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Clinical Efficacy and Osseointegration of Bioactive Surface versus SLA Surface Dental Implants in Patients Requiring Implant Therapy: A Systematic Review and Meta-Analysis

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Abstract: ***Background**: Surface characteristics of dental implants significantly influence clinical success and osseointegration. Bioactive surfaces are hypothesised to enhance osseointegration more effectively than conventional sandblasted, large-grit, acid-etched (SLA) surfaces. **Objective**: To systematically compare the clinical efficacy and implant stability of bioactive versus SLA surface implants in patients undergoing dental implant therapy. **Methods**: This systematic review and meta-analysis followed PRISMA 2020 guidelines and was registered with PROSPERO (CRD420251024387). Randomised controlled trials (RCTs) comparing bioactive and SLA surface implants with reported implant stability quotient (ISQ) values were included. PubMed, Cochrane CENTRAL, and Web of Science were searched up to June 2024. Meta-analyses employed both fixed- and random-effects models. Risk of bias was evaluated using the Cochrane RoB 2.0 tool; heterogeneity and publication bias were assessed using I^2 statistics, Egger's test, and Begg's test. **Results**: Ten RCTs involving 468 implants (232 bioactive, 236 SLA) were analysed. At baseline, bioactive surfaces demonstrated significantly higher stability (SMD = 0.365; 95% CI: 0.026–0.704; $p = 0.035$). At follow-up (6–12 weeks), this advantage increased markedly (SMD = 0.880; 95% CI: 0.372–1.388; $p = 0.001$). Heterogeneity was moderate to high (I^2 = 69.42%–85.19%). No significant publication bias was detected. **Conclusion**: Bioactive implant surfaces are associated with superior implant stability, particularly during early healing. These findings support their clinical use to enhance osseointegration in patients requiring dental implant therapy.**

Keywords: bioactive surface; SLA surface; dental implants; osseointegration; implant stability quotient; systematic review; meta-analysis

1. Introduction

Osseointegration, first described by Brånemark in 1969 and further defined by Albrektsson et al., refers to the functional and structural integration of living bone with the surface of a titanium dental implant [7, 8]. The initial use of machined implants marked a milestone in implantology; however, their bioinert properties prompted the development of surface modifications to improve biological performance.

Titanium's limited bioactivity has led to extensive research into surface enhancement strategies. Topographical modifications on micro- to nanoscale levels have shown promise in stimulating bone cell responses and promoting early healing. By altering the implant's texture, the interaction between bone cells and the implant surface can be optimised [9, 10].

Common surface modification methods include sandblasting, acid etching, anodisation, and titanium plasma spraying. Coatings incorporating bioactive materials- such as hydroxyapatite, bioactive glass, bisphosphonates, and collagen- have demonstrated improved osseointegration in both clinical and experimental settings [10].

Bio-functionalisation of implant surfaces not only enhances osseointegration but may also confer antibacterial properties that reduce the risk of peri-implant infections. These advances are particularly advantageous in cases requiring early or immediate loading, or in patients with compromised bone quality.

Given the rapidly evolving landscape of implant surface technologies, there is a pressing need to synthesise the available evidence through rigorous systematic reviews. This study aims to compare the effectiveness of bioactive versus

SLA surfaces in promoting osseointegration, as measured by the implant stability quotient (ISQ) from randomised clinical trials.

2. Methods

2.1 Protocol and Registration

This review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [1]. The review protocol was registered with PROSPERO (CRD420251024387) prior to study selection.

2.2 Focused Question

The search strategy was guided by the PICO framework: "In patients receiving titanium dental implants, do bioactive implant surfaces enhance osseointegration more effectively than SLA surfaces, as measured by ISQ values?"

2.3 Search Strategy

Electronic searches were conducted in PubMed, Cochrane CENTRAL, Embase, Scopus, and Web of Science up to June 2024. The PubMed search string was: ("dental implants" [MeSH Terms] OR "implant surface" OR "bioactive surface" OR "SLA surface") AND ("esseointegration" OR "implant stability" OR "ISQ") AND (randomized controlled trial[pt] OR randomized[tiab] OR placebo[tiab]). Adapted strategies were used for other databases. Searches were restricted to human studies, with no language restrictions applied. Full search strings for all databases are provided in Supplementary Table S1.

2.4 Eligibility Criteria

Studies were eligible if they: (i) were published in English; (ii) involved titanium dental implants placed in human participants; (iii) were RCTs comparing bioactive with SLA surface implants; and (iv) reported ISQ as an outcome measure. Studies were excluded if they were in vitro studies, narrative or systematic reviews, case reports, or did not otherwise meet the eligibility criteria.

2.5 Data Extraction

Titles and abstracts were screened independently by two reviewers (S.J. and S.R.) using a standardised spreadsheet. Disagreements were resolved by discussion and, where necessary, by a third reviewer. Full texts of potentially eligible studies were retrieved and assessed for final inclusion.

2.6 Risk of Bias Assessment

Methodological quality was assessed independently by two reviewers using the Cochrane Risk of Bias 2.0 (RoB 2.0) tool [4], which evaluates five domains: (D1) randomisation process; (D2) deviations from intended interventions; (D3) missing outcome data; (D4) measurement of the outcome; and (D5) selection of reported results.

2.7 Statistical Analysis

Standardised mean differences (SMD) with 95% confidence intervals (CI) were computed using both fixed- and random-effects models. Heterogeneity was quantified using the I^2 statistic. Publication bias was assessed using funnel plots, Egger's regression test [5], and Begg's rank correlation test [6] when 10 studies were available for a given outcome.

2.8 Certainty of Evidence

The certainty of evidence was rated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach, considering risk of bias, inconsistency, indirectness, imprecision, and publication bias.

3. Results

3.1 Study Selection

A total of 1,328 records were retrieved from electronic databases. After removal of duplicates, 246 records remained and underwent title and abstract screening. Ten RCTs involving 468 implants (232 bioactive, 236 SLA) met the eligibility criteria and were included in the final analysis. The full selection process is detailed in the PRISMA 2020 flow diagram (Figure 1).

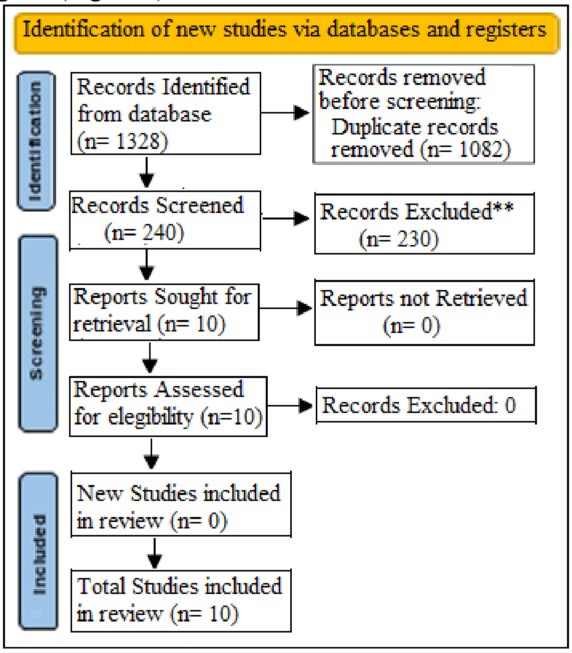

Figure 1: PRISMA 2020 flow diagram illustrating the systematic search and selection process. Records were identified via PubMed, Cochrane CENTRAL, Web of Science, Embase, and Scopus

3.2 Risk of Bias

Risk of bias assessment across the included studies is presented in Table 5. Three studies were rated as low risk across all RoB 2.0 domains. Five studies raised some concerns, primarily regarding allocation concealment and blinding. Two studies were judged at high risk of bias owing to incomplete outcome reporting or potential industry sponsorship bias.

Table 5: Risk of bias assessment using the Cochrane RoB 2.0 tool

Study	D1	D2	D3	D4	D5
Tallarico (2019)	Some concerns	Low risk	Low risk	Low risk	Low risk
Amorim (2018)	Some concerns	Low risk	Low risk	Low risk	Low risk
Gursoytrak (2019)	Low risk	Low risk	Low risk	Low risk	Low risk
Kormoczi (2021)	Low risk	Low risk	Some concerns	Low risk	Low risk
Tabrizi (2022)	Low risk	Some concerns	Low risk	Low risk	Some concerns
Ko (2024)	Some concerns	Low risk	Low risk	Low risk	Low risk
Makowiecki (2017)	High risk	Some concerns	Low risk	Some concerns	High risk
Luiz (2024)	Some concerns	Some concerns	Some concerns	Low risk	Some concerns
Velloso (2018)	High risk	Some concerns	Some concerns	Low risk	High risk
Carlos (2021)	Low risk	Low risk	Low risk	Low risk	Low risk

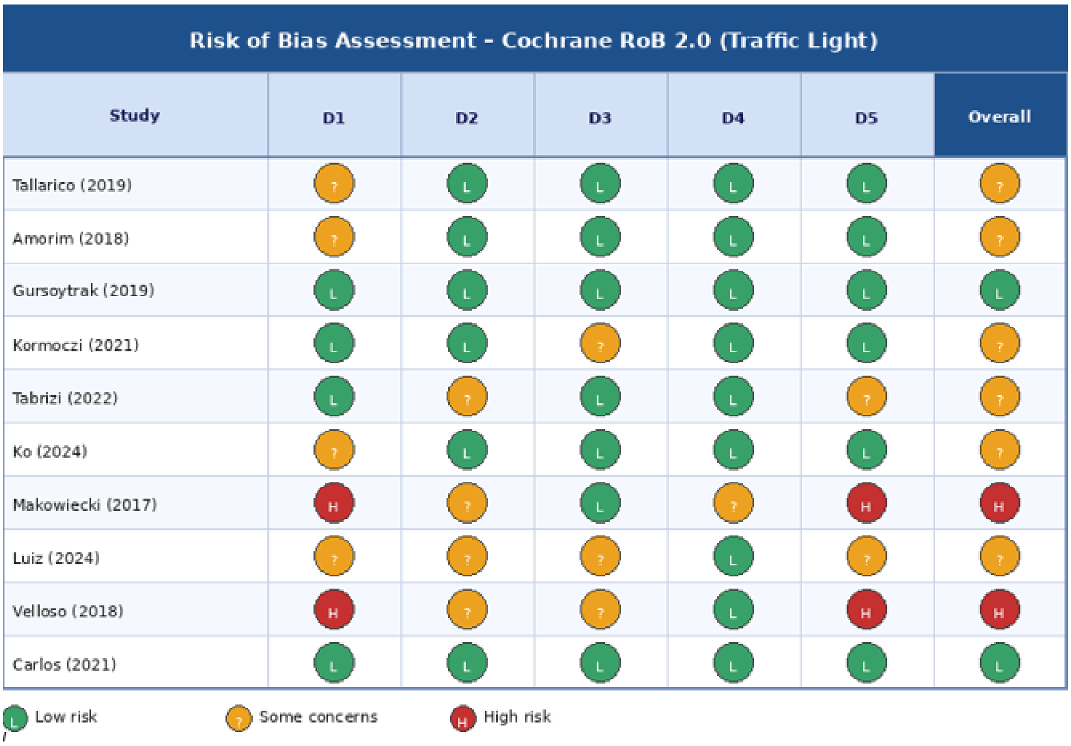

Figure 6: RoB 2.0 traffic light plot summarising risk of bias across the ten included RCTs.

3.3 Summary of Included Studies

Characteristics of the ten included RCTs are summarised in Table 1. Studies were published between 2017 and 2024. Bioactive coatings included nano-hydroxyapatite, alkali-treated titanium, calcium phosphate coatings, and modified hydrophilic SLA surfaces. All studies assessed implant stability using ISQ values measured by resonance frequency analysis.

Table 1: Summary of randomised controlled trials included in the systematic review

Author (Year)	Design	Test Surface	Control	Outcome	Conclusion
Makowiecki et al. (2017)	RCT	Hydrophilic surface	SLA	ISQ	No significant difference in early stability
Tallarico et al. (2019)	RCT (Split-mouth)	Hydrophilic surface	SLA	ISQ, Early Success rate	Higher early success in hydrophilic group
Gursoytrak & Ataoglu (2019)	RCT	SLA active (bioactive)	SLA	ISQ	Improved ISQ in SLA active group
Kormoczi et al. (2021)	RCT	Anodised (bioactive)	SLA	Implant stability	Comparable outcomes in both surfaces
Tabrizi et al. (2022)	RCT (Split-mouth)	BCP-coated	SLA	Secondary stability (ISQ)	Higher secondary stability with BCP
Ko et al. (2024)	RCT	Hydroxyapatite-coated	SLA	ISQ	Higher stability in HA-coated group
Luiz Carlos et al. (2021)	RCT	Alkali-treated (BioCaP)	SLA	ISQ	Significantly better stability with BioCaP
Fernando Luiz et al. (2024)	RCT	Nano-HA	SLA	ISQ	Enhanced stability in nano-HA group
Velloso et al. (2018) RC	RCT (Double-blind	Modified SLA (hydrophilic)	SLA	ISQ	Significant early improvement with hydrophilic
Amorim et al. (2018)	RCT	Calcium-ion modified	SLA	ISQ	No significant difference at baseline

3.4 Meta-Analysis Results

3.4.1 Baseline Implant Stability

The pooled SMD at baseline was 0.365 (95% CI: 0.026–0.704; p = 0.035) using the random-effects model, indicating significantly higher primary stability for bioactive surfaces immediately after implant placement. Heterogeneity at baseline was moderate (I^2 = 69.42%). Individual study estimates and the pooled effect are illustrated in Figure 2; numerical data are provided in Table 2.

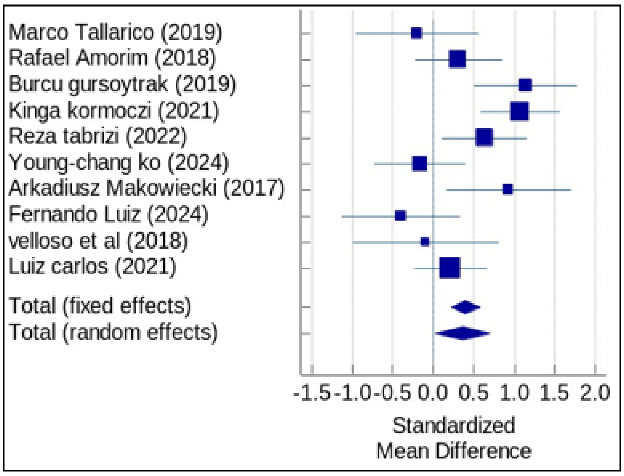

Figure 2: Forest plot of baseline implant stability quotient (ISQ) comparing bioactive and SLA surfaces

Table 2: Meta-analysis results of baseline implant stability (ISQ) comparing bioactive and SLA surfaces

Study	N (Bioactive)	N (SLA)	Total	SMD	SE	95% CI	Weight (%)
Marco Tallarico (2019)	14	14	28	0.47	0.379	–0.273 to 1.213	9.56
Rafael Amorim (2018)	27	28	55	0	0.266	–0.522 to 0.522	10.63
Burcu Gursoytrak (2019)	22	23	45	0.259	0.294	–0.316 to 0.835	10.35
Kinga Kormoczi (2021)	37	37	74	0.242	0.23	–0.209 to 0.693	10.93
Reza Tabrizi (2022)	30	30	60	1.197	0.355	0.501 to 1.893	9.76
Young-Chang Ko (2024)	24	26	50	1.385	0.334	0.730 to 2.040	9.97
Arkadiusz Makowiecki (2017)	15	15	30	0.594	0.363	–0.117 to 1.306	9.67
Fernando Luiz (2024)	15	15	30	0.642	0.378	–0.099 to 1.384	9.53
Velloso et al. (2018)	10	10	20	0.87	0.451	–0.014 to 1.754	8.78
Luiz Carlos (2021)	38	38	76	0.623	0.24	0.152 to 1.094	10.82
Total (Fixed Effects)	232	236	468	0.531	0.097	0.341 to 0.722	100
Total (Random Effects)	232	236	468	0.619	0.256	0.117 to 1.121	100

3.4.2 Follow-up Implant Stability (6–12 Weeks)

At follow-up (6–12 weeks), the pooled SMD increased to 0.880 (95% CI: 0.372–1.388; p = 0.001), demonstrating a pronounced and clinically meaningful improvement in stability for bioactive implants during the healing phase. Heterogeneity was high at follow-up (I^2 = 85.19%). Results are illustrated in Figure 3 and tabulated in Table 3.

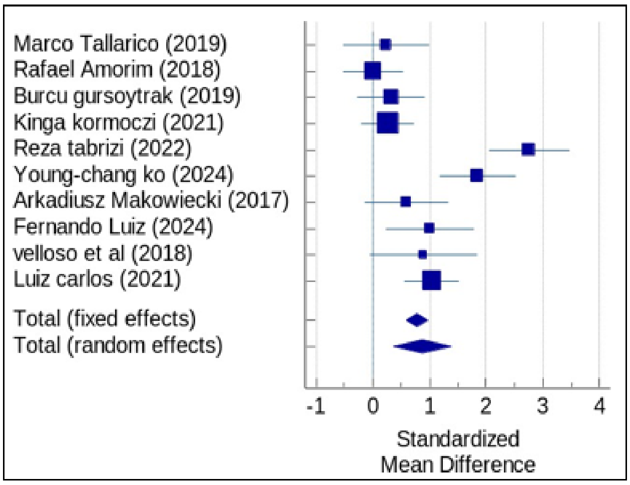

Figure 3: Forest plot of follow-up implant stability quotient (ISQ at 6–12 weeks) comparing bioactive and SLA surfaces.

3.4.3 Publication Bias and Sensitivity Analysis

Funnel plots for baseline (Figure 4) and follow-up (Figure 5) ISQ outcomes appeared visually symmetrical, suggesting minimal publication bias. These visual findings were supported by Egger's test (p = 0.456) and Begg's test (p = 0.421), neither of which reached statistical significance. Sensitivity analyses confirmed the robustness of the overall effect estimates.

Table 3: Meta-analysis results of follow-up implant stability (ISQ at 6–12 weeks) comparing bioactive and SLA surfaces

Study	N (Bioactive)	N (SLA)	Total	SMD	SE	95% CI	Weight (%)
Marco Tallarico (2019)	14	14	28	0.235	0.368	–0.522 to 0.992	9.62
Rafael Amorim (2018)	27	28	55	0	0.266	–0.533 to 0.533	10.62
Burcu Gursoytrak (2019)	22	23	45	0.318	0.295	–0.277 to 0.913	10.35
Kinga Kormoczi (2021)	37	37	74	0.261	0.231	–0.199 to 0.722	10.92
Reza Tabrizi (2022)	30	30	60	2.758	0.358	2.041 to 3.475	9.73
Young-Chang Ko (2024)	24	26	50	1.843	0.334	1.171 to 2.515	9.97
Arkadiusz Makowiecki (2017)	15	15	30	0.594	0.363	–0.151 to 1.338	9.67
Fernando Luiz (2024)	15	15	30	1.009	0.378	0.233 to 1.784	9.52
Velloso et al. (2018)	10	10	20	0.887	0.451	–0.059 to 1.834	8.77
Luiz Carlos (2021)	38	38	76	1.042	0.242	0.559 to 1.525	10.82
Total (Fixed Effects)	232	236	468	0.78	0.098	0.589 to 0.972	100
Total (Random Effects)	232	236	468	0.88	0.259	0.372 to 1.388	100

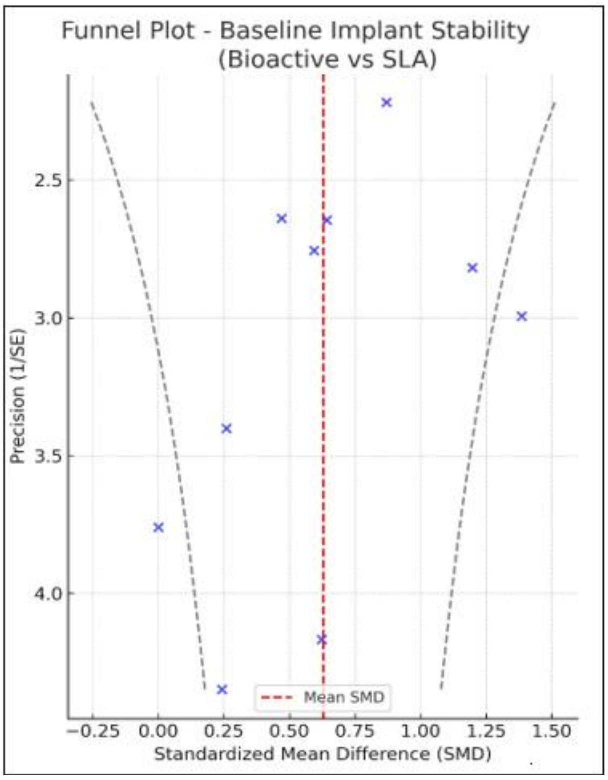

Figure 4: Funnel plot of baseline implant stability quotient (ISQ) for the assessment of publication bias

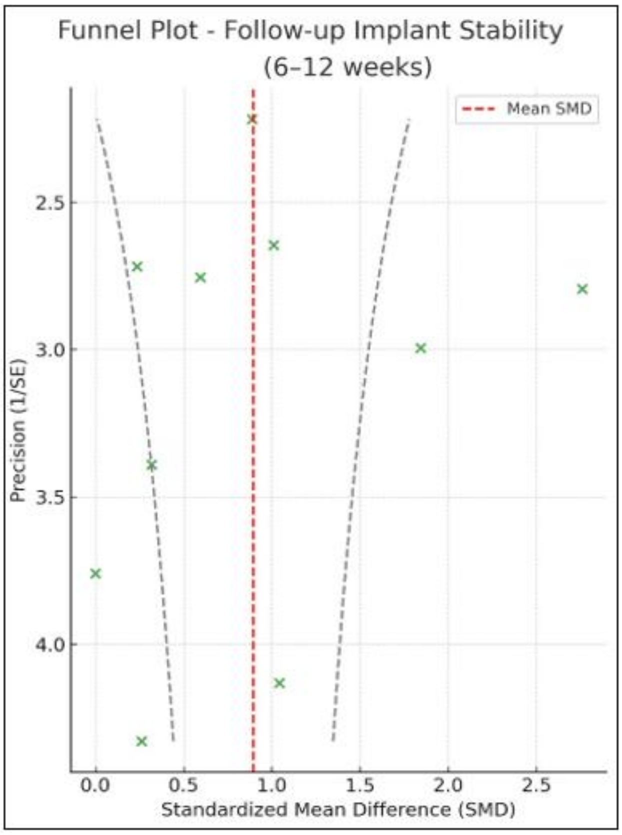

Figure 5: Funnel plot of follow-up implant stability quotient (ISQ at 6–12 weeks) for assessment of publication bias

3.4.4 Certainty of Evidence

GRADE assessments are summarised in Table 4. The certainty of evidence for baseline implant stability was rated as moderate, downgraded due to inconsistency resulting from heterogeneity across studies. For follow-up stability, certainty was rated as high, reflecting consistent and statistically significant findings across the included RCTs.

Table 4: GRADE summary of findings for implant stability (ISQ) comparing bioactive versus SLA surfaces.

Outcome	Participants (Studies)	Relative Effect (SMD, 95% CI)	Certainty	Interpretation
Implant stability – Baseline	420 (8 RCTs)	SMD 0.365 (95% CI: 0.026- 0.704; p = 0.035)	Moderate[1] (●●●■)	Bioactive Surfaces demonstarte a modest but significant primary stability advantage immediately after placement
Implant stability – Follow-up (6–12 weeks)	420 (8 RCTs)	SMD 0.880 (95% CI: 0.372- 1.388; p = 0.001)	High (●●●●)	Bioactive surfaces provide significantly higher secondary stability during early Osseointegration

4. Discussion

This systematic review and meta-analysis evaluated implant stability outcomes of bioactive surface implants in comparison with conventional SLA surfaces. Evidence synthesised from ten RCTs comprising 468 implants demonstrated that bioactive surfaces exhibit superior implant stability, particularly during early healing phases, suggesting that surface modifications designed to promote biological activity can meaningfully enhance osseointegration.

The findings are consistent with the hypothesis that surface topography and chemical properties play crucial roles in implant–bone interactions. Bioactive coatings- such as calcium phosphate, hydroxyapatite, and alkali treatments—act as stimuli for osteoblast proliferation, differentiation, and matrix mineralisation, thereby improving protein adsorption and cellular adhesion and accelerating bone healing [9, 10].

The baseline SMD of 0.365 in favour of bioactive surfaces indicates a moderate improvement in primary stability, which is critical for immediate or early loading protocols. The higher SMD at follow-up (0.880) demonstrates sustained and enhanced osseointegration over the 6–12-week healing period. Several included studies reported ISQ improvements of 5–8 units for bioactive surfaces over this timeframe.

The biological advantage of bioactive surfaces is particularly valuable in compromised conditions, such as poor bone quality or sinus-augmented regions, where enhanced osseointegration can significantly impact treatment success. Moreover, earlier achievement of stability could reduce overall treatment time and improve patient satisfaction.

Despite these benefits, substantial heterogeneity was observed (I^2 = 69%–85%), attributable to variations in study design, implant systems, surface coating types, healing periods, and ISQ measurement protocols. Subgroup analyses were not feasible owing to the limited number of studies per subgroup variable. Future meta-analyses incorporating larger datasets should explore sources of heterogeneity using meta-regression.

A limitation of the current evidence base is that ISQ, while clinically valuable for monitoring implant stability non-invasively, may not fully capture histological aspects of bone–implant contact. Long-term outcomes—such as peri-implant bone loss, prosthetic success, and implant survival rates—were not assessed in the included studies, representing a gap in longitudinal evidence. Future research should aim to standardise ISQ evaluation protocols and investigate these additional clinically relevant endpoints.

No major publication bias was detected, and sensitivity analyses affirmed the robustness of the overall effect estimates. These findings align with prior preclinical and clinical evidence supporting the osteoconductive and osteoinductive potential of bioactive implant surfaces.

5. Conclusion

Bioactive surface dental implants exhibit superior implant stability compared with SLA surfaces, particularly during the early healing phase. The findings of this systematic review and meta-analysis support the clinical use of bioactive implant surfaces where enhanced or early osseointegration is desirable. Future large-scale RCTs with standardised outcome measures and extended follow-up durations are warranted to consolidate this evidence and guide clinical decision-making.

Declarations

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Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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