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Shahriar Shahi, Parisa Jalali, Saba Jabbari & Ahmad Qarebigloo

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Dental Implant Outcomes in Patients with Diabetes Mellitus: A Systematic Review

Shahriar Shahi[1,2], Parisa Jalali[2], Saba Jabbari [3], Ahmad Qarebigloo[4*]

[1] Dental and Periodontal Research Center, Tabriz University of Medical Sciences, Tabriz, Iran

[2]Department of Endodontics, Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran

[3]Department of Oral and Maxillofacial Medicine, Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran

[4]Department of Periodontics, Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran

***Corresponding authors:**

Ahmad Qarebigloo:

Department of Periodontics, Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran.

Tel: +98 41 33363231, +98 9143137315; Fax: +98 41 33363231

E-mail addresses; Aqarebigloo@gmail.com

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Abstract

Objective: This systematic review aimed to evaluate the outcomes of dental implant therapy in patients with diabetes mellitus (DM), focusing on survival rates, peri-implant health, the impact of glycemic control, and the efficacy of adjunctive therapies.

Methods: Following PRISMA 2020 guidelines, a comprehensive search of multiple databases was conducted up to July 2025. Included studies reported on implant outcomes in diabetic patients or relevant animal models. The methodological quality of the included studies was assessed using appropriate tools such as CONSORT, STROBE, and ARRIVE checklists.

Results: Out of 3,637 identified records, 54 studies were included. While overall implant survival rates in diabetic patients were often high (>90-95%), diabetes, particularly when poorly controlled (HbA1c >8%), was consistently associated with significantly worse outcomes. These included greater marginal bone loss (MBL), higher probing depths, increased bleeding on

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probing, and elevated levels of peri-implant inflammatory markers (e.g., IL-6, TNF-α) compared to non-diabetic controls. Well-controlled diabetics (HbA1c ≤7%) often had outcomes comparable to non-diabetics. Adjunctive antimicrobial photodynamic therapy (aPDT) proved effective in improving clinical parameters and reducing inflammation. Preclinical studies on advanced implant surfaces, such as bioactive coatings and 3D-printed porous structures, showed enhanced osseointegration in diabetic conditions.

Conclusion: Dental implant therapy can be successful in well-controlled diabetic patients. However, poor glycemic control significantly increases the risk of peri-implant complications and failure. Successful long-term outcomes necessitate stringent glycemic control, meticulous treatment planning, aggressive maintenance, and the potential application of advanced adjunctive therapies.

Keyword: Diabetes Mellitus, Dental Implants, Peri-Implantitis, Glycemic Control, Treatment Outcome

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Introduction

The rehabilitation of fully or partially edentulous patients through the use of osseointegrated dental implants represents one of the most significant advancements in modern dentistry, offering a predictable and durable solution that restores function, aesthetics, and quality of life. The long-term success of implant therapy, historically reported at high rates in healthy individuals, is fundamentally dependent on a complex biological process of bone healing and adaptation known as osseointegration. This process, however, is highly susceptible to systemic conditions that compromise the host's healing capacity and inflammatory response (1, 2).

Among these conditions, Diabetes Mellitus (DM) stands as a paramount concern for clinicians (3). As a global pandemic, DM affects hundreds of millions of individuals worldwide and is characterized by chronic hyperglycemia resulting from defects in insulin secretion, insulin action, or both (4). The pathophysiological hallmarks of diabetes including the accumulation of Advanced Glycation End-products (AGEs), microangiopathy, immune dysfunction, and a chronic state of low-grade inflammation create a suboptimal environment for bone metabolism and soft tissue healing (5). These systemic alterations pose a direct biological challenge to the osseointegration process and the long-term maintenance of peri-implant health (6). Key concerns include impaired osteoblast function, reduced bone

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formation, increased bone resorption, and a heightened inflammatory response to bacterial biofilm, all of which can predispose diabetic patients to higher rates of early implant failure and late-term complications such as peri-implantitis (7-9).

The clinical dilemma for dental practitioners is a pressing one: while the demand for implant therapy within the growing diabetic population is substantial, the evidence regarding its predictability has been historically ambiguous (10, 11). Early consensus often deemed poorly controlled diabetes a relative or even absolute contraindication for implant placement (12). However, as clinical experience and research have evolved, a more nuanced understanding has emerged. A critical factor modulating this risk appears to be the level of glycemic control, with emerging evidence suggesting that well-controlled diabetic patients may experience outcomes comparable to non-diabetic individuals (13, 14). Yet, the precise thresholds for "safe" glycemic control, the comparative impact of Type 1 versus Type 2 diabetes, and the efficacy of specific surgical protocols and adjunctive therapies in mitigating risk remain areas of active investigation and debate (10, 11).

Furthermore, the existing body of literature is fragmented, comprising studies with heterogeneous designs, varying definitions of success, and diverse follow-up periods. While several systematic reviews have touched upon this topic, the rapid pace of new research including randomized controlled trials on novel adjunctive treatments like antimicrobial photodynamic therapy (aPDT) and pioneering preclinical studies on bioactive implant surfaces necessitates a contemporary and comprehensive synthesis.

Therefore, this systematic review aims to consolidate the current evidence to provide a definitive analysis of the outcomes of dental implant therapy in patients with diabetes mellitus. Specifically, it seeks to: (1) evaluate implant survival and failure rates in diabetic versus non-diabetic populations; (2) assess the impact of diabetes on key clinical, radiographic, and immunological parameters of peri-implant health; (3) elucidate the dose-response relationship between glycemic control (HbA1c levels) and implant outcomes; and (4) synthesize evidence on the efficacy of modern therapeutic strategies, including advanced implant technologies and adjunctive treatments, in optimizing success in this patient cohort. By addressing these objectives, this review will provide an evidence-based foundation to guide clinical decision-making, enhance risk assessment, and improve long-term treatment prognoses for the vast and growing population of diabetic patients seeking dental implant therapy.

Materials and methods

This systematic review was conducted in 2025 following the guidelines provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guide (15).

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Literature search

The information for this systematic review was collected from various databases including PubMed, Scopus, Science Direct, and Web of Science. Relevant keywords were selected through a review of primary texts, consultation with subject experts, and utilizing keywords available in the Mesh (Medical Subject Headings) database. The search strategy was developed and executed by an experienced librarian, guided by an expert in the subject area (Appendix1 - Search strategy in databases). The search period for articles was extended until up to 30 July 2025. To ensure comprehensive coverage, additional manual searches were conducted in relevant journals and Google Scholar. After removing articles weakly related to the study objectives, the selected articles and their references were further searched online to enhance reliability in identifying and reviewing existing literature. Subject experts were also engaged throughout the research process.

The inclusion and exclusion criteria

The study selection will be based on specific criteria. For inclusion, studies must involve diabetic patients (including type 1, type 2, or prediabetes) with dental implants or animal models of diabetes with implants. These studies must evaluate implant outcomes such as survival rates, bone health, or soft tissue conditions and concurrently assess glycemic control (e.g., via HbA1c levels) or related adjunctive therapies. All primary study designs, including randomized controlled trials, cohort, case-control, and cross-sectional studies, are eligible. Conversely, studies will be excluded if their topic is unrelated to the intersection of dental implants and diabetes, if they are review articles, meta-analyses, or abstracts lacking complete data, or if they present no extractable data on the relevant outcomes.

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P (Population): Human patients (or animal models) with a diagnosis of diabetes mellitus (type 1, type 2, or prediabetes).

I (Intervention): Placement and/or maintenance of osseointegrated dental implants, including specific adjunctive therapies (e.g., aPDT) or advanced implant technologies.

C (Comparison): Non-diabetic control groups OR comparisons between diabetic subgroups stratified by glycemic control level (e.g., HbA1c ≤7% vs. >8%) OR comparison of different interventions within diabetic populations.

O (Outcomes): Primary: Implant survival/failure rates, marginal bone loss (MBL). Secondary: Peri-implant clinical parameters (probing depth, bleeding on probing), inflammatory markers, and measures of osseointegration (in animal studies).

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Reporting quality assessment

In this study, the methodological quality of the 17 included retrospective studies was systematically assessed using the JBI Critical Appraisal Checklist for Cohort Studies (16).To assess the reporting quality of the clinical trial studies obtained from the selected databases using the mentioned keywords, two evaluators utilized the Consolidated Standards of Reporting Trials (CONSORT: 2010) checklist. The choice of this checklist was based on its relevance for evaluating interventional studies, specifically clinical trials. Moreover, its translation and validation in the Persian language were considered to evaluate the articles in this study (17). The CONSORT evaluation tool is widely recognized as one of the most important tools for assessing clinical trial articles. It was introduced in the mid-1990s by a group of clinical trial experts, statisticians, and epidemiologists to establish an international standard for reporting clinical trials. The latest version of this checklist, CONSORT 2010, comprises 37 items that assess six main areas of clinical trial studies. These sections include title and abstract, introduction, materials and methods, results, discussion, and other information. Each section consists of various components for evaluation (18-20). Observational studies (In addition to the longitudinal study) were assessed using the STROBE checklist. The STROBE Statement was developed to assist authors when writing up analytical observational studies, to support editors and reviewers when considering such articles for publication, and to help readers when critically appraising published articles (21). Animal studies were assessed with the ARRIVE checklist. The ARRIVE guidelines (Animal Research: Reporting of in Vivo Experiments) were originally developed in 2010 to improve the reporting of animal research. They consist of a checklist of information to include in publications describing in vivo experiments to enable others to scrutinize the work adequately, evaluate its methodological rigor, and reproduce the methods and results (22). In addition, the JBI Critical Appraisal Checklist for Cross-sectional (23), Case-Control (24),was used. This checklist provides specific criteria for assessing methodological rigor and reporting standards(25) . The case report study was also reviewed with the CARE tool. The CARE Checklist provides a framework for writing case reports that can be adapted to include specialty-specific information (26). Each article was scored based on the final agreement of two evaluators. In cases where the two evaluators did not agree, a third person (SH.SH) with more knowledge and experience in the field was consulted for an opinion. (Appendix 3)

Data extraction

To extract data, three separate data collection forms were designed using Word 2016 software. These forms included a general characteristics form for article information, an intervention information and

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results form, and a form for recording outcomes. During the pilot phase, these forms were used to collect data from three articles and any defects or problems in the initial forms were corrected. The actual data collection was then conducted independently by two people using the revised forms.

Data entered from studies include the following:

Author/Year, country, Study Design, participants, follow-up, Type of diabetes, HbA1c level, Implant characteristics, Diabetes control medications, Immediate implants or delayed implants, Inflammatory markers, Use of technology, Nutritional support, Duration of illness, Implant position, Changes in indicators, outcome.

Data analysis methods

The extracted data were analyzed manually, and descriptive statistics such as percentages, frequencies, averages, and other relevant measures were utilized to report the findings.

Due to the huge diversity in the reporting format of results and the nature of data reporting in included studies, conducting the meta-analysis was not viable.

Publication Bias Assessment

Given the narrative nature of this synthesis and the significant heterogeneity among the included studies in terms of design, outcome measures, and patient populations, a formal quantitative assessment of publication bias (such as funnel plot asymmetry or Egger's test) was not feasible or methodologically appropriate. However, to minimize the risk of publication bias and to ensure a comprehensive search, the following strategies were employed:

1. **Comprehensive Search Strategy:** We conducted systematic searches across multiple databases (PubMed, Scopus, Web of Science, ScienceDirect) without language restrictions up to July 2025.
2. **Grey Literature Search**: We actively searched for unpublished studies, ongoing trials, and conference abstracts through sources such as the Healthcare Management Information Consortium (HMIC), as well as manual searches in Google Scholar
3. **Hand-Searching of References:** The reference lists of all included studies and relevant review articles were manually screened to identify any additional eligible studies that might not have been captured by the electronic search.
4. **Comprehensive Search Strategy:** We conducted systematic searches across multiple databases (PubMed, Scopus, Web of Science, ScienceDirect) without language restrictions up to July 2025.

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GRADE Certainty of Evidence Assessment

The certainty of the evidence for key outcomes assessed in this systematic review was evaluated using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) framework. The GRADE approach assesses evidence across five domains that may lower certainty: risk of bias, inconsistency, indirectness, imprecision, and publication bias. Evidence can also be upgraded based on a large magnitude of effect, a dose-response gradient, or if residual confounding would likely reduce an apparent effect. Given the narrative synthesis of this review, a formal GRADE assessment with evidence profile tables (Summary of Findings tables) was not constructed for all outcomes. However, the overall certainty of the body of evidence for the main review conclusions was appraised as follows:

- **the association between diabetes (especially poor glycemic control) and increased peri-implant bone loss/inflammation:** The certainty was judged as moderate. While consistent across numerous observational studies and supported by plausible biological mechanisms (dose-response gradient), the evidence is primarily from non-randomized studies (mainly cohort and case-control designs), which start as low certainty due to potential residual confounding. The consistency of findings across different populations and study designs supports an upgrade.

- **the comparable implant survival rates between well-controlled diabetics and non-diabetics:** The certainty was judged as Low. This conclusion is based on observational comparisons where "well-controlled" groups are self-selected. Unmeasured confounding factors (e.g., overall health behaviors, access to care) could influence both glycemic control and implant outcomes.

- **the efficacy of adjunctive aPDT in improving clinical parameters in diabetic patients with peri-implant disease:** The certainty was judged as moderate. This is based on several randomized controlled trials (RCTs), which start as high-certainty evidence. The rating was downgraded one level due to **imprecision**, as the total number of participants across trials is still relatively modest, and confidence intervals around effect estimates are sometimes wide.

- **the findings from preclinical (animal) studies on advanced implant surfaces:** The certainty of evidence for direct clinical applicability is judged as very low. While these studies provide important mechanistic insights, they constitute indirect evidence for human outcomes (serious **indirectness**) and are at high risk of bias due to the inherent limitations of animal models in fully replicating human diabetic pathophysiology and the oral environment.

Definition and Harmonization of Outcome Measures

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Implant Survival: Most commonly defined as the implant remaining in situ at follow-up, regardless of its condition. Some studies used more stringent criteria (e.g., absence of pain, infection, or mobility).

Implant Success: Cited criteria included those by Albrektsson et al., Misch, or study-specific composites (e.g., survival + MBL < 1.5 mm + absence of suppuration).

Marginal Bone Loss (MBL): Measured from implant-abutment junction or a baseline radiograph, with thresholds for "success" ranging from <1.0 mm to <2.0 mm after the first year.

Peri-Implantitis: Varied definitions based on combinations of BOP/suppuration, probing depth increases, and radiographic bone loss thresholds (e.g., ≥2 mm, ≥3 mm).

Because of this definitional heterogeneity, we did not aggregate these outcomes quantitatively in a meta-analysis. Instead, our narrative synthesis focused on identifying consistent directional trends (e.g., greater bone resorption in diabetics) and dose-response relationships (e.g., worsening outcomes with increasing HbA1c) that were robust across definitions.

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Results

A total of 3,637 records were identified through database searching (n=3,546) and additional sources (n=91). After removal of 325 duplicates, 3,312 records were screened by title and abstract. Of these, 3,223 were excluded as irrelevant. Full-text assessment was performed for 89 articles, of which 35 were excluded with reasons. Ultimately, 54 studies met the inclusion criteria and were included in the systematic review. (Fig 1).

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A total of 54 studies, published until 2025, were included in this systematic review. The findings are structured according to the extracted data on study characteristics, and methodological quality (Table 1) (Appendix2 - data extractions forms included detailed data from included studies).

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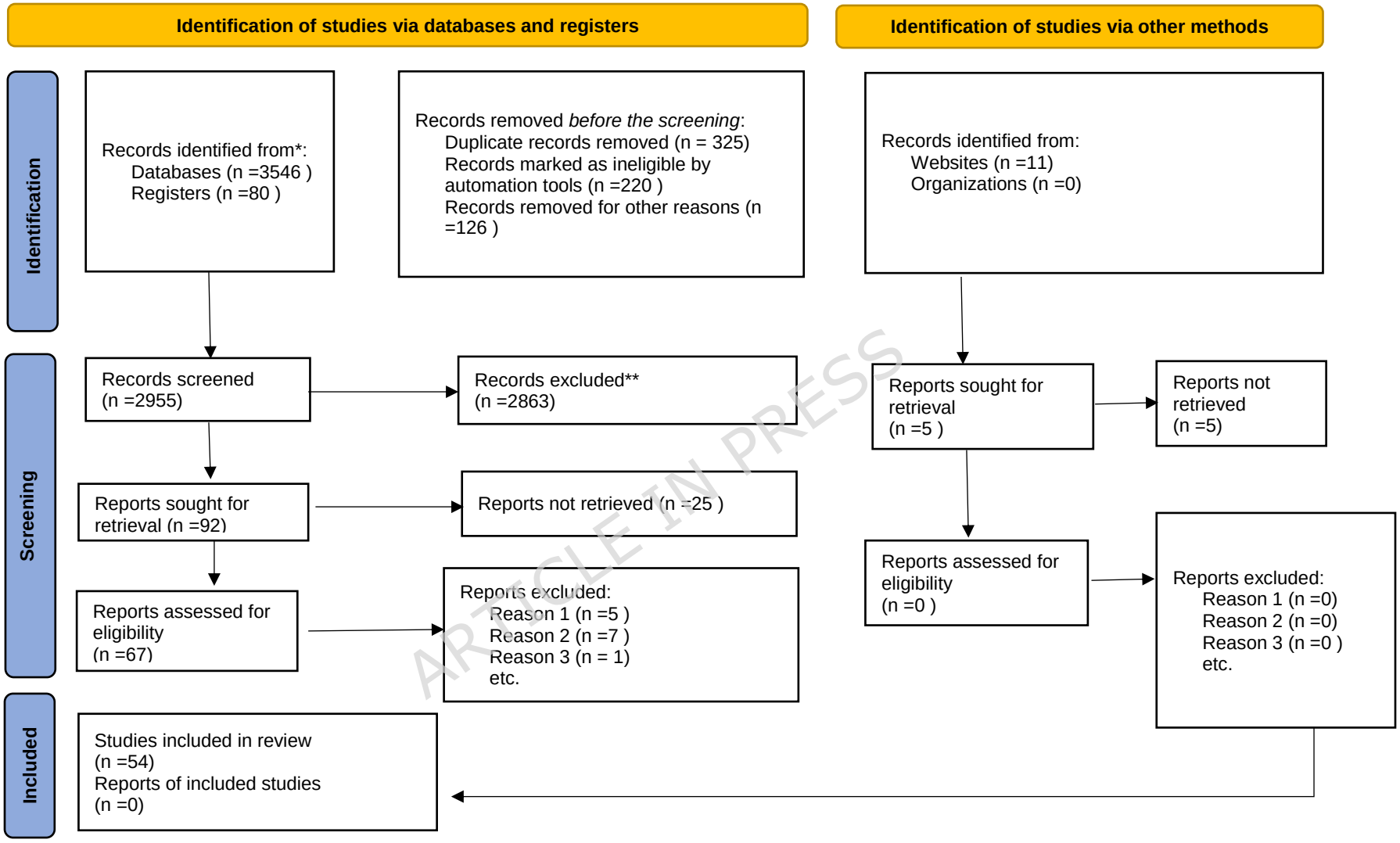

*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools. *From:* Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Fig 1: PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources

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Study Selection and Characteristics

This systematic review included 54 studies that examined the outcomes of dental implants in patients with diabetes mellitus. Study designs were diverse, with most studies including 17 retrospective clinical studies, 14 (RCT[1]), and nine prospective clinical/observational studies. The geographical distribution was broad, with a significant number of studies conducted in Saudi Arabia (17), followed by India (7), China (4), and Egypt (5). The vast majority of studies focused on Type 2 Diabetes Mellitus (T2DM) (Table 1).

Table 1: Summary of the characteristics of the articles that reported the results of the dental implants in patients with diabetes mellitus

Variables	Variable level	*N (%)*	*Variables*	Variable level	*N (%)*
Countries Conducting Studies (54)	Saudi Arabia	17 (31)	**Type of Diabetic**	Type 2	44 (81)
	India	7 (13)		Type 1	1 (2)
	Egypt	5 (9)		Both types	1 (2)
	China	4 (7)		Prediabetes	1 (2)
	USA	3 (5)		No Reports	7 (13)
	South Korea	3 (5)	**The year of the study(54)**	2017	7 (13)
	Brazil	2 (4)		2023	6 (11)
	Pakistan (1), Greece(1), Russia(1),Thailand(1), Italy(1),Romania(1), Sweden(1), Bangladesh(1), Spain(1), Iraq(1), Nepal(1), Turkey(1), no reports(1)			2020	5 (9)
				2021	5 (9)
				2018	5 (9)
				2024	4 (7)
				2022	4 (7)
				2019	4 (7)
				2016	3 (5)
				2012	2 (4)
				2009	2 (4)
				2025	2 (4)
Study design (54)	retrospective clinical studies	18 (33)		2000	1 (2)

[1] Randomized Controlled Trials

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	RCT	18 (33)		2002	1 (2)
	Observational study	2 (4)		2003	1 (2)
	Animal Study	8 (15)		2014	1 (2)
	Cross sectional	5 (9)		2010	1 (2)
	Case control	1 (2)			
	Case report	1 (2)			
	Longitudinal study	1 (2)			

Participant numbers in clinical studies ranged from single case reports to large-scale retrospective analyses, such as a nested case-control study with 830 patients and a retrospective analysis of 1,090 patients. Follow-up periods were equally diverse, spanning from short-term assessments at 3 months to long-term evaluations exceeding 5 years, with some studies reporting outcomes up to 13 years [28] and a mean follow-up of approximately 9.2 years.

1. Glycemic Control

Well-controlled (HbA1c ≤7%): Studies such as Kim et al. (2009), Kaushik (2024), and Turkyilmaz (2010) reported high implant survival rates (≥95%) and minimal complications in well-controlled diabetic patients. Al Amri et al. (2016) and Elserity et al. (2023) showed that good glycemic control is associated with stable peri-implant parameters and reduced crestal bone loss (CBL).

Moderately controlled (HbA1c 7–8%): Gomez-Moreno et al. (2014) and Goel et al. (2017) observed gradual increases in marginal bone loss (MBL) and inflammatory markers as HbA1c rose within this range. Al Amri et al. (2016) noted higher probing depth (PD) and bleeding on probing (BOP) in moderately controlled groups compared to well-controlled patients.

Poorly controlled (HbA1c >8%): Studies such as Ahmed et al. (2020), Alsayed et al. (2023), and Alshahrani et al. (2020) consistently reported higher plaque indices, BOP, PD, and CBL in poorly controlled diabetics.

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Alberti et al. (2020) noted that the only patient with multiple implant failures had HbA1c levels between 8–9%.

2. Diabetes Type

Type 2 Diabetes (T2DM): The majority of studies (48/54) focused on T2DM. Outcomes varied widely based on glycemic control and comorbidities. Well-controlled T2DM patients exhibited outcomes comparable to non-diabetics in studies like Al-Shibani et al. (2018) and Al Zahrani et al. (2018).

Type 1 Diabetes (T1DM): Limited data; Ayele et al. (2023) reported significantly higher marginal bone loss in T1DM compared to T2DM and non-diabetics. Alberti et al. (2020) noted that the only patient with early implant failures had T1DM with poor control.

Prediabetes: Abduljabbar (2017) found that adjunctive antimicrobial photodynamic therapy (aPDT) improved peri-implant outcomes in prediabetic patients, suggesting early intervention may mitigate risks.

3. Follow-up Duration

Short-term (≤1 year): Most RCTs (e.g., Ahmed et al., 2020; Elsadek, 2023) focused on short-term outcomes, showing significant improvements in clinical parameters with adjunctive therapies like aPDT. Animal studies (e.g., Huang et al., 2021; Duan et al., 2020) demonstrated early osseointegration challenges in diabetic models.

Medium-term (1–5 years): Studies such as Gomez-Moreno et al. (2014) and Al Amri et al. (2016) reported stable implant survival but gradual increases in MBL over time in diabetic groups.

Long-term (>5 years): Kim et al. (2009), Al Zahrani et al. (2018), and Ayele et al. (2023) showed that diabetes—especially poorly controlled—is associated with higher long-term bone loss and implant failure rates. Kaushik (2024) reported successful 8-year survival in a well-controlled T2DM patient, highlighting the importance of glycemic management.

4. Implant Loading Protocol

Immediate Loading: Studies such as Said (2022) and Juncar et al. (2019) reported successful outcomes in well-controlled diabetics with immediate loading. Ibraheem et al. (2019) found no significant difference in bone loss between immediate and delayed loading in controlled T2DM patients.

Delayed Loading: The majority of clinical studies employed delayed loading protocols, especially in patients with poorer glycemic control. Al Zahrani et al. (2018) noted significantly greater CBL in poorly

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controlled diabetics with delayed loading, suggesting that glycemic status outweighs loading protocol influence.

Glycemic Control and Diabetes-Related Parameters

Glycemic control was primarily assessed using HbA1c levels. Inclusion criteria for diabetic participants varied across studies, with many defining "controlled" diabetes as HbA1c ≤7%, while others included poorly controlled patients with HbA1c >8%. Baseline HbA1c values reflected this range, from well-controlled levels around 6.1% in prediabetes studies to poorly controlled levels exceeding 9% in others. Diabetes management typically involved a combination of oral hypoglycemic agents (e.g., Metformin), insulin therapy, and dietary control. The mean duration of diabetes illness was frequently reported, often ranging between 8 to 12 years in long-standing T2DM cohorts.

Implant Characteristics and Surgical Protocols

A wide array of implant systems was utilized, including Straumann , Astra Tech, Nobel Biocare , and BioHorizons , among others. Implant dimensions varied, with diameters commonly between 3.3 mm and 4.8 mm and lengths from 8.5 mm to 15 mm. Surface characteristics were often moderately rough or sandblasted, acid-etched (SLA). Platform-switching designs were noted in several studies.

Surgical and loading protocols were diverse. The majority of studies employed a delayed loading protocol, while others investigated immediate loading. Implant placement included both crestal and subcrestal positions, with one RCT finding significantly less mesiodistal crestal bone loss and higher initial stability with subcrestal placement. Flapless surgery was compared to conventional flap surgery in one study, with the flapless technique demonstrating better soft tissue parameters and less crestal bone loss over one year.

Impact of Diabetes on Clinical, Radiographic, and Immunological Outcomes

Implant Survival and Failure: Overall implant survival rates in diabetic patients were generally high, often reported above 90-95% over medium- to long-term follow-up. However, several studies identified diabetes as a significant risk factor for implant failure. A large nested case-control study (n=830) found T2DM to be associated with increased odds of implant failure (early and late) in univariate and partially adjusted models, alongside other significant risk factors like advanced periodontitis (Stages III-IV),

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smoking, and osteoporosis. Another multicenter retrospective study (n=663) reported a marginally higher failure rate in T2DM patients (92.2% survival vs. 93.2% in non-diabetics over 36 months).

Marginal Bone Loss (MBL/CBL): The impact of diabetes on peri-implant crestal bone loss was a key finding. Multiple studies reported significantly greater MBL in diabetic patients compared to non-diabetic controls. Ayele et al. (2023) demonstrated that MBL over 5-10 years was significantly greater in diabetic patients, with T1DM patients showing the highest bone loss (-2.28 mm), followed by T2DM patients (-1.47 mm), and non-diabetics (-0.91 mm). Al Zahrani et al (2018) found that poorly controlled T2DM patients experienced significantly greater bone loss at all follow-up intervals (1, 2, 3, and 7 years) compared to well-controlled diabetics. Conversely, some studies found no significant difference in MBL between well-controlled diabetics and non-diabetics.

Peri-Implant Tissue Health: Diabetic patients, particularly those with poor glycemic control, consistently exhibited worse peri-implant clinical parameters. Studies reported significantly higher Plaque Index (PI), Gingival Index (GI), Bleeding on Probing (BOP), and Probing Depth (PD) in diabetic groups compared to non-diabetic controls. Gomez-Moreno et al. (2014) observed a direct correlation, with groups having higher HbA1c levels (8.1-10.0% and >10.1%) demonstrating significantly greater BOP and a gradual increase in MBL over three years.

Implant Survival vs. Peri-Implant Health by Glycemic Control

Glycemic Control (HbA1c)	Implant Survival Rate (Range/Summary)	Peri-Implant Health (Key Findings)
Well-controlled (≤7%)	95–100% in most studies	- Minimal crestal bone loss (CBL) <1.5 m - Low BOP & PD - Comparable to non-diabetics
Moderately controlled (7–8%)	92–98% (slight increase in late failures)	- Gradual increase in CBL (1.5–2.5 mm) - Mild inflammation - Higher BOP than well-controlled
Poorly controlled (>8%)	85–94% (higher early failure risk)	- Significant CBL (>2 mm) - High BOP, PD, plaque - Elevated inflammatory cytokines

Inflammatory and Microbiological Markers: A strong pro-inflammatory state was evident in diabetic implant patients. Multiple RCTs reported significantly elevated levels of inflammatory cytokines, including Interleukin-6 (IL-6), IL-1β, and Tumor Necrosis Factor-alpha (TNF-α), in the Peri-Implant Sulcular Fluid (PISF) of diabetics. Adjunctive therapies like antimicrobial photodynamic therapy (aPDT) were effective in significantly reducing these cytokine levels. One cross-sectional study found

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significantly higher IL-6 levels and a different bacterial profile (predominance of Streptococcus pyogenes) in the peri-implant crevicular fluid of diabetics compared to controls.

Efficacy of Adjunctive Therapies

Antimicrobial Photodynamic Therapy (aPDT): Several RCTs demonstrated the efficacy of aPDT as an adjunct to mechanical debridement (MD) for treating peri-implant diseases in diabetics. aPDT using various photosensitizers (Indocyanine Green, Methylene Blue, Phenothiazine Chloride) led to significant improvements in BOP, PD, microbial counts, and inflammatory markers compared to mechanical debridement alone. The benefits were often more pronounced in the short-term (3 months) but remained significant at 6 months.

Advanced Implant Technologies and Surface Modifications:

Surface Modifications: An animal study by Zhang et al. (2023) showed that titanium implants with TiO_2 nanotube arrays loaded with a recombinant peptide (minTBP-1-IGF-1) significantly improved osseointegration in T2DM rats, resulting in higher bone volume, mineral apposition rate, and better bone-implant contact compared to machined surfaces.

Selective Laser Melting (SLM): Duan et al. (2020) reported that 3D-printed porous Ti-6Al-4V implants fabricated via SLM promoted significantly better early osseointegration in T2DM rats at 4 weeks compared to traditional SLA and pure titanium implants.

Gene Delivery: A novel approach using chitosan-gold nanoparticles to deliver PPARγ cDNA to implant surfaces in diabetic rats resulted in enhanced bone volume, reduced inflammation, and improved mitochondrial function, indicating a potential future therapeutic strategy.

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Findings from Animal Studies

Animal models consistently corroborated clinical findings. Diabetes was shown to impair bone density around implants, decrease Bone-Implant Contact (BIC) and new bone formation, and reduce biomechanical retention (removal torque). Insulin therapy in animal models helped maintain bone density but did not fully normalize biomechanical retention to non-diabetic levels. Therapeutic interventions in animals, such as treatment with the adiponectin receptor agonist AdipoRon or the use of porous Titanium Nickelide (TiNi) implants, showed promising results in improving osseointegration under diabetic conditions.

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Preclinical Evidence from Animal Studies

Animal models provide crucial mechanistic insights and a platform for testing novel interventions. Findings are organized into two themes: Consistent Negative Impact of Diabetes on Osseointegration: Studies in rat, rabbit, and mouse models uniformly confirmed that induced diabetes (primarily T2DM) significantly impairs osseointegration. Key findings included: Reduced bone-to-implant contact (BIC%) and bone volume/total volume (BV/TV) Diminished biomechanical retention (lower removal torque values) Elevated pro-inflammatory osseous microenvironment (De Morais et al., 2009; Margonar et al., 2003; Sam et al., 2020).

Comparative Analyses

Diabetic vs. Non-Diabetic: The synthesized evidence indicates that while dental implants can be successful in well-controlled diabetic patients, the condition—particularly when poorly controlled poses a significant risk for increased peri-implant inflammation, accelerated crestal bone loss, and a higher rate of implant failure.

Impact of Control Level: A clear gradient of risk was observed, where poorly controlled diabetics (higher HbA1c) consistently had worse outcomes than well-controlled diabetics, who, in turn, often had outcomes comparable to or only slightly worse than non-diabetics.

Comorbidities: The presence of comorbidities such as smoking and Major Depressive Disorder (MDD) was found to compound the risks associated with diabetes, leading to poorer peri-implant health.

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Discussion

This systematic review synthesized evidence from 54 studies to evaluate the complex relationship between diabetes mellitus and dental implant outcomes. The findings paint a multifaceted picture: while dental implant therapy in well-controlled diabetic patients can achieve high survival rates comparable to non-diabetic populations, diabetes mellitus, particularly when poorly controlled, unequivocally presents a significant biological challenge that heightens the risk of peri-implant complications and failure. The discussion will contextualize these findings within the established pathophysiological framework of diabetes and explore their clinical implications.

The Dual Paradigm: Survival vs. Health

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A central theme emerging from this review is the critical distinction between implant survival and peri-implant health. The consistently reported high survival rates (often >90-95%) in diabetics [18, 28, 30, 43] might suggest that implant therapy is universally successful in this population. However, this metric alone is misleading. Survival simply denotes the presence of the implant, while a more informative measure is the health of the surrounding tissues (27). Our analysis reveals that even in cases of high survival, diabetic patients frequently exhibit significantly worse peri-implant parameters, including increased probing depths, bleeding on probing, and accelerated marginal bone loss. This aligns with the well-documented "survivorship bias" in implant dentistry, where successful implants are counted, but the subclinical or early-stage disease processes affecting them are often overlooked. Therefore, the clinical goal in diabetic patients should not merely be osseointegration and retention of the implant, but the long-term maintenance of peri-implant tissue health.

Glycemic Control: The Cornerstone of Predictability

The most compelling evidence from this review underscores glycemic control as the paramount determinant of implant success. The results demonstrate a clear "dose-response" relationship: poorer glycemic control (reflected by higher HbA1c levels) is directly associated with worse clinical outcomes. Studies that included well-controlled diabetics (HbA1c ≤7%) often found no significant differences in crestal bone loss or survival rates compared to non-diabetics. In contrast, poorly controlled diabetics (HbA1c >8%) consistently experienced significantly greater bone loss and inflammatory markers.

This dichotomy is explainable by the underlying pathobiology of diabetes. Chronic hyperglycemia drives the formation of Advanced Glycation End-products (AGEs), which accumulate in periodontal and peri-implant tissues. The interaction of AGEs with their receptors (RAGE) on macrophages and fibroblasts perpetuates a state of chronic inflammation, characterized by the upregulation of pro-inflammatory cytokines such as IL-1β, IL-6, and TNF-α markers that were significantly elevated in the PISF of diabetic patients in several included studies. Furthermore, hyperglycemia impairs neutrophil function, angiogenesis, and osteoblast activity, thereby compromising the host's defensive and regenerative capacities. Consequently, the osseointegration process is slower and less robust, and the peri-implant tissues are rendered more susceptible to the destructive effects of bacterial biofilm, leading to accelerated bone loss. The finding that Type 1 Diabetic (T1DM) patients exhibited the greatest marginal bone loss is particularly noteworthy and may reflect the longer disease duration and more labile glycemic control often associated with T1DM.

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The Compounding Effect of Comorbidities and Risk Factors

Diabetes rarely exists in isolation. This review highlights that its detrimental effects are significantly amplified by the presence of other risk factors. Smoking and diabetes have a well-established synergistic negative effect on periodontal health, and this review confirms the same is true for peri-implant tissues (28). The large nested case-control study by Sobhani et al. (2025) identified periodontitis (Stages III-IV) as the strongest risk factor for implant failure, with an odds ratio of 12.82, far exceeding that of T2DM alone. This underscores the critical concept of the "periodontally compromised patient," where a history of periodontitis is a major predictor of future peri-implantitis (29). The presence of other systemic conditions, such as Major Depressive Disorder (MDD) and osteoporosis, further complicates the clinical picture, likely through mechanisms involving neglect of oral hygiene, altered healing responses, and systemic bone metabolism. This cumulative risk model necessitates a holistic patient assessment rather than considering diabetes as an isolated variable (30-32).

The Promising Role of Adjunctive and Advanced Therapies

The challenges posed by the diabetic environment have spurred research into therapeutic countermeasures. The consistent positive outcomes of Antimicrobial Photodynamic Therapy (aPDT) across multiple RCTs are highly significant. aPDT appears to be a powerful tool for disrupting the dysbiotic biofilm and mitigating the hyperinflammatory state in diabetic patients (33). Its ability to significantly reduce key pathogens and pro-inflammatory cytokines in PISF offers a mechanism to break the cycle of inflammation and tissue destruction, making it an invaluable adjunct to conventional mechanical debridement in the management of peri-implant diseases in this vulnerable population (34).

Furthermore, the evolution of implant surface technology holds great promise. Animal studies included in this review demonstrate that merely achieving osseointegration is not sufficient; enhancing the quality and speed of integration is crucial in a compromised host. Surface modifications such as TiO_2 nanotubes functionalized with osteogenic peptides (minTBP-1-IGF-1) represent a shift from a passive to an active implant surface that can locally stimulate bone healing. Similarly, the use of 3D-printed porous implants fabricated via Selective Laser Melting (SLM) and implants coated with gene-activated nanoparticles (PPARγ cDNA) are groundbreaking approaches that aim to directly counteract the cellular and molecular deficits induced by diabetes. While these technologies are predominantly in the preclinical stage, they point toward a future of "smart" implants designed specifically for challenging medical conditions.

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Translating Preclinical Innovation to Clinical Practice

The promising results from animal studies on surface-modified and drug-eluting implants represent a frontier for clinical translation. Future human trials should evaluate these technologies, particularly in moderate- and high-risk diabetic patients. The preclinical evidence solidifies the biological rationale for stringent glycemic control and supports investigation of adjuvant systemic medications that may enhance bone metabolism in diabetics.

Clinical Recommendations and Future Directions

Synthesizing these findings allows for the formulation of evidence-based clinical recommendations:

1. Strict Patient Selection and Preparation: Implant therapy should be approached with caution in diabetic patients. A prerequisite should be a period of stable glycemic control (HbA1c <7-8%, with a lower threshold being preferable) demonstrated pre-operatively. A comprehensive periodontal evaluation and treatment are mandatory to establish a stable oral environment (35).

2.Meticulous Surgical and Prosthetic Protocol: Employing proven implant systems with modern, hydrophilic surfaces is advised. Consideration of a longer healing period before loading may be beneficial to allow for delayed osseointegration (36). The choice between flap and flapless surgery, as well as crestal and subcrestal placement, should be made based on individual patient anatomy and risk profile, with some evidence favoring subcrestal placement for bone preservation in controlled diabetics (37, 38).

3. Aggressive and Specialized Maintenance: Diabetic patients must be enrolled in a stringent, lifelong supportive peri-implant care program. This should include more frequent recall visits (e.g., every 3-4 months) and a low threshold for employing adjunctive therapies like aPDT at the first signs of mucositis to prevent progression to peri-implantitis.

4. Holistic Risk Management: Clinicians must actively screen for and address co-existing risk factors, such as smoking and poor oral hygiene, through counseling and intervention.

Future research should focus on long-term (>10 years) prospective studies that track not just survival but also detailed clinical, radiographic, and immunological parameters in well-characterized diabetic cohorts. Randomized trials comparing different implant surfaces and loading protocols specifically in diabetic

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patients are needed. Finally, translational research to bring innovative surface modifications and local drug delivery systems from the laboratory to the clinic should be prioritized.

Limitations

This discussion is based on the data extracted from the provided table, which itself is a summary. The inherent limitations of the included studies, such as variation in study design, definitions of "success," follow-up duration, and criteria for glycemic control, contribute to heterogeneity. Furthermore, publication bias towards positive outcomes is possible. The conclusions are therefore a synthesis of trends and consistent findings across a diverse body of literature.

Conclusion

In conclusion, diabetes mellitus transforms the peri-implant environment into a pro-inflammatory and healing-compromised state, tipping the balance from health to disease. While not an absolute contraindication, it is a significant modifier of risk and outcome. Success is not guaranteed by the implant's survival alone but is defined by the sustained health of the peri-implant tissues. Achieving this requires a rigorous, multifaceted approach centered on stringent glycemic control, meticulous surgery, and an intensive, proactive maintenance regimen supported by advanced adjunctive therapies. The future of implant dentistry in diabetic patients lies in personalized treatment planning that acknowledges this biological challenge and leverages both established protocols and emerging technologies to ensure long-term success.

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Declarations:

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable.

Availability of data and materials

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All data generated or analysed during this study are included in this published article [and its supplementary information files]

Competing interests

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Author contributions

SH.SH and GH. A gave the idea of this study and searched the databases in cooperation with each other and analyzed them after screening and extracting the data and wrote the initial manuscript. J.P and J.S contributed to the screening and analysis of this study. SH.SH and GH. A participated in data extraction and writing the initial manuscript.

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