information.

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Another emerging application of AI involves computer-assisted and robotic implant surgery. Navigation systems and robotic platforms aim to improve the transfer accuracy between virtual treatment planning and clinical execution. AI-enhanced surgical systems may provide real-time guidance, recognize deviations, and assist clinicians during implant placement procedures. Recent investigations have reported high accuracy of digitally guided and robotic-assisted implant placement, although additional prospective clinical studies are required to establish their routine clinical applicability [8]. It should be noted that computer-guided surgery, dynamic navigation, and robotic systems are not inherently AI-based; they were considered within the scope of this review only when an identifiable AI-component contributed to planning, analysis, guidance, or decision support.

Beyond implant placement, AI applications are also being explored in implant prosthodontics and maintenance. AI-supported systems have been investigated for prosthetic design optimization, implant component recognition, occlusal analysis, and prediction of implant-related complications. These technologies may contribute to more efficient restorative workflows and improved communication between surgical and prosthetic teams [9,10].

Peri-implant disease management represents another potential field for AI implementation. Peri-implantitis is a multifactorial condition influenced by microbial dysbiosis, host immune response, implant characteristics, and patient-related risk factors. AI-based predictive models may assist in identifying patients at increased risk of biological complications by integrating clinical, radiographic, and biological information. Although promising, these applications remain largely at the research stage and require further clinical validation [11].

Despite the considerable potential of AI in implant dentistry, several limitations must be considered. The performance of AI algorithms depends strongly on the quality, quantity, and representativeness of training datasets. Many published studies are based on retrospective datasets obtained from single institutions, which may limit external validity and generalizability. Variability in imaging protocols, annotation procedures, algorithm architecture, and outcome definitions creates additional challenges when comparing results between studies [12].

Furthermore, the clinical implementation of AI raises important ethical and practical considerations. Issues related to patient data protection, algorithm transparency, responsibility for AI-assisted decisions, and clinician acceptance must be carefully addressed. AI should therefore be considered as an assistive technology designed to enhance clinical decision-making rather than replace professional expertise [13].

Recent reviews have highlighted that current AI research in dentistry is characterized by rapid technological development but limited clinical translation. Most available studies focus on technical performance, image analysis accuracy, and algorithm development, whereas fewer investigations evaluate long-term clinical outcomes, cost-effectiveness, and real-world integration into routine implant practice[14]. Consequently, there remains a need for comprehensive evidence mapping to clarify current applications, technological trends, and future research priorities.

The continuous evolution of AI, three-dimensional imaging, and digital manufacturing suggests that implant dentistry is moving toward a more automated and personalized model of care. Future developments may involve integration of AI with virtual surgical planning, additive manufacturing, patient-specific implants, and regenerative approaches, creating highly individualized treatment pathways [15–17]. However, standardized reporting frameworks, multicenter validation studies, and interdisciplinary collaboration between clinicians, engineers, and data scientists are essential for responsible implementation.

Although previous publications have investigated specific AI applications in dental imaging or implant planning, the available evidence remains fragmented across different clinical domains and technological platforms. A comprehensive mapping of current knowledge is therefore necessary to understand the scope of AI applications in dental implantology and identify existing evidence gaps.

Therefore, this scoping review aims to map the current literature regarding artificial intelligence applications in dental implantology, including diagnostic imaging, implant planning, surgical guidance, prosthetic workflows, predictive modelling, and future clinical perspectives. By synthesizing available evidence, this review seeks to provide a comprehensive overview of the current state of AI-driven implant dentistry and highlight directions for future research and clinical innovation (Figure 1).

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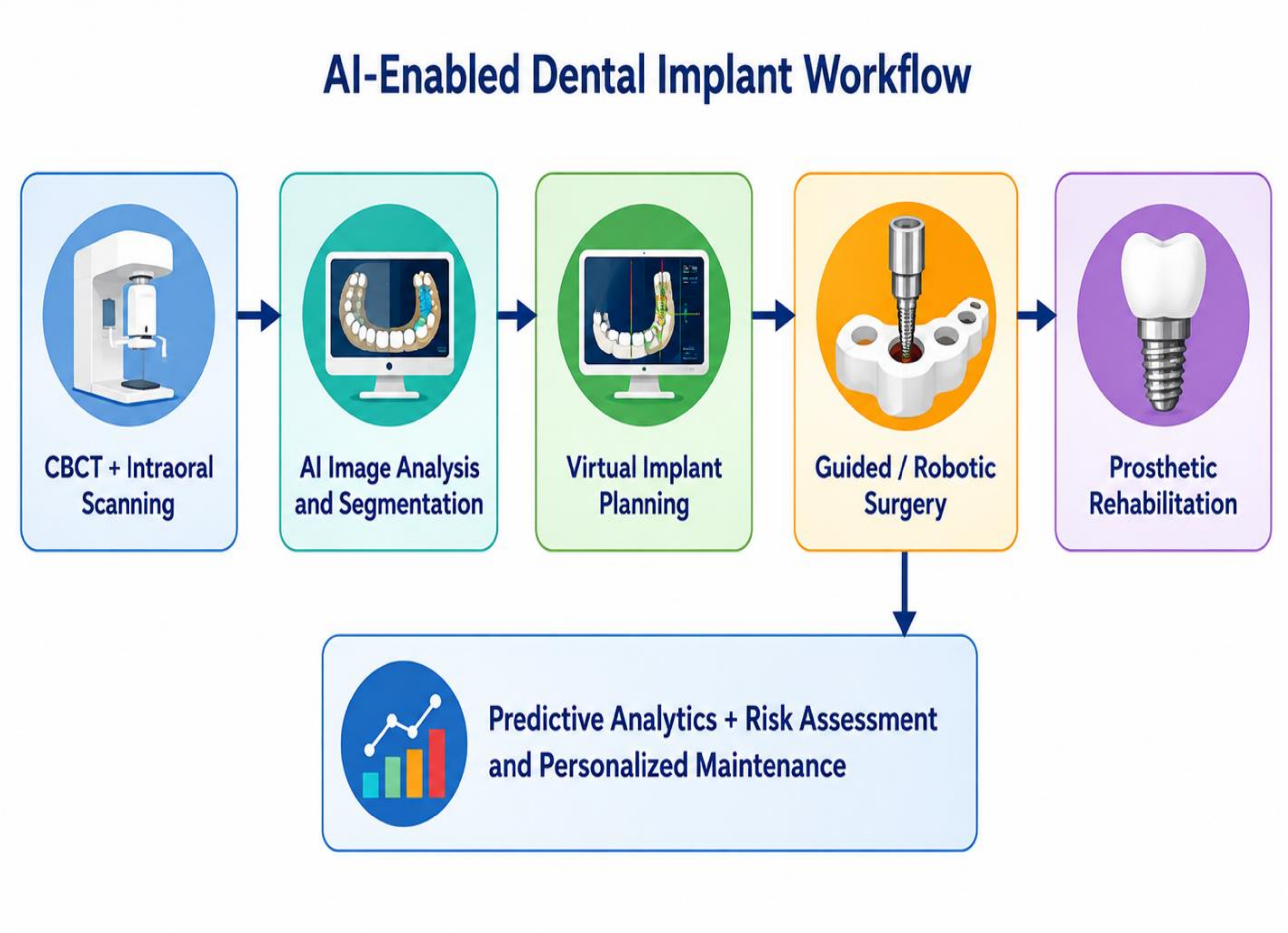

Figure 1. AI-enabled dental implant workflow integrating CBCT, intraoral scanning, AI-assisted analysis, virtual planning, computer-assisted surgery, prosthetic rehabilitation, and predictive maintenance.

3.2 Characteristics and Distribution of AI Applications in Dental Implantology

These studies represented the current evidence landscape regarding artificial intelligence applications in dental implantology, including AI-assisted imaging analysis, implant treatment planning, computer-guided surgery, prosthetic workflows, and predictive modelling approaches.

The included literature demonstrates a rapid expansion of research investigating artificial intelligence applications across different areas of dental implantology. The available evidence consisted of various study designs, including diagnostic studies, methodological investigations, retrospective analyses, clinical evaluations, and review articles.

Most studies were published within the last five years, reflecting the recent acceleration of AI integration into digital dentistry. The majority of investigations originated from countries with established digital dentistry research programs, including South Korea, China, European countries, and the United States.

The reviewed studies demonstrated considerable variation regarding AI models, datasets, imaging protocols, and clinical objectives. Deep learning approaches, particularly convolutional neural networks, represented the most frequently investigated methods, mainly because of their ability to analyse complex three-dimensional imaging data.

The included studies demonstrated that artificial intelligence applications in dental implantology are mainly concentrated in five major clinical domains: CBCT-based image analysis, implant treatment planning, computer-guided surgery, prosthetic rehabilitation, and predictive modelling. These applications reflect the increasing integration of AI into digital implant workflows and indicate its potential role in improving diagnostic accuracy, treatment personalization, and clinical decision support (Table 1).

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Table 1. Main Applications of Artificial Intelligence in Dental Implantology

AI Application	Clinical Purpose	Common AI Methods	Potential Clinical Benefits
CBCT image analysis	Detection and segmentation of anatomical structures	Deep learning, CNNs	Improved radiographic interpretation, reduced observer variability
Implant treatment planning	Virtual implant positioning and bone assessment	Machine learning, computer vision	Personalized treatment planning
Guided implant surgery	Surgical navigation and accuracy improvement	AI-assisted navigation systems	Improved transfer accuracy from virtual plan to surgery
Implant prosthodontics	Automated restoration design and CAD/CAM optimization	AI-based design algorithms	More efficient restorative workflow
Predictive modelling	Prediction of implant complications and outcomes	Machine learning models	Risk assessment and personalized follow-up

3.3 Artificial Intelligence in Diagnostic Imaging and CBCT Analysis

Artificial intelligence (AI) has emerged as one of the most extensively investigated technologies in dental implantology, with diagnostic imaging representing the most mature application domain. The majority of the included studies evaluated AI-assisted interpretation of cone-beam computed tomography (CBCT) images using deep learning algorithms, particularly convolutional neural networks (CNNs), for automated detection, segmentation, and classification of anatomical structures relevant to implant treatment planning.

The principal applications included automatic identification of the mandibular canal, mental foramen, maxillary sinus boundaries, inferior alveolar nerve, alveolar crest morphology, residual ridge dimensions, and bone quality assessment. Several investigations also explored automated localization of missing teeth, assessment of available bone volume, and segmentation of cortical and cancellous bone to facilitate virtual implant planning. Compared with conventional manual image interpretation, AI-assisted systems demonstrated high reproducibility and reduced observer-dependent variability, while substantially decreasing the time required for radiographic analysis.

Despite these encouraging findings, considerable heterogeneity was observed among studies regarding CBCT acquisition protocols, annotation strategies, dataset size, AI architectures, and validation methods.

Most studies focused on algorithm development and internal technical validation, whereas relatively few evaluated diagnostic performance under routine clinical conditions or across external datasets. Consequently, although AI-assisted CBCT analysis appears highly promising, additional multicenter prospective validation studies are required before widespread clinical implementation (Figure 3).

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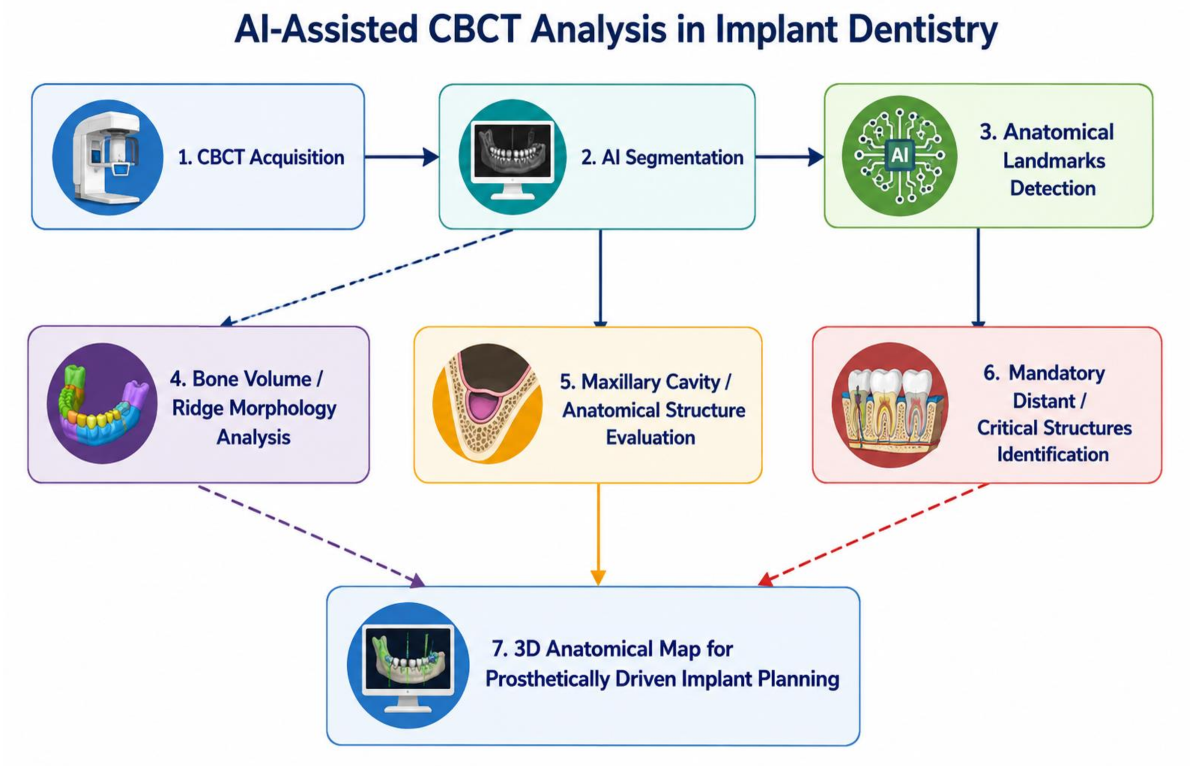

Figure 3. AI-assisted CBCT analysis for dental implantology, illustrating automated anatomical segmentation, landmark detection, and generation of a three-dimensional anatomical map for implant planning.

3.4 AI-Assisted Implant Treatment Planning

Virtual implant treatment planning represented another major research domain identified in the evidence mapping. The reviewed studies investigated the ability of AI systems to support clinicians in determining optimal implant position by simultaneously analyzing prosthetic requirements, available bone volume, anatomical limitations, implant dimensions, and occlusal relationships.

Machine learning and computer vision algorithms were integrated into digital planning software to generate treatment recommendations based on multidimensional patient-specific datasets. Several studies suggested that AI-assisted planning may improve consistency between clinicians, reduce planning time, and facilitate prosthetically driven implant placement. AI was also reported to assist in selecting implant diameter and length, evaluating bone availability, and identifying potential surgical limitations before treatment.

However, the current evidence remains heterogeneous because different commercial planning platforms employ proprietary algorithms and varying validation strategies. Furthermore, most studies assessed technical planning accuracy rather than clinically meaningful outcomes such as implant survival, surgical complications, or patient-reported satisfaction. Standardized evaluation criteria and prospective clinical trials are therefore necessary to determine the true clinical value of AI-assisted treatment planning.

3.5 AI Integration with Digital and Computer-Assisted Implant Surgery

The integration of AI-components into computer-assisted implant surgery represents an emerging area within digital dentistry. Several studies described AI-supported workflows combining CBCT imaging, intraoral scanning, virtual implant planning, CAD/CAM surgical guide fabrication, dynamic navigation systems, and robotic-assisted implant placement.

The reviewed evidence indicates that AI facilitates communication between diagnostic imaging, virtual planning, surgical execution, and prosthetic rehabilitation by improving the transfer accuracy from digital planning to clinical treatment.

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Navigation-assisted and robotic implant surgery has demonstrated high placement precision in experimental and early clinical studies; however, the specific incremental contribution of AI to this accuracy remains insufficiently established.

Nevertheless, current clinical evidence remains limited. Most available studies were feasibility investigations or retrospective analyses involving relatively small patient populations. High equipment costs, increased workflow complexity, limited accessibility, and the absence of standardized clinical protocols currently restrict widespread implementation. Future multicenter clinical trials are needed to evaluate whether AI-assisted surgical systems improve long-term implant success compared with conventional guided surgery.

3.6 AI Applications in Implant Prosthodontics and Rehabilitation

Artificial intelligence applications extend beyond surgical planning into prosthetic rehabilitation and digital restorative dentistry. The reviewed studies described AI-assisted workflows for implant-supported prosthesis design, automated recognition of implant components, digital smile analysis, occlusal optimization, and CAD/CAM restoration planning.

AI algorithms were incorporated into digital design software to automate prosthetic workflows by identifying implant platforms, selecting restorative components, optimizing emergence profiles, and assisting laboratory technicians during restoration fabrication. These technologies have the potential to reduce laboratory time, improve standardization of prosthetic design, and enhance communication between clinicians and dental technicians.

Despite these advantages, evidence supporting AI-assisted implant prosthodontics remains relatively limited. Most investigations consisted of technical feasibility studies rather than controlled clinical trials. Long-term evaluation of prosthetic complications, restoration survival, maintenance requirements, and patient-centered outcomes remains insufficient, highlighting the need for well-designed prospective clinical research.

3.7 Predictive Models and Peri-implant Disease Assessment

Predictive modelling represents one of the newest applications of AI in implant dentistry. Machine learning algorithms were developed to integrate clinical variables, CBCT findings, periodontal history, systemic risk factors, smoking status, and biological markers to estimate the probability of implant failure or peri-implant disease.

Several studies demonstrated encouraging predictive performance using supervised machine learning approaches such as random forests, support vector machines, artificial neural networks, and gradient boosting algorithms. These models may assist clinicians in identifying high-risk patients, supporting individualized maintenance protocols, and improving preventive strategies.

However, important methodological limitations remain. Most predictive models were trained using retrospective datasets from single institutions, limiting external validity. Differences in patient populations, outcome definitions, follow-up duration, and predictor selection also hinder comparison across studies. Consequently, current AI prediction systems should be regarded as promising decision-support tools rather than fully validated clinical decision-making instruments. Future research should emphasize prospective multicenter validation, explainable AI methodologies, standardized reporting guidelines, and integration into routine clinical practice. AI can function as a clinical decision-support system rather than a replacement for professional judgment. A conceptual model illustrating this interaction is presented in Figure 4.

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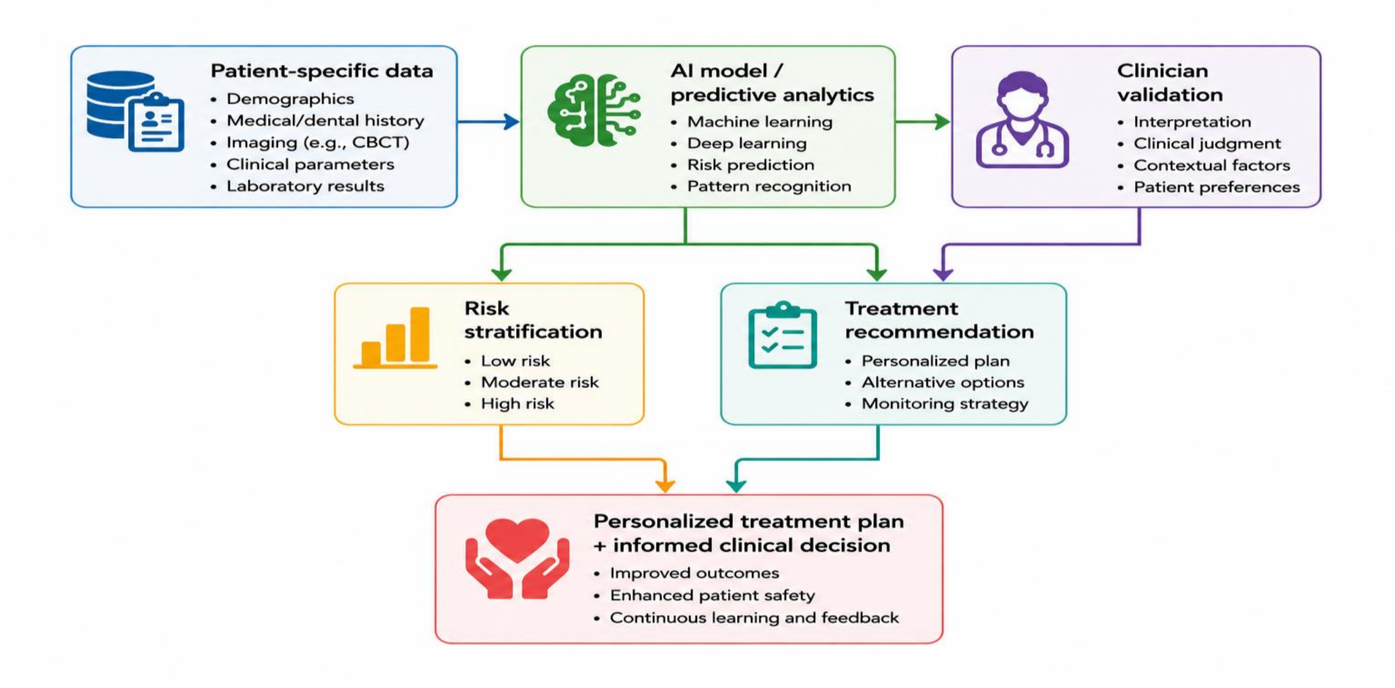

Figure 4. Conceptual model of AI as a clinical decision-support system. Patient-specific data are processed by AI models and subsequently reviewed and validated by the clinician.

Overall, the evidence synthesized in this scoping review demonstrates that artificial intelligence applications span the entire implant treatment workflow, from diagnosis and treatment planning to surgery, prosthetic rehabilitation, and long-term outcome prediction. As summarized in Table 2, the most developed body of evidence currently concerns AI-assisted diagnostic imaging and CBCT analysis, where deep learning algorithms have consistently demonstrated high technical accuracy and reproducibility. AI-assisted implant planning and digital surgical guidance have also shown promising results, particularly in improving workflow efficiency and treatment precision; however, robust clinical validation remains limited. In contrast, applications in implant prosthodontics and predictive modelling are still at an earlier stage of development, with most available studies focusing on technical feasibility rather than long-term clinical effectiveness. Collectively, these findings indicate that although AI has considerable potential to enhance clinical decision-making and personalized implant therapy, further multicenter prospective studies, standardized validation protocols, and transparent reporting are required before these technologies can be routinely integrated into evidence-based implant practice (Table 2).

Table 2. Summary of Artificial Intelligence Applications in Dental Implantology

Research Domain	Main AI Applications	Common AI Methods	Main Findings	Current Limitations	Future Research Priorities
Diagnostic imaging and CBCT analysis	Anatomical landmark detection, segmentation, bone assessment, nerve identification	Deep learning (CNN), image segmentation	Promising to high technical performance in selected diagnostic tasks	Heterogeneous datasets; limited external validation	Multicenter validation and standardized imaging datasets
Implant treatment planning	Virtual implant positioning, implant selection,	Machine learning, computer vision	Improved planning consistency and workflow efficiency	Lack of standardized planning protocols	Prospective clinical outcome studies

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	bone evaluation				
Digital and computer-assisted surgery	Surgical guides, navigation systems, robotic implant placement	AI-assisted navigation, robotics	Improved transfer accuracy from virtual planning to surgery	High cost, limited clinical evidence	Randomized multicenter clinical trials
Implant prosthodontics and rehabilitation	CAD/CAM restoration design, implant recognition, occlusal optimization	AI-assisted CAD/CAM algorithms	More efficient digital restorative workflow	Predominantly technical studies	Long-term prosthetic outcome evaluation
Predictive modelling and peri-implant disease	Implant failure prediction, peri-implant disease risk assessment	Random forests, neural networks, SVM, gradient boosting	Personalized risk prediction and maintenance planning	Retrospective datasets and limited external validation	Explainable AI, prospective validation, real-world implementation

.3.8 Evidence Gaps and Future Research Needs

The evidence mapping identified several important limitations in the current literature on artificial intelligence (AI) in dental implantology. First, most available studies are based on retrospective datasets or single-center experiences, limiting the generalizability of their findings. Second, considerable heterogeneity exists in AI model development, validation strategies, and reporting methodologies, making comparisons across studies difficult. Third, despite encouraging technical performance, relatively few investigations have evaluated clinically relevant outcomes, cost-effectiveness, patient-centered benefits, and long-term performance under routine clinical conditions.

Overall, the current evidence suggests that AI has substantial potential to improve implant diagnosis, treatment planning, surgical guidance, prosthodontic rehabilitation, and outcome prediction. However, the level of clinical evidence remains variable across different application domains. As summarized in Table 3, future research should prioritize multicenter prospective clinical studies, external validation of AI models, standardized reporting frameworks, and the integration of explainable and clinically validated AI systems into routine implant workflows.

Table 3. Evidence Mapping of AI Applications in Dental Implantology.

Domain	**Current maturity of evidence**	**Main Findings**	**Evidence Gaps / Future Directions**
Imaging analysis	Relatively developed	Strong technical performance of deep learning models	External multicenter validation and evaluation across different CBCT systems
Implant planning	Developing	Promising planning accuracy but limited clinical validation	Prospective clinical trials and standardized outcome measures
Surgical guidance	Early to developing	Improved digital workflow integration	Long-term clinical effectiveness and cost-

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		and surgical precision	effectiveness studies
Implant prosthodontics	Early-stage	Early-stage evidence for AI-assisted CAD/CAM restoration design	Clinical validation and integration into routine prosthodontic workflows
Prediction models	Developing	Machine learning shows potential for predicting implant outcomes and complications	Prospective validation, explainable AI models, and real-world implementation

4. DISCUSSION

Artificial intelligence has rapidly evolved from an experimental technology into a clinically relevant tool in dentistry, particularly in implant dentistry, where accurate diagnosis, three-dimensional planning, and individualized treatment strategies are essential for predictable outcomes. The present review highlights that AI applications in implant dentistry extend beyond automated image interpretation and increasingly integrate radiographic analysis, anatomical segmentation, implant planning, surgical guidance, and digital workflow optimization. These findings are consistent with previous reports demonstrating that AI may improve diagnostic performance, workflow efficiency, and clinical decision support while simultaneously introducing challenges related to validation, transparency, and implementation into routine practice [1,2,18,20].

Previous systematic reviews have primarily focused on AI performance in diagnostic imaging and implant-related radiographic assessment. Hung et al. reported that AI applications in implant dentistry demonstrated promising accuracy, particularly in image-based tasks such as implant detection, anatomical landmark identification, and risk assessment; however, they emphasized the limited availability of high-quality clinical validation studies [18]. Similarly, Revilla-León et al. demonstrated that AI has substantial potential in implant dentistry but concluded that most available evidence remains based on retrospective datasets rather than prospective clinical outcomes [20]. In comparison, the current evidence landscape suggests a progressive shift from isolated diagnostic applications toward integrated AI-assisted workflows that combine imaging, digital planning, and personalized treatment strategies.

The role of AI in dental imaging represents one of the most mature areas of application. Deep learning algorithms, particularly convolutional neural networks (CNNs), have demonstrated high performance in detecting anatomical structures, pathological findings, and implant-related conditions on radiographic images [6,22]. Studies evaluating CBCT-based AI models have shown reliable performance in segmentation and three-dimensional reconstruction of anatomical structures, which are critical for implant placement planning [15,23]. These findings support the concept that AI may reduce operator-dependent variability and enhance precision during complex implant procedures. However, unlike traditional diagnostic studies, implant dentistry requires not only image recognition accuracy but also clinical relevance, surgical applicability, and measurable improvement in patient outcomes.

Recent investigations have expanded AI applications toward fully digital implant workflows. Wang et al. demonstrated that deep learning technologies could facilitate automated analysis of dental imaging data and improve integration between radiographic information and treatment planning [9]. Similarly, Ying et al. emphasized that AI-assisted workflows may influence multiple stages of implant prosthodontics, including diagnosis, prosthetic design, and treatment optimization [11]. These developments correspond with broader trends in digital implant dentistry, where intraoral scanning, computer-guided surgery, and virtual planning have become increasingly integrated into clinical practice [26,27]. Nevertheless, AI should currently be considered an assisting technology rather than a replacement for clinician expertise, as final treatment decisions remain dependent on biological considerations, patient preferences, and surgical judgment.

A major difference between early AI studies and contemporary applications is the movement from algorithm performance toward clinical integration. Earlier investigations predominantly evaluated whether AI systems could correctly identify structures or conditions, whereas newer research focuses on how AI can support personalized treatment planning and improve predictability. For example, three-dimensional reconstruction models and automated landmark detection systems have demonstrated potential for improving implant positioning and anatomical evaluation

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[25]. However, similar to findings reported in other medical fields, technical accuracy does not necessarily translate into improved clinical outcomes without prospective validation and standardized implementation protocols [31,40].

Despite encouraging developments, several challenges remain. One of the major limitations identified across the literature is the lack of external validation and standardized datasets. Many AI models are trained using single-center datasets, which may reduce generalizability across different populations, imaging devices, and clinical environments [10,41]. Furthermore, differences in CBCT acquisition parameters, image quality, annotation protocols, and algorithm architecture make direct comparison between studies difficult. Similar concerns have been reported in healthcare AI research, where reproducibility, transparency, and responsible implementation remain essential requirements for clinical adoption [39,44].

The practical implementation of AI in implant dentistry involves a balance between technological advantages and current limitations. AI provides significant benefits in rapid image interpretation, personalized treatment planning, digital surgical workflows, and predictive decision support. However, barriers including limited external validation, lack of standardized protocols, economic considerations, technical complexity, and ethical concerns continue to restrict widespread clinical adoption. The major advantages and challenges associated with AI implementation across different clinical domains are summarized in Table 4.

Table 4. Advantages and Challenges of Artificial Intelligence Implementation in Implant Dentistry.

Aspect	Advantages	Current Challenges
Diagnosis	Rapid analysis of complex imaging data	Limited external validation
Treatment planning	Patient-specific planning support	Lack of standardized protocols
Surgery	Improved digital workflow integration	Cost and technical complexity
Prosthetic workflow	Automated design assistance	Limited clinical outcome studies
Decision support	Predictive analysis	Explainability and ethical issues

Another important consideration is explainability. Although deep learning models may achieve high predictive performance, their decision-making processes are often difficult to interpret. Explainable artificial intelligence (XAI) approaches have therefore gained increasing attention to improve clinician trust and facilitate safe clinical adoption [32,33]. In implant dentistry, where surgical decisions involve irreversible interventions and anatomical risks, transparent AI systems that provide understandable rationale for recommendations will likely be essential.

The economic and ethical aspects of AI implementation should also be considered. Although AI may reduce planning time and improve workflow efficiency, adoption requires investment in infrastructure, software validation, clinician training, and data security systems.

Previous healthcare analyses have emphasized that successful AI integration depends not only on technological performance but also on regulatory frameworks, interdisciplinary collaboration, and appropriate clinical governance [36–38].

Limitations

Several limitations should be acknowledged. First, despite the rapidly expanding literature on AI in implant dentistry, many available studies remain retrospective and heterogeneous, limiting direct comparison of reported outcomes. Differences in AI algorithms, imaging modalities, clinical indications, and evaluation metrics contribute to variability between studies.

Second, the majority of published investigations focus on technical performance parameters, such as accuracy, sensitivity, specificity, or segmentation quality, rather than clinically meaningful outcomes including implant survival, complication rates, patient satisfaction, or long-term functional results. Therefore, the current evidence supports the potential of AI but does not yet establish definitive superiority over conventional clinical workflows.

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Third, AI models are highly dependent on the quality and diversity of training datasets. Models developed from limited institutional datasets may demonstrate reduced performance when applied to different populations or imaging systems. Future research should prioritize multicenter datasets, standardized reporting frameworks, and prospective clinical validation.

Finally, ethical considerations related to patient data protection, algorithm transparency, responsibility for AI-assisted decisions, and regulatory approval remain important barriers to widespread clinical implementation.

Future Perspectives and Emerging Trends

The future development of AI in implant dentistry is expected to move toward fully integrated, intelligent digital ecosystems. Future AI platforms may combine CBCT imaging, intraoral scanning, facial analysis, clinical history, biological parameters, and patient-specific risk factors to generate comprehensive predictive models for implant treatment planning.

A major emerging direction is the development of multimodal AI systems capable of integrating different sources of clinical information rather than relying on isolated imaging data. Such systems may enable personalized implant strategies by predicting anatomical limitations, biological risks, and potential treatment outcomes.

Another important trend is the expansion of explainable and responsible AI. Future systems will likely incorporate XAI methodologies to provide clinicians with interpretable recommendations rather than purely automated decisions [32,33]. This approach may improve clinician acceptance and facilitate regulatory approval.

Generative artificial intelligence and large language models may also contribute to future clinical workflows by assisting with treatment documentation, clinical decision support, patient communication, and evidence-based treatment recommendations. However, these applications require careful validation to ensure reliability and prevent inappropriate clinical recommendations.

Furthermore, integration between AI and robotic or computer-guided implant surgery may represent an important future direction. Combining AI-based planning with dynamic navigation and robotic assistance could potentially improve surgical precision, particularly in complex anatomical cases.

The expected clinical impact of these emerging technologies is summarized in Table 5.

Table 5. Future Directions of AI in Dental Implantology.

Future Development	Expected Clinical Impact
Multimodal AI systems (CBCT + intraoral scans + clinical data)	Comprehensive personalized implant planning
Explainable AI (XAI)	Increased clinician confidence and transparency
AI combined with 3D printing	Patient-specific surgical guides and implants
AI-assisted robotic surgery	Increased procedural precision
Predictive implant models	Early identification of complications
Digital twins in implant dentistry	Simulation-based treatment optimization

Overall, the future role of AI in implant dentistry is unlikely to involve replacement of clinicians; rather, AI will function as an advanced decision-support system that enhances human expertise and enables more predictable, personalized, and efficient treatment **Figure 5.**

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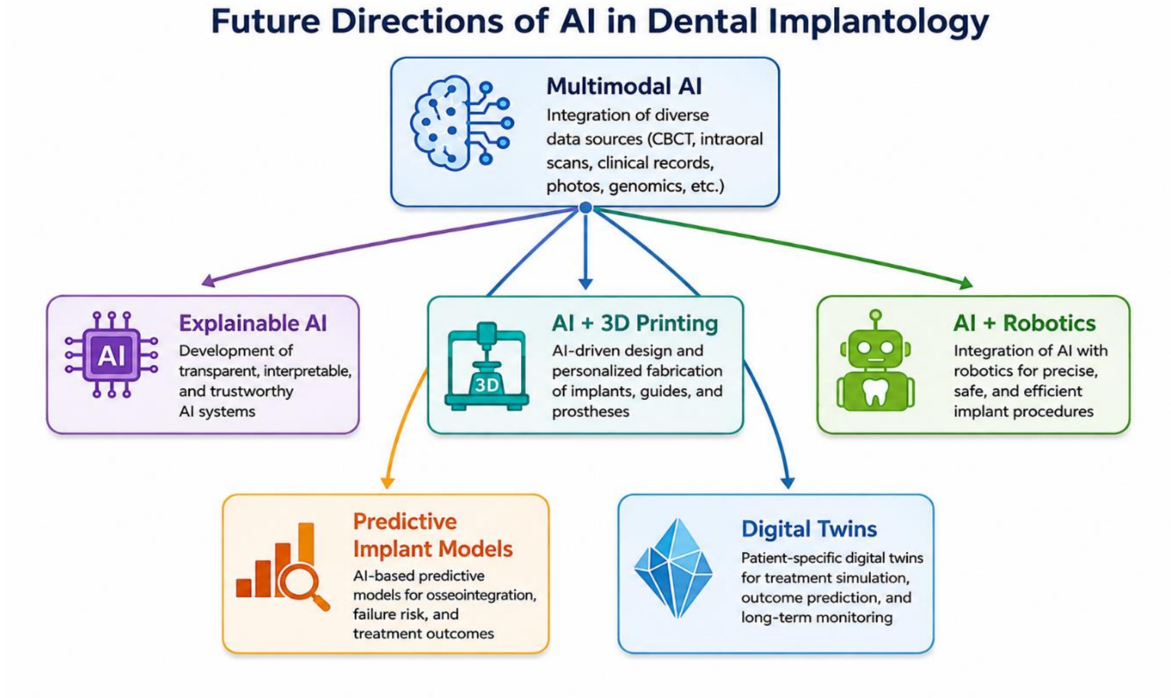

Figure 5. Future directions of AI in dental implantology, including multimodal AI, explainable AI, three-dimensional printing, robotic surgery, predictive models, and digital twins.

5. CONCLUSION

Artificial intelligence represents a transformative development in implant dentistry, with applications ranging from radiographic interpretation and anatomical segmentation to digital implant planning and personalized treatment optimization. Current evidence suggests that AI technologies may improve diagnostic performance, enhance workflow efficiency, and support clinical decision-making in selected implant-related applications.

However, the available evidence remains limited by methodological heterogeneity, insufficient prospective validation, and a lack of standardized clinical outcome assessment. Future research should focus on multicenter clinical studies, explainable AI approaches, integration of multimodal patient data, and evaluation of long-term treatment outcomes.

Rather than replacing clinical expertise, AI should be considered a complementary technology that enhances precision, predictability, and personalization in modern implant dentistry. With appropriate validation and responsible implementation, AI has the potential to become an integral component of future digital implant workflows.

DECLARATIONS

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Competing Interests
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