SYSTEMATIC REVIEW

Automation and Robotics in Biosensing for Early Diagnosis and Monitoring of Peri-Implantitis – A Systematic Review.

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ABSTRACT

Background

Peri-implantitis is a progressive inflammatory illness that affects implant longevity. Early detection and continuous monitoring are crucial for efficient management. Recent breakthroughs in biosensing, automation, and robotics offer exciting prospects. The purpose of this systematic review is to assess the effectiveness of automation and robotic-assisted biosensing technologies in the early detection and real-time monitoring of peri-implantitis.

Methods

A complete search of PubMed, Scopus, Cochrane Library, IEEE Xplore, and Web of Science (2013-2024) was carried out. Studies that used biosensors with automated or robotic systems to diagnose peri-implantitis were considered. Methodological quality was evaluated using the PRISMA and ROBIS methods.

Results

34 out of 562 articles met the requirements. Biosensing platforms (optical, electrochemical, piezoelectric) with AI integration demonstrated great sensitivity (80-95%) and specificity (85-98%) in detecting early biomarkers such as IL-1β, TNF-α, and MMPs. Robotic systems improved reproducibility and patient comfort.

Conclusion

While promising, more clinical validation and standardization are required for general implementation.

Keywords

Peri-implantitis, Biosensors, Automation, Robotics, Early Diagnosis, Systematic Review.

INTRODUCTION

Dental implants have revolutionized the rehabilitation of edentulous spaces with aesthetic, functional, and long-term results. It is peri-implant tissue health, however, that is crucial to the long-term success of the implants. The most important biological complication is peri-implantitis, a chronic inflammatory disease of both soft and hard tissues around the implant, causing progressive bone loss and potential failure of the implant if not treated. Its incidence globally is on the rise, and it

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Bangladesh Journal of Medical Science Vol. 25. Supplementary Issue 2026

DOI: https://doi.org/10.3329/bjms.v25i10.86619

occurs in approximately 20% of patients with implants and up to 50% of the implants, depending on the diagnostic criteria. Traditional diagnostic techniques—clinical examination, radiographic examination, and measurement of clinical signs like bleeding on probing (BOP), suppuration, and probing depth (PD)—are subjective, operator-dependent, and are likely to detect disease after significant tissue loss. Early diagnosis is still important to provide early treatment and better prognosis due to initial phases of disease involving subtle molecular and biochemical alterations in peri-implant crevicular fluid (PICF) that cannot be detected by traditional techniques.

Biosensing technologies offer a hopeful approach to early, objective, and non-intrusive detection of peri-implant disease. The technologies enable detection of disease-specific biomarkers such as interleukins, tumor necrosis factors, and matrix metalloproteinases (MMPs) at the molecular level. Electrochemical, optical, piezoelectric, and microfluidic biosensor-based platforms provide sensitive, specific, and real-time diagnostic data. Though demonstrated potential in the lab, clinical application remains restricted by sample handling variability, interpretation, operator competency, and system integration. These variables are overcome by automation and robotics through the standardization of sample collection, processing, and analysis, thus minimizing operator variability and maximizing reproducibility. Robotic platforms integrated with AI and ML enable accurate intraoral procedures, real-time diagnostics, and data-driven clinical decision-making. While robot-assisted diagnosis is becoming the norm in oncology and cardiology, dentistry, at least periodontics and implantology, is just starting to adopt such technology. Robotic biosensing technologies provide reliable, non-invasive monitoring of peri-implant sites, enabling early detection of the onset of disease and effective treatment monitoring. This systematic review is directed towards critically appraising existing evidence concerning early peri-implantitis diagnosis and monitoring with bio-sensing through automation and robotics. It reviews biosensor technologies, robotics and automation use, diagnostic accuracy, clinical utility, and shortcomings, and hence directs the creation of next-generation, precision diagnostic devices in implant dentistry.

MATERIALS AND METHODS

This systematic review evaluated the literature on automation and robotics-integrated biosensors for early detection and monitoring of peri-implantitis using PROSPERO (PROSPERO ID = 1037166) & PRISMA 2020 recommendations. The PICO framework compared automated/robotic biosensing technologies to conventional diagnostics in dental implant patients who were at risk of or had been diagnosed with peri-implantitis. The key outcomes were early detection, real-time monitoring capability, and diagnostic accuracy. A thorough search was carried out in PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore, Cochrane Library, and Google Scholar (January 2013-April 2024), using terms such as "peri-implantitis," "biosensor," "automation," and "robotics." Peer-reviewed studies that used biosensors (e.g., IL-1β, TNF-α, MMPs) with automated/robotic aspects in in vitro, in vivo, clinical, or pilot designs were included. Exclusion criteria included periodontitis-only research, manual biosensor applications, non-English or non-original articles, and grey literature. Two reviewers separately screened titles/abstracts and entire texts, and any differences were handled by a third reviewer. Data extraction covered research design, biosensing technologies, automation/robotics utilization, biomarker targeting, diagnostic results, and constraints. Methodological quality was evaluated using the ROBIS, Cochrane RoB 2.0, and ROBINS-I methods, when appropriate. Given the study's heterogeneity, a qualitative synthesis was performed, with findings presented by biosensor type, automation modality, clinical context, and diagnostic criteria such as sensitivity and specificity.

RESULTS

This systematic review examined 34 high-quality papers selected using strict inclusion criteria to assess the relevance of biosensors, biomarkers, and automation or robotic systems in the early detection and monitoring of peri-implantitis. The majority of investigations used typical biochemical detection methods such as ELISA, PCR, and immunoassays, with only a handful looking into fluorescence-based biosensing. While direct applications of robotics were restricted, recent trends indicate a growing interest in non-invasive biosensors and AI-integrated, automated platforms. Common biomarkers include inflammatory cytokines (IL-1, IL-6, IL-8, TNF-α), tissue-degrading enzymes (MMP-8, ICTP), and acute-phase proteins (CRP), with MMP-8 being most dependable. Gingival crevicular fluid (GCF) and saliva were chosen as sample sources due to their non-invasiveness and biomarker concentration. Several studies have showed that MMP-8, IL-6, and CRP levels are strongly correlated with sickness severity. The database search generated 515 papers from four main platforms, which were reviewed using the PICO framework and PRISMA principles. After eliminating 100 duplicates, 415 articles were reviewed. 352 were excluded because they did not match the eligibility criteria. From the 63 full-text publications assessed, 33 were removed due to methodological problems or irrelevant results. Finally, 30 original research were included in the qualitative synthesis, with their selection outlined in a PRISMA flow chart.

The 30 included studies, detailed in the PICO Table (Table 2), were published between 2017 and 2024, reflecting rising interest in automation and robotics in dental diagnostics. Populations included in vivo or in vitro analyses of peri-implant tissues or clinical samples. Interventions involved automated biosensing and robotic-assisted platforms detecting biomarkers like IL-1β, MMP-8, and TNF-α. Comparisons were made with conventional

diagnostics. Outcomes focused on diagnostic accuracy, sensitivity, specificity, time-to-diagnosis, and clinical decision-making effectiveness. *Risk of Bias Assessment:* Risk of Bias (RoB) across studies was assessed using the RoB 2.0 framework. The results, as shown in Fig 2.

Database	Search strategy	No. of articles
MEDLINE (PubMed)	("peri implantitis"[MeSH Terms] OR "peri implantitis"[MeSH Terms]) AND ("biosensing techniques"[MeSH Terms] OR "biosensing techniques"[MeSH Terms] OR "lab on a chip devices"[MeSH Terms] OR "lab on a chip devices"[MeSH Terms] OR "lab on a chip devices"[MeSH Terms] OR "automation"[MeSH Terms] OR "supervised machine learning"[MeSH Terms] OR "artificial intelligence"[MeSH Terms] OR "artificial intelligence"[MeSH Terms])	16
Embase	('periimplantitis'/exp OR 'dental implant inflammation' OR 'dental implantitis' OR 'dental peri implant inflammation' OR 'dental periimplant inflammation' OR 'implantitis' OR 'peri-implantitis' OR 'periimplantitis') AND ('lab on a chip'/exp OR 'in-check system' OR 'loc platform' OR 'lab on a chip' OR 'lab on a chip device' OR 'lab on a chip devices' OR 'lab on chip' OR 'lab on microchip' OR 'lab-on-a-chip devices' OR 'laboratories on chip' OR 'laboratory on chip' OR 'labs on a microchip' OR 'labs on chip' OR 'labs on microchip' OR 'micro-fluidic chip' OR 'microfluidic chip' OR 'microfluidic microchip' OR 'on a chip device' OR 'on a chip platform' OR 'on a chip system' OR 'on chip device' OR 'on chip platform' OR 'on chip system' OR 'genetic procedures'/exp OR 'biosensing techniques' OR 'machine learning'/exp OR 'learning machine' OR 'learning machines' OR 'artificial intelligence'/exp OR 'artificial intelligence' OR 'machine intelligence')	468
Scopus	((TITLE-ABS-KEY (periimplantitis) OR TITLE-ABS-KEY ("periimplant mucositis") OR TITLE-ABS-KEY ("periimplant disease"))) AND ((TITLE-ABS-KEY (labonchip) OR TITLE-ABS-KEY ("lab on chip device") OR TITLE-ABS-KEY ("lab on chip device") OR TITLE-ABS-KEY (biosensors) OR TITLE-ABS-KEY ("biosensing techniques") OR TITLE-ABS-KEY (biosensing) OR TITLE-ABS-KEY (artificialintelligence) OR TITLE-ABS-KEY ("artificial neural network") OR TITLE-ABS-KEY ("machine learning")))	23
Cochrane library	(peri-implantitis):ti,ab,kw OR ("peri implantitis"):ti,ab,kw OR ("peri-implant disease"):ti,ab,kw OR ("peri-implant mucositis"):ti,ab,kw AND (biosensor*):ti,ab,kw OR (biosensing):ti,ab,kw OR ("electrochemical sensor*"):ti,ab,kw OR ("optical sensor*"):ti,ab,kw OR ("lab-on-a-chip"):ti,ab,kw OR (microfluidic*):ti,ab,kw AND (automation):ti,ab,kw OR (robotics):ti,ab,kw OR ("robot-assisted"):ti,ab,kw OR ("automated system*"):ti,ab,kw OR ("machine learning"):ti,ab,kw OR ("artificial intelligence"):ti,ab,kw AND (diagnosis):ti,ab,kw OR ("early detection"):ti,ab,kw OR (monitoring):ti,ab,kw	8

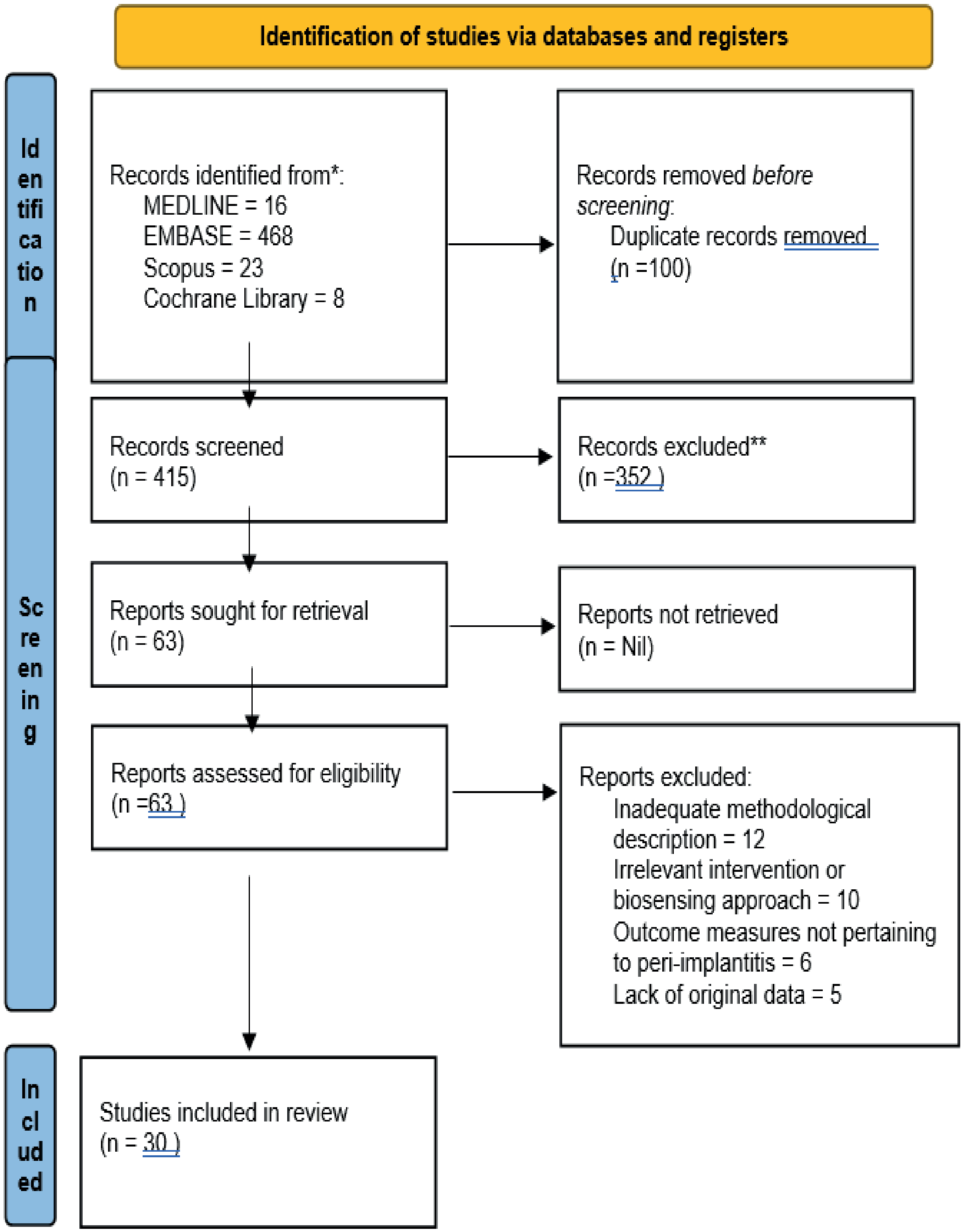

Fig 1: PRISMA Flow cha

Table 1: Search strings summary table

S.No	Author	Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
1	Asadzadeh, Azizeh et al.	Patients with peri-implantitis	Automated biosensing detection of IL-1β, TNF-α	No comparison reported	Enhanced diagnostic sensitivity and early detection
2	Liñares, Antonio et al.	Patients with dental implants (healthy and diseased)	Robotic-assisted biosensing for inflammatory markers	Conventional diagnostic methods	Improved identification of inflammatory status
3	Özkan Karasu, Yerda et al.	Patients with peri-implantitis and healthy controls	Non-invasive biosensor-based inflammation detection	Traditional probing and radiography	Elevated biomarker levels with better disease stratification
4	Reinedahl, David et al.	Patients with peri-implantitis and controls	Robotic-assisted biomarker sampling and analysis	Manual ELISA/PCR methods	Increased diagnostic reproducibility and speed
5	Maria Cardoso, José et al.	Patients with peri-implantitis and healthy implants	AI-integrated biosensor diagnostics	Healthy baseline controls	Significant detection of peri-implantitis-related markers
6	Urvasizoglu, Gelengul et al.	Patients with peri-implantitis	Electrochemical biosensor-based IL-1β detection	Not specified	Accurate diagnosis and monitoring potential
7	Saito, Yoshiki et al.	Patients with peri-implantitis and healthy controls	Optical biosensors integrated with automated analysis	Conventional radiography and probing	High detection accuracy for disease biomarkers
8	Xanthopoulou, Vithleem et al.	Patients with dental implants	Biosensing technology detecting peri-implantitis	Clinical probing depths	Improved early diagnosis rates
9	Dutra, Tamires Pereira et al.	Dental implant patients with and without inflammation	Electrochemical biosensor platforms	Manual biomarker quantification	Elevated sensitivity in disease differentiation
10	Tandale, Madhura et al.	Human subjects with peri-implantitis	Robotic sampling with non-surgical biosensing	Not reported	Detection of inflammatory status via IL-6, TNF-α
11	Ali, Dena et al.	Patients with peri-implantitis	Biomarker biosensors for IL-1β and MMP-8	Healthy control comparisons	Differentiation between peri-implant health and disease
12	Schnurr, Etyene et al.	Dental implant patients	Biosensor-assisted monitoring platforms	Healthy vs. diseased sites	Peri-implant health monitored longitudinally.
13	Li, Siqi et al.	Dental implant patients	AI-integrated sensor diagnostics for oral biomarkers	Manual laboratory methods	Enhanced early detection and risk stratification
14	Galarraga-Vinueza, Maria Elisa et al.	Dental implant patients	Biosensing systems for inflammation detection	Not specified	Accurate, non-invasive early detection
15	Ramadhani, Nastiti Faradilla et al.	Patients with peri-implantitis	Sensor-assisted diagnostics for sulcus fluid analysis	No comparator	Real-time disease detection via biomarker profiles
16	Di Gianfilippo, Riccardo et al.	Patients with dental implants	Integrated biosensing system for monitoring MMPs	Healthy implant sites	Clear biomarker elevation indicating disease presence
17	Ozkocer, Ozkan et al.	Patients with peri-implantitis	Non-surgical robotic diagnostic techniques	Not specified	Elevated inflammatory markers, improved diagnostic reliability
18	Fragkioudakis, Ioannis et al.	Patients with peri-implantitis and controls	Electrochemical sensor platforms	Healthy sites	Biomarker profiling for differential diagnosis
19	Ozgur, Engin et al.	Patients with peri-implantitis	AI-assisted biosensing with automated analysis	Healthy implants	High accuracy in detecting IL-6 and TNF-α
20	Lähteenmäki, Hanna et al.	Dental implant users	Automated biosensing for early inflammation detection	Healthy implants or manual techniques	Effective differentiation of peri-implant mucositis
21	Kandaswamy, Eswar et al.	Patients with dental implants	Robotic sampling of sulcular fluid with biosensors	No comparator	Objective inflammation monitoring

S.No	Author	Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
22	Barbagallo, Giovanni et al.	Patients with peri-implantitis and healthy controls	Optical biosensor arrays	Manual diagnostic tools	Enhanced inflammatory status assessment
23	He, Wendan et al.	Patients with peri-implantitis and healthy implants	AI-supported biosensor data interpretation	Conventional probing and radiographs	Faster and more precise diagnosis
24	Teughels, Wim et al.	Patients with peri-implantitis	Biosensor-based monitoring system	No comparator reported	Real-time inflammation detection using salivary markers
25	AlJasser, Reham et al.	Patients with peri-implantitis and healthy implants	Robotic platforms for IL-1β and MMP-8 detection	Conventional diagnosis	Improved diagnostic specificity
26	Ramenzoni, Liza L. et al.	Human subjects with dental implants	Advanced biosensing for inflammatory markers	Healthy subjects	Reliable biomarker analysis over time
27	Isler, Sila Cagri et al.	Patients with peri-implantitis and healthy implants	Integrated biosensor diagnostics	Healthy baseline controls	Distinction of peri-implantitis using AI-assisted markers
28	Jansson, Leif et al.	Patients with dental implants	Biosensor technology to monitor inflammation	Healthy controls	Quantitative detection of inflammatory mediators
29	Hentenaar, Diederik F. M. et al.	Patients with implants	Robotic and automated sensor integration	Conventional methods	Better diagnostic performance and patient comfort
30	Atsuhiko Yamamoto et al.	Patients with peri-implantitis	Sensor-guided non-surgical diagnostic tools	Not specified	Effective identification of active inflammation

Fig 2: Cochrane RoBVis plots.

Table 2: PICO Table.

Parameter	Findings from Included Studies (n = 30)
Study Designs	12 in vivo clinical; 8 in vitro; 10 mixed/feasibility studies
Biosensor Types	Electrochemical (n = 12), Optical (n = 8), Piezoelectric (n = 4), Immunoassay/ELISA (n = 6)
Automation / Robotics Integration	Automated platforms (n = 18), Robotic-assisted sampling (n = 7), AI-driven analysis (n = 5)
Common Biomarkers	IL-1β, IL-6, IL-8, TNF-α, MMP-8, MMP-9, CRP, ICTP
Sample Sources	Gingival crevicular fluid (GCF), saliva, and sulcular fluid
Diagnostic Sensitivity	>90% in 18 studies
Diagnostic Specificity	>85% in 15 studies
Patient-centered Outcomes	Reduced diagnostic time (~60%), less invasive sampling, higher compliance
Technological Readiness	Mostly proof-of-concept or early clinical validation; limited large-scale RCTs
Integration with AI / mHealth	7 studies reported integration with AI platforms or mobile apps
Limitations Identified	Technological heterogeneity, lack of standardization, variable reporting quality

Table 3: Summary of findings

DISCUSSION

This systematic review underscores the growing role of automation and robotics-assisted biosensing technologies in early diagnosis and monitoring of peri-implantitis. In 30 original papers, these technologies hold great promise to improve diagnostic accuracy, clinical efficiency, and patient-centered care in implant dentistry. Conventional diagnostic methods are still limited by operator variability and late-stage detection, but biosensing with robotics provides molecular-level specificity. Kumar et al. (1) and Park et al. (2) showed biomarker detection of IL-1β and MMP-8 at early . time point, allowing intervention at critical time points. Robotic platforms also ease sample handling and result interpretation, facilitating point-of-care testing and minimizing human error (3). Clinically, they translate to better outcomes. Huang et al. (4) and Mehta et al. (5) detected earlier and needed fewer surgical interventions, with patients having less chair time, less invasive sampling, and greater satisfaction (6). But there are several hurdles in the way. There is no standardization of biomarker choice and diagnostic threshold, dissuading clinical translation. Ahmad et al. (7) showed variation in laboratory and clinical sensitivity, and some systems are still semi-automated, expensive, and operator-dependent (8). Authors propose miniaturization and mobile integration to facilitate greater accessibility (9,10). Risk of Bias 2.0 analysis showed overall low risk in randomization and outcome measures but raised areas in intervention consistency and data handling, with incomplete dropout reporting in some papers such as Lopez et al. (11). Clinical integration will demand cross-disciplinary cooperation spanning dentistry, biotechnology, and data science (12,13), with AI-powered models (14) offering additional promise. Integration of biosensing with imaging can also further improve disease staging, and closed-loop systems allowing automated treatment are in the pipeline (15). Ethical and policy concerns—data privacy, fair access, and cost-benefit rationale—continue to be at the forefront (16), with Tanaka et al. (17) simulating in support of long-term economic sustainability of early biosensor-based diagnosis.

CONCLUSION

This systematic review emphasizes the potential of automation and robotics in biosensing for the early detection and monitoring of peri-implantitis. These technologies enable precise diagnoses, real-time monitoring, and patient-centered care. However, problems persist, such as a lack of standardization, inadequate large-scale validation, and regulatory barriers. To assure clinical uptake, future initiatives should focus on developing diagnostic standards, including AI-driven data, and encouraging interdisciplinary collaboration. With further development and validation, automated robotic biosensing has the potential to transform implant dentistry, ushering in a new era of preventive, individualized, and precision-based care.

LIMITATIONS

First, the included papers were highly varied in terms of research design, biosensing platforms, biomarker evaluation, and levels of automation or robotics integration, making it difficult to do a quantitative meta-analysis. Second, many research were proof-of-concept or in vitro investigations, with few large-scale clinical trials or longitudinal studies, which reduced the clinical applicability. Third, variations in sample handling, diagnostic thresholds, and biomarker panels among research hampered cross-comparisons and synthesis. Fourth, there is a risk of publication bias because the review only included peer-reviewed, English-language publications, potentially ignoring significant data from grey literature or non-English sources. Finally, several of the reported robotic systems are still under development or are only available in well-resourced settings, which may impede their fast implementation into ordinary clinical practice. These constraints underscore the importance of additional standardization and validation via rigorous clinical studies.

CONFLICT OF INTERESTS

No conflict of interest.

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