Received: 24 June 2024 | Revised: 30 September 2024 | Accepted: 1 October 2024

DOI: 10.1111/php.14033

RESEARCH ARTICLE

The effect of photobiomodulation therapy on implant stability: A systematic review and meta-analysis

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Abstract

This study was designed to determine the effect of photobiomodulation therapy on dental implant stability. A complete systematic search was performed in PUBMED/MEDLINE, COCHRANE library databases, EMBASE, SCOPUS, and Google Scholar databases on articles published until June 2024. All the RCTs and CCTs reported the solo impact of photobiomodulation on dental implant stability in humans were included. The means and standard deviation for implant stability and sample size were extracted for the meta-analysis. The statistical analysis was conducted using Stata 17 software, and random effect models were applied to assess the source of heterogeneity. The I2 statistic was used to estimate the significance of any discrepancies in the therapy result. After a full-text inspection, 17 articles were qualified for systematic review, and 14 were included in the meta-analysis. Statically significant differences in implant stability were observed between the laser and the control groups on weeks 2 in ISQ reporting groups ($p = 0.01$, CI 95%) and weeks 4 and 8 in PTV reporting groups ($p < 0.001$, CI 95%). Despite limitations, the study suggests that PBM therapy benefits patients with dental implants at different periods, particularly during the early phases of healing.

KEYWORDS

clinical protocols, dental implants, dental prosthesis, implant-supported, low-level light therapy, meta-analysis

INTRODUCTION

Dental implants succeed in the stability of the implant and the process of osseointegration.[1,2] Both short-term and long-term implant stability are crucial for ensuring dental implants' functionality and longevity.[3] Osseointegration, "the direct structural and functional connection between the implant surface and the surrounding bone", plays a key role in achieving and maintaining this stability.[4] A number of conditions, including aging, systemic diseases such as diabetes, and specific medications, can negatively impact the osseointegration of implants.[5–8] Various non-invasive methods, including photobiomodulation (PBM), have emerged as treatment options to address these issues and improve the successful outcomes of implant treatment.[9–11]

Abbreviations: ATP, Adentosine triphosphate; CCT, Controlled clinical trial; IL-1B, Interleukin 1 beta; ISQ, implant stability Quotient; LED, Light-emitting diode; LLT, Low level laser; PBM, Photobiomodulation; PGE2, Prostaglandin E2; PTV, Periotest value; RCT, Randomised control trial; RELM, random effect model based on restricted maximum liklihood; RFA, Resonance frequency anlysis; ROS, Reactive oxygen species.

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PBM involves the use of red and near-infrared light to enhance cellular processes, accelerate the inflammatory process, and promote wound healing.[12,13] By employing specific light wavelengths typically ranging from 600 to 1100, this therapy can stimulate the synthesis of Adenosine triphosphate (ATP) and the proliferation of osteoblasts, thereby increasing cell viability and supporting bone growth around implants.[14–16] This non-invasive and non-thermal treatment effectively reduces pain and inflammation while facilitating tissue repair.[14,15,17]

Non-invasive methods are available to assess dental implant stability, such as "damping capacity assessment" (Periotest) and "resonant frequency analysis" (RFA).[18] The Periotest device records tooth movement in quantitative units by evaluating the periodontal ligament's damping capability, using "The Periotest Value" (PTV), which ranges from −8 to +50. Lower PTV scores indicate higher implant stability.[19] Resonance frequency analysis (RFA) measures implant stability by analyzing implant vibration in response to transducer-generated pulses. This data calculates the "Implant Stability Quotient" (ISQ), which varies from 0 to 100. Higher ISQ scores indicate better implant stability.[20]

Prados-Frutos et al. explored the effects of photobiomodulation (PBM) on osseointegration in a systematic review published in 2016.[21] Despite animal models showing promising results, there is insufficient data to support translation to human clinical care.[21] Recent clinical studies have provided insight into how to optimize PBM for osseointegration.[22,23] Previous meta-analyses failed to separately analyze PBM outcomes for each value, despite the differing physical principles and scales of RFA and PTV.[1,18,24,25] However, RFA and PTV can both provide useful information about implant stability and should be interpreted separately.[18]

In prior studies, Chen et al. and Sourvanos et al. reviewed the combined effects of PBM on dental implants and orthodontic mini-implants (mini-screws).[1,11] It is crucial to consider the differences in materials (titanium for dental implants and stainless steel for mini-implants) and their applications, as orthodontic mini-implants are primarily used for temporary anchorage.[26,27] Consequently, high levels of osseointegration in mini-implants may cause complications when removed after treatment is completed.[26]

Consequently, this current systematic review and meta-analysis aims to assess the impacts of photobiomodulation therapy on changes in implant stability during the healing period in humans.

MATERIALS AND METHODS

This systematic review was developed based on "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Prisma)" guidelines.[28] The study protocol was registered on Prospero with the ID #crd42021281772.

PICOS criteria

The focused question followed the PICOS framework:

Population (P): Patients of any age or gender who have received dental implants for missing teeth.

Intervention (I): the PBM therapy (low-level laser and LED).

Comparison (C): Treatment without photobiomodulation (PBM) involved patients who did not receive laser therapy or control implants in a split-mouth study.

Outcomes (O): The effect of photobiomodulation (PBM) therapy on implant stability was assessed using both the implant stability quotient (ISQ) and Periotest value (PTV). Study design (S): RCTs and CCTs that solely investigate the effect of PBM on implant stability were included.

The focused question was "Does photobiomodulation therapy result in higher implant stability in dental implant patients?"

Literature search

A search using electronic means was conducted in the databases listed: PUBMED/MEDLINE, COCHRANE library databases, EMBASE, SCOPUS, and Google Scholar, from the start of the database through June 2024. Also, an in-depth search was carried out through the references of the included studies and gray literature from ProQuest and OpenGrey. Search algorithms used the following terms in each database: "(dental implant OR Dental Implantology OR "Dental Implants"[Mesh]) AND (Photobiomodulation OR Low-Level Laser Therapy OR Low-Level Light Therapy OR LLLT OR Low Intensity Laser OR Soft Laser OR Laser Bio-Stimulation OR "Low-Level Light Therapy"[Mesh] OR Low-Level Laser Therapy OR Low-Level Laser Therapies) AND (Osseointegration OR Implant Stability OR "Osseointegration"[Mesh] OR Success Rate)". This study did not specify the language or publication date. Two investigators screened the titles and abstract independently (M.A, Y.M). Then, the second screening was done by evaluating the full text of the articles.

Inclusion and exclusion criteria

Study inclusion criteria contained human randomized clinical trial (RCT) and controlled clinical trial (CCT)

that assessed the impacts of photobiomodulation therapy of titanium implants. Exclusion criteria included in vitro studies, animal studies, case reports, orthodontic mini-screw studies, short implant studies, and studies that combined PBM with calcium or growth factor treatment. The studies that did not meet minimum reporting requirements of irradiation parameters (wavelength and laser power) were excluded in the meta-anlysis but their results were reported in the review.

Quality assessment

The Cochrane Collaboration's risk of bias tool[29] was employed to assess the risk of bias in eligible RCTs by two researchers (M.A, Y.M) individually in an MS Excel file. The following criteria analyzed the articles: random sequence generation (selection bias), allocation concealment (selection bias), blinding of participants and personnel (performance bias), blinding of outcome assessment (detection bias), incomplete outcome data (attrition bias), selective reporting (reporting bias), and other biases.

The risk of bias in non-randomized studies of interventions (ROBINS I tool) was used to assess the risk of bias in eligible CCTs by two researchers (M.A, Y.M) individually in an MS Excel file.[30] The following criteria analyzed the articles: bias due to confounding, bias in the selection of participants into the study, bias in the measurement of interventions, bias due to departures from intended interventions, bias due to missing data, bias in the measurement of outcomes, bias in the selection of the reported result, overall.

The studies were categorized as low, moderate, and high risk of bias. The study was classified as low risk if all domains were evaluated as low risk. If one or some domains were categorized as unclear, the study was considered moderate risk, and any high-risk domains resulted in a high-risk bias classification for the study.

Data extraction

Studies included in this review provide data regarding the variables listed below: author, year of publication, country, study design, study type, mean age, gender, sample size, bone type, implant position, performed analysis (ISQ or PTV), device, laser type, wavelength, laser power, energy density, power density, spot size, laser output mode, laser probe distance from the tissue, total dose per implant, exposure time, probe distance from the tissue, application area, number of contact points per session, frequency of laser treatment, frequency of evaluation, and the primary result. All the extracted data were listed in an MS Excel file by Y.M. We did not reach out to each author for clarification of irradiation parameters. This was intentional to highlight the limitations of incomplete irradiation parameters reported by authors and manufacturers.

Meta-analysis

We conducted two separate meta-analyses for each of the two outcome measures, RFA and PTV, for indicating implant stability. The study group and the control group mean, standard deviation, and sample size were extracted to perform the meta-analysis. Analysis of the data was performed using Stata software, version 17, developed by StataCorp LLC. Random effect models based on restricted maximum likelihood (RELM) were applied for statistical analysis. Hedges's G as the standardized mean difference with 95% confidence intervals (CI) was calculated for implant stability. The forest plots were created to provide a visual representation of the standardized mean difference in outcomes among studies. Heterogeneity was measured using the I2 statistic to determine the significance of any differences in treatment effect, which indicates the overall percentage variability across studies. A random effect model based on restricted maximum likelihood (RELM) assessed the source of heterogenicity. The possible sources of heterogenicity were laser wavelengths, total dose per implant (all sessions and one session), total exposure time, number of laser applications, laser output power, and power density were analyzed in this study.

RESULTS

Article selection

The four electronic databases yielded 2611 articles. There were 51 articles qualified by title and abstract. Seventeen articles qualified for systematic review, and 14 for meta-analysis after full-text reviews (Figure 1).

Characteristics of studies

Four studies were completed in Iran,[31–34] three in Egypt,[23,35,36] three in Brazil,[37–39] three in Turkey,[22,40,41] and the remaining were performed in India,[42] Serbia,[43] Poland,[44] and Spain.[45] Fifteen studies were randomized control trials[23,31–34,36–45] and only two studies that were controlled clinical trials.[22,35] Nine studies had a split-mouth design,[23,31,32,34–37,40,43] and eight had a parallel group design.[22,33,38,39,41,42,44,45]

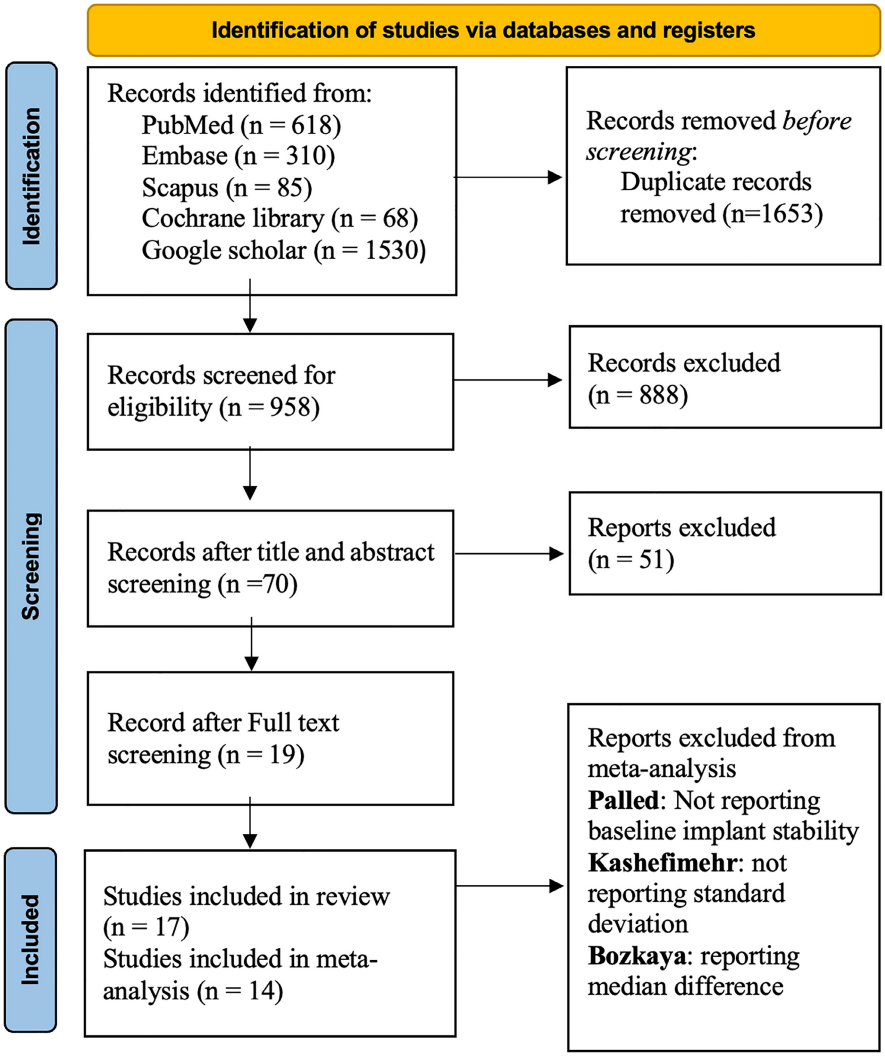


FIGURE 1 PRISMA diagram for the study selection.

Thirteen studies measured ISQ,[22,31,33–35,37–43,45] while four studies[23,32,36,44] measured PTV. The age of the participants ranged between 36 and 61 years. The total sample size is 760 subjects. PBM parameters varied between studies. Laser wavelength was applied from 626 nm to 1064 nm with a total exposure time of 40 s–1200 s. The number of laser applications also differed from 2 to 11 sessions. Tables 1–3 summarize study characteristics and other information.

Quality assessment

Cochrane Collaboration's risk of bias tool was used to assess the risk of bias in 20 eligible RCTs.[29] Three studies presented a low risk of bias,[37,43,45] while the remaining 12 had a moderate risk.[23,31–34,36,38–42,44] Six studies had a low selection risk of bias (random sequence generation and allocation concealment),[37–40,43,45] and nine had an unclear risk of bias.[23,31–34,36,41,42] In performance bias, nine studies had a low-risk,[23,33,38–43,45] and six had an unclear risk.[31,32,34,36,41,44] Four studies had a low-risk,[31,37,43,45] and 11 had an unclear detection risk of bias.[23,32–34,36,38–42,44,46] All RCTs presented a low risk of bias in attrition bias, reporting bias, and other biases[23,31–34,36–39,41–46] (Figure 2). In total, three studies showed a low risk of bias[37,43,45] while the rest showed a moderate risk.[22,23,31–36,38–42,44]

ROBINS I tool was used to assess the risk of bias in two eligible CCTs[22,35] was[30] (Figure 3). Both studies presented a moderate risk of bias.[22,35] One of them showed a low risk of bias due to confounding and intervention classification,[35] and the other one had an unclear selection bias.[22] One of the CCTs[22] had a low risk, and one had an unclear risk of bias due to deviation from the intended intervention. Both studies contained a low risk of bias due to the selection of participants, missing data, measurement of outcome, and selection of the reported results[22,35] (Figure 3).

TABLE 1 General characteristics of eligible articles.

Author	Year	Country	Study Design	Study Type	Analysis Type	Device	Mean Age	Gender	Bone type	Implant position	Sample Size
Memarian	2018	Iran	RCT	Split mouth	PTV	Periotest	NR	NR	Type 2,3	Mandible (midline and left and right canine teeth)	36
Gokmenoglu	2014	Turkey	RCT	Parallel group	RFA in ISQ	Osstell ISQ	T:50.43 ± 9.25; C:45.87 ± 13.46	6 F/9 M	Type 2,3	NR	22
Camolesi	2023	Spain	RCT	Parallel group	RFA in ISQ	Osstell ISQ	NR	8 F/5 M		NR	40
Mohajerani	2020	Iran	RCT	Parallel group	RFA in ISQ	Osstell ISQ	T:36.57 ± 11.08, C:39.34 ± 9.31	25 F/32 M		NR	58
Matys	2019	Poland	RCT	Parallel group	PTV	Periotest	46.7 ± 8.7	8 F/16 M	Type D2/A	Posterior mandible	40
Mandic	2015	Serbia	RCT	Split mouth	RFA in ISQ	Osstell ISQ	61.28 (55–75)	6 F/6 M		Premolar and/or molar maxillary regions	44
Fahmy	2018	Egypt	CCT	Split mouth	RFA in ISQ	Osstell ISQ	52 (45–60)	1 F/9 M		Right and left mandibular canine area	20
El Makaky	2020	Egypt	RCT	Split mouth	PTV	Periotest	NR	11 F/9 M		Posterior mandible	40
Kinalski	2021	Brazil	RCT	Parallel group	RFA in ISQ	Osstell ISQ	49.94 ± 11.29 (27–70)	*NR		NR	64
Lobato	2020	Brazil	RCT	Parallel group	RFA in ISQ	Osstell ISQ	50.77 ± 11.25 (22–77)	NR		Anterior and Posterior regions	50
Karaca	2018	Turkey	CCT	Parallel group	RFA in ISQ	Osstell ISQ	51.2 ± 2.3 (36–64)	14 F/11 M		Posterior mandible	50
Garcia	2012	Brazil	RCT	Split mouth	RFA in ISQ	Osstell ISQ	36 (20–55)	6 F/2 M		Posterior mandible	30
Torkzaban	2017	Iran	RCT	Split mouth	RFA in ISQ	Osstell ISQ	41.95	10 F/9 M	Type D3,4	Posterior maxillary teeth	80
ELsyad	2019	Egypt	RCT	Split mouth	PTV	Periotest	59.32 ± 4 4.1 (55–65)	NR		canine regions of the mandible	39
Bozkaya	2021	Turkey	RCT	Split mouth	RFA in ISQ	Osstell ISQ	T:55.6 ± 12.0 (47), C:54.9 ± 12.0 (46)	17 F/5 M		NR	93
Palled	2021	India	RCT	Parallel group	RFA in ISQ	Osstell ISQ	NR	17 F/13 M	Type A	NR	30
Kashefimehr	2021	Iran	RCT	Split mouth	RFA in ISQ	Mega ISQ	44.75 (35–75)	6 F/6 M	Type 3,4	premolars or first molars	24

Abbreviations: CCT, controlled clinical trial; F, female; ISQ, implant stability quotient; M, male; NR, not reported; PTV, Periotest Value; RCT, randomized clinical trial; RFA, resonance frequency analysis.

TABLE 2 PBM characteristics of the eligible articles.

		Laser Parameters					
Author	**Laser type**	**Wavelength**	**laser power**	**spot size**	**Power density**	**Energy density**	**Laser output mode**
Memarian	Diode laser (Diode laser doctor smile 810 nm, Italy)	810 nm	50 mW	1 cm^2	NR	20 J/cm^2	CW
	LED (osseopulsetmar 300, Biolux Research Ltd., Canada)	626 nm	185 mW	4.80 cm^2	38.5 mW/cm^2	46.2 J/cm^2	CW
Gokmenoglu	LED (osseopulsetm AR 300, Biolux Research Ltd., Canada)	626 nm	185 mW	4.80 cm^2	38.5 mW/cm^2	46.2 J/cm^2	CW
Camolesi	Diode laser (Laser Duo, MMO-São Carlos)	630 nm 808 nm	100 mw	NR	NR	33.3 J/cm^2	CW
Mohajerani	LLL	830 nm	10 mW	0.0015 cm^2	15 mw/cm^2	NR	CW
	LED	632 nm	NR	NR	10 mw/cm^2	NR	CW
Matys	Red diode laser (smartm, Lasotronix, Poland)	635 nm	100 mW	0.5024 cm^2	199.04 mW/cm^2	8 J/cm^2	CW
Mandic	Gaalas laser (Medicolaser 637, Technoline, Belgrade, Serbia)	637 nm	40 mW	NR	NR	6.26 J/cm^2	CW
Fahmy	Semi-conductor diode LASER (typeiv) sirolaser Blue	660 nm	25 mW	NR	NR	NR	CW
El Makaky	Aluminum gallium indium phosphide (Thor Photomedicine Ltd., Chesham, UK)	660 nm	75 mW	0.260 cm^2	0.245 W/cm	0.980 J/cm^2	CW
Kinalski	Gaala laser (Therapy XT, DMC Group, Sao Carlos, Brazil)	808 nm	50 mW	0.4 cm^2	NR	66 J/cm^2	NR
Lobato	Gaalas laser (Therapy XT, DMC Group, Sao Carlos, Brazil)	808 nm	50 mW	0.4 cm^2	NR	NR	CW
Karaca	Gaalas laser (Laser BTL-4000, Brno, Czech Republic)	830 nm	86 ± 2 mW	0.0028 cm^2	NR	92.1 J/cm^2	NR
Garcia	Gaalas laser (Thera Lase, DMC, São Carlos-SP, Brazil)	830 nm	86 ± 2 mW	0.0028 cm^2	NR	92.1 J/cm^2	NR
Torkzaban	Biolase diode laser (epic10, BIOLASE, Inc., Irvine, CA, USA)	940 nm	100 mW	0.2826 cm^2	354.6 mW/cm^2	28.36 J/cm^2	CW
Elsyad	Gallium aluminum-arsenide diode low-level laser 940-nm wavelength (Epic, Biolase, Inc., San Clemente, Calif)	940-nm	2 ± 0.50 mW	0.004 cm^2	NR	NR	NR
Bozkaya	Gaa1as diode laser (BTL 4110 Laser Professional, BTL Indus- tries, UK)	830 nm	300 mW	0.0028 cm^2	NR	810 J/cm^2	CW
Palled	Nd: YAG laser (Fotona lightwalker dental laser system, Ljubljana, Slovenia)	1064 nm	NR	NR	NR	7.07 J/cm^2	NR
Kashefimehr	LED radiation	NR	NR	NR	NR	NR	NR

Abbreviations: CW, continous wave; NR, not reported.

Implant stability measurement

Stability measurement immediately after implant Insertion

Thirteen studies assessed implant stability using ISQ values immediately after implant placement and 10 studies met the meta-analysis criteria[22,33–35,37–39,41,43,45] and three studies were excluded.[31,40,42] Palled et al.'s study[42] was excluded from the meta-analysis because it did not report baseline implant stability. Kashefimehr et al.[31] did not report standard deviation, and Bozkaya et al. (40) reported outcomes in median difference. Due to these reasons, it was impossible to perform a meta-analysis.

Total energy dose Per Implant	Total exposure time per session	Probe distance from the implant	Clinical site of application	Number of contact points per session	Applications frequency
20 J	400 s	Contact mode	Intra-oral/Buccal mucosa	1	5
222 J	1200 s	Non-contact mode	Extra-oral	1	5
222 J	1200 s	Non-contact mode	Extra-oral	1	9
10 J	100 s	Contact mode	Intra-oral/ occlusal side	1	2
			Intra-oral/Buccal and lingual mucosa	2	
NR	1200 s	NR	Extra-oral	4	10
8 J	80s	Contact mode	Intra-oral/Buccal and lingual mucosa	2	6
NR	NR	NR	Intra-oral/Buccal mucosa	1	8
NR	120 s	Non-contact (5 mm)	Intra-oral/Buccal mucosa	1	8
5.12	40s	Contact mode	Intra-oral/Buccal and lingual mucosa	2	8
26.4 J	480 s	NR	Intra-oral /Buccal and lingual mucosa and occlusal side	6	2
66 J	442.8 s	Contact mode	Intra-oral /Buccal and lingual mucosa and occlusal side	6	2
5 J	60s	Contact mode	Intra-oral /Buccal and lingual mucosa and vestibular region	20	8
5 J	60s	Contact mode	Intra-oral /Buccal and lingual mucosa and vestibular region	20	8
8 J	80s	Contact mode	Intra-oral/Buccal and lingual mucosa	2	7
30	360 s	Non-contact (2-3 m)	Intra-oral/Buccal and lingual mucosa	6	3
6 J	60s	Noncontact (0.5–1 cm)	Intra-oral /Buccal and lingual mucosa and vestibular region	20	7
2 J	60s	NR	Intra-oral	1	4
NR	1200s	NR	Extra-oral	NR	11

The heterogeneity between studies ($I^2 = 0\%$, $p = 0.65$) and the difference between the test and control groups was statically insignificant (z = 0.27, $p = 0.78$, Hedges's g = 0.3, 95% CI: [−0.16, 0.21]) (Figure 4).

Four studies evaluated the implant stability using the Periotest value (PTV) immediately after the implant insertion.[23,32,36,44] The result presented relatively high heterogeneity among the studies ($I^2 = 72.78\%$, $p = 0.01$) (Figure 5), but the difference between groups was insignificant (z = −0.40, $p = 0.69$, Hedges's g = −0.12, 95%CI: [−0.71, 0.47]). The extracted source of hetrogenicity was a difference in output power (Table 4).

TABLE 3 Outcomes of the eligible articles.

Author	Treatment Frequency	Follow up	Result
Memarian	Immediately and on days 3,7,10, and 14	Immediately and 3, 4 and 8 weeks	Positive effect on the stability of the implants after 3–4 weeks
Gokmenoglu	Immediately and 3 times per week for 3 weeks	Immediately and 2,4,8 and 12 weeks later	Positive effect on osseointegration and implant stability in LED
Camolesi	Immediately and day 7 day	Immediately and 1, 4 and 8 weeks later	Effective in reducing inflammation and improving early healing of mucosal tissue, but ineffective to increase or accelerate the secondary stability of implants.
Mohajerani	Immediately and on days 1 to 10	Immediately and 10 days, 3 weeks, 6 weeks and 9 weeks after	LLL and LED resulted in increased stability of implants after 9 weeks of follow-up
Matys	Day before, immediately and on days 2, 4, 7, and 14	Immediately and 2, 4,8 and 12 weeks later	PBMT enhanced secondary implant stability and bone density
Mandic	Immediately and on days 1,2,3,4,5,6,7	Immediately and1,2,3,4,5, 6 weeks later	No significant influence on osseointegration of self-tapping Implants placed into low-density bone
Fahmy	Immediately and on days 2, 4, 6, 8, 10, 12 and 14	Immediately and 14, 30, 90 days later	Application of LLLT improves bone reaction and resulting implant stability.
El Makaky	Immediately and on days 2, 4, 6, 8, 10, 12 and 14	Immediately and 6 and 12 months later	No statistically significant impact on the osseointegration
Kinalski	Before the preparation of the implant bed and after suturing	Immediately and 6 months later	No positive effect
Lobato	Immediately	Immediately and 6 months later	No significant effect on dental implant stability
Karaca	Immediately and on days 2, 4, 6, 8, 10, 12 and 14	Immediately and 6 months later	Positive effect on dental implant stability
Garcia	Immediately and on days 2, 4, 6, 8, 10, 12 and 14	Immediately,10 days and 3,6,9,12 weeks later	No positive effect
Torkzaban	Immediately and on days 2, 4, 6, 8, 10, and 12	Immediately and 10, 21,42 and 90 days later	No significant effect on dental implant stability
Elsyad	Immediately, on days 3 and 7	Immediately and 6 and 12 months later	PMB was beneficial in improving implant stability 6 months after overdenture insertion
Bozkaya	Immediately and three times a week for 15 days	Immediately and 30,60 and 90 days later	No significant effect on dental implant stability
Palled	Immediately and on weeks 2 and 6; and3 months later	Immediately and 2,6 weeks and 3 months later	Enhanced osseointegration and early implant stability can be achieved for loading, thus shortening the time required for conventional loading.
Kashefimehr	Day before, immediately and on days 1,2,3,4,5,6,7,8 and 9	Immediately and 1 and 3 months later	LED irradiation led to a favorable increase in the ISQ value 3 months after surgery

Stability measurement in the first month after implant insertion

After 1 week of implant insertion, the ISQ evaluation found no heterogeneity between Mandic et al. and Camolesi et al. ($I^2 = 0.00\%$, $p = 0.44$) and no significant differences between test and control groups ($z = 0.97$, $p = 0.33$, Hedges's g = 0.2, 95% CI: [−0.22, 0.65])[43,45] (Figure 6).

Eight studies reported implant stability after 2 weeks of insertion. Seven studies reported ISQ[33–35,37,41–43]; one was excluded from the meta-analysis,[42] and one reported PTV.[44] A statistically significant difference between laser and control groups was found ($z = 2.68$, $p = 0.01$, Hedges's g = 0.34, 95% CI: [0.09, 0.59]), with no evidence of heterogeneity among the studies ($I^2 = 0.00\%$, $p = 0.82$).[33–35,37,41,43] Matys et al. reported that both the test and control groups showed significant improvements in implant stability

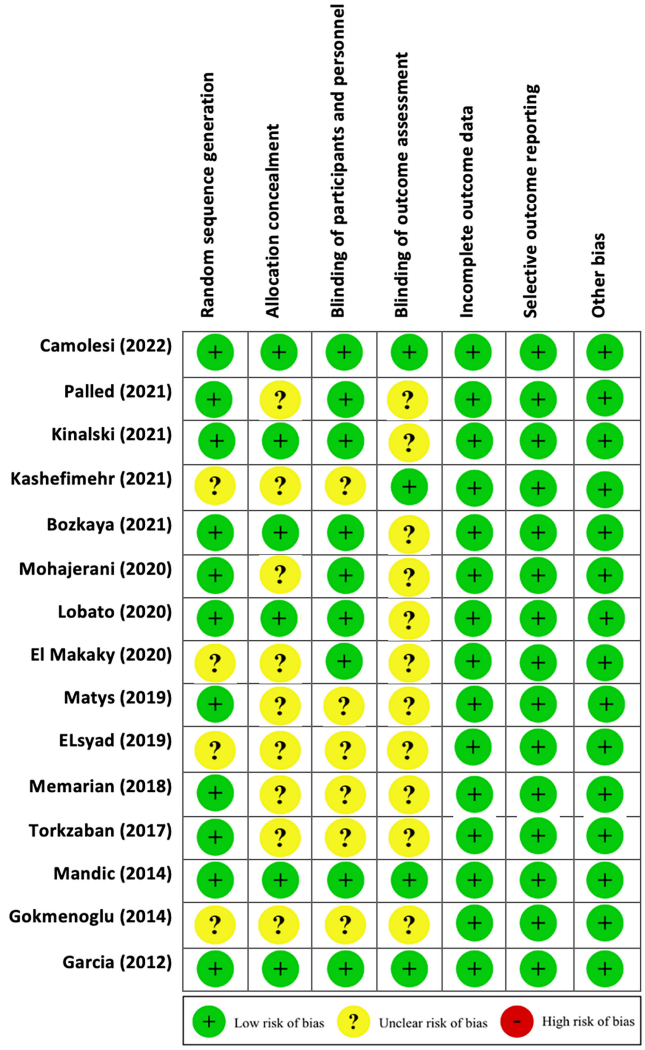


FIGURE 2 Bias assessment summary graph of eligible randomized clinical trials based on Cochrane Collaboration's risk-of-bias tool.

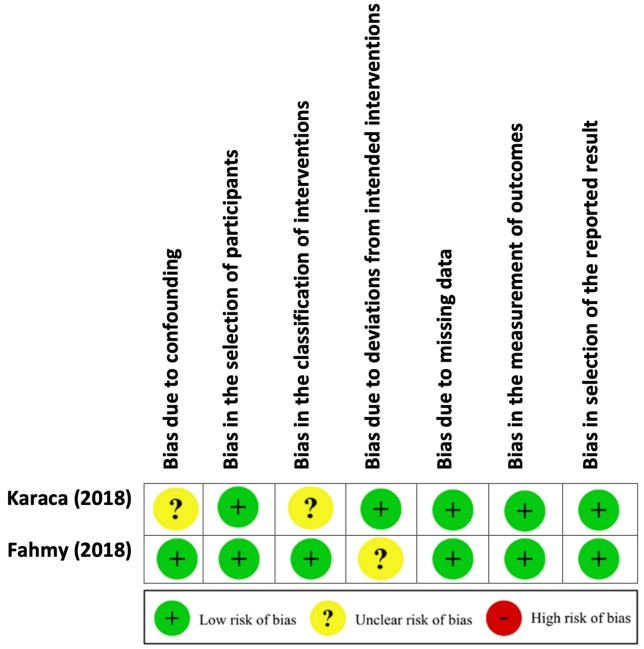


FIGURE 3 Bias assessment summary graph of eligible controlled clinical trials-based ROBINS I tool.

from baseline to 2 weeks after intervention ($p = 0.01$). After 2 weeks of observation, the laser-irradiated group exhibited higher implant stability than the non-irradiated group.[44] Also, Palled et al. reported statistically significant differences between control and test groups at 2 weeks ($p < 0.001$)[42] (Figure 7).

Five studies reported outcomes 3 weeks after implant insertion. In one study, implant stability was reported in PTV[32]; in the remaining four, implant stability was confirmed with no heterogeneity ($I^2 = 44.34\%$, $p = 0.05$), and no statistically significant difference between laser and control groups ($z = 1.76$, $p = 0.08$, Hedges's g = 0.34, 95% CI: [−0.04, 0.71])[23,27,34,41] (Figure 8). Memarian et al. reported the control group exhibited significantly lower implant stability ($p < 0.001$) in the third week compared to the time of surgery. Conversely, minimal changes were observed in the laser and LED PBM groups during the same period.[32]

Eight studies reported outcomes after 4 weeks. Six reported RFA in ISQ,[31,35,40,41,43,45] two of them were not included in the meta-analysis,[31,40] and two in PTV.[32,44] According to ISQ studies, there was no significant difference in stability between the PBM and control groups ($z = 1.49$, $p = 0.14$, Hedges's g = 0.26, 95% CI: [−0.08, 0.61]), and the heterogeneity was also insignificant ($I^2 = 0.00\%$, $p = 0.67$)[35,41,43,45] (Figure 9). Two studies measuring PTV have reported that using PBM significantly improves implants' stability 4 weeks after surgery.[32,44] The results of the PBM group and the control group were significantly different ($z = -4.65$, $p < 0.001$, Hedges's g = −1.03, 95% CI: [−1.47, −0.60]) and there was no heterogeneity among studies ($I^2 = 0.00\%$, $p = 0.90$)[32,44] (Figure 10). Kashefimehr reported that the ISQ value was notably higher on the irradiated than on the non-irradiated side 1 month after surgery ($p = 0.04$).[31]

Stability measurement in 6, 8, and 9 weeks after implant insertion

Five studies reported RFA in ISQ after 6 weeks[33,34,37,42,43], while one was excluded from the meta-analysis.[42] The analysis showed significant heterogeneity ($I^2 = 59.20\%$, $p = 0.06$) and insignificant differences among outcomes ($z = 1.35$, $p = 0.18$, Hedges's g = 0.30, 95% CI: [−0.14, 0.75]) (Figure 11)[33,34,37,43] total exposure time was extracted as the primary source of heterogeneity (Table 5).

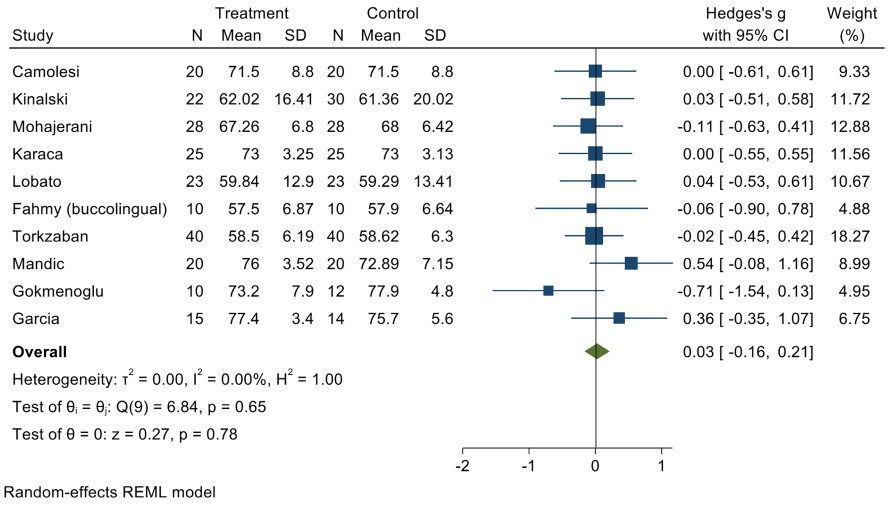


FIGURE 4 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups immediately after implant insertion. Studies PBM wavelength: Camolesi[45]:630,808 nm, Kinalski[38]:808 nm, Mohajerani[33]:832,830 nm, Karaca[22]:830 nm, Lobato[39]:808 nm, Fahmy[35]:660 nm, Torkzaban[34]:940 nm, Mandic[43]:637 nm, Gokmenoglu[41]:626 nm, Garcia[37]:830 nm.

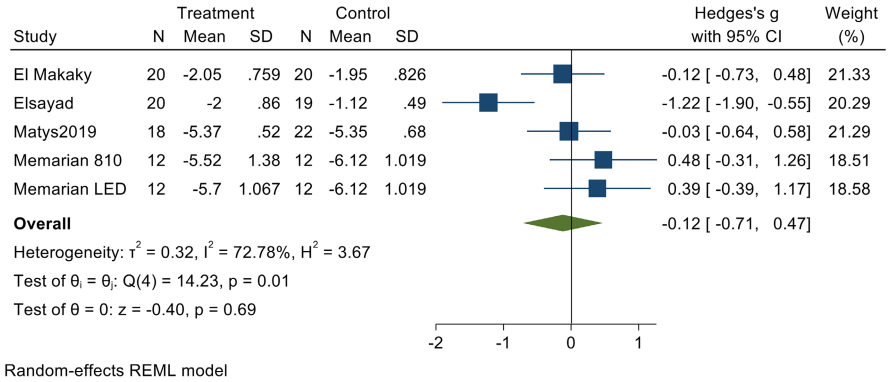


FIGURE 5 Forest plot comparing implant stability (PTV values) between laser-treated and control groups immediately after implant insertion. Studies PBM wavelength: El Makaky[23]:660 nm, ElSayad[36]:940 nm, Matys[44]:635 nm, Memarian[32]:626,810 nm.

TABLE 4 Meta-regression results using restricted maximum likelihood (RELM) based on photobiomodulation characteristic variables to determine the source of heterogeneity (implant stability in PTV values) immediately after implant insertion.

Meta estimate	Coefficient	Standard error	*z*	*p* > |*z*|	[95% confidence interval]	
Output power	0.007025	0.004079	1.72	0.085	−0.00097	0.01502
Constant	−0.69731	0.40754	−1.71	0.087	−1.49607	0.101456

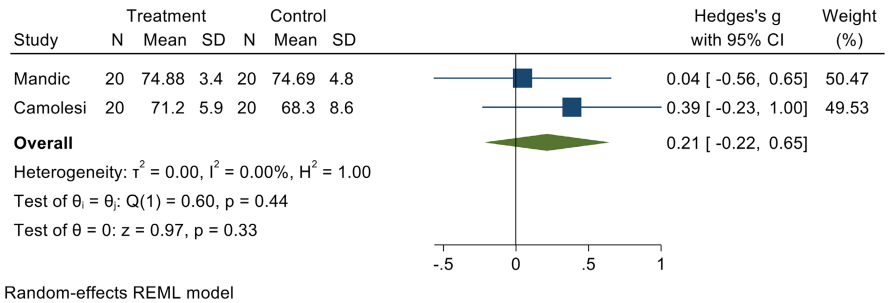


FIGURE 6 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups one-week post-implant insertion. Studies PBM wavelength: Mandic[43]:637 nm, Camolesi[45]:630,808 nm.

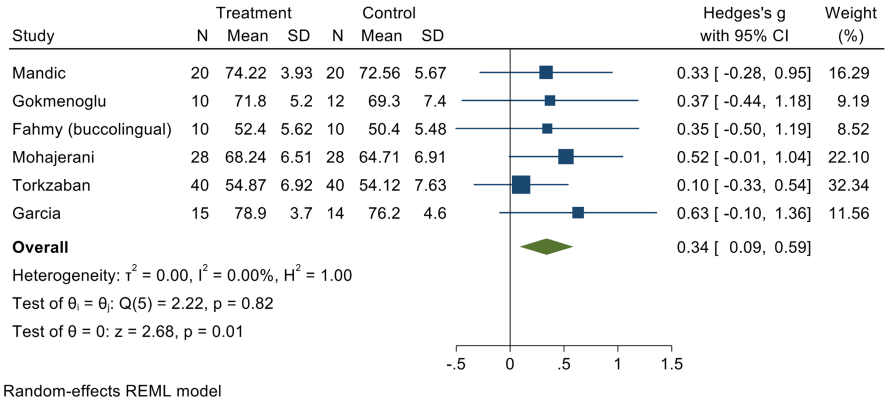


FIGURE 7 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 2 weeks post-implant insertion. Studies PBM wavelength: Mohajerani[33]:832,830 nm, Fahmy[35]:660 nm, Torkzaban[34]:940 nm, Mandic[43]:637 nm, Gokmenoglu[41]:626 nm, Garcia[37]:830 nm.

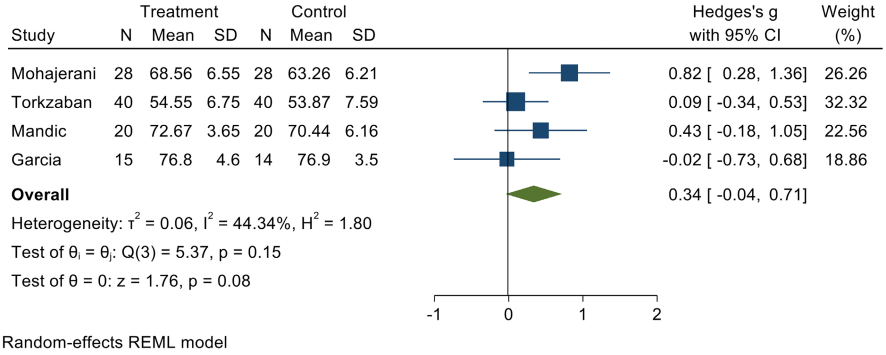


FIGURE 8 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 3 weeks post-implant insertion. Studies PBM wavelength: Mohajerani[33]:832,830 nm, Torkzaban[34]:940 nm, Mandic[43]:637 nm, Garcia[37]:830 nm.

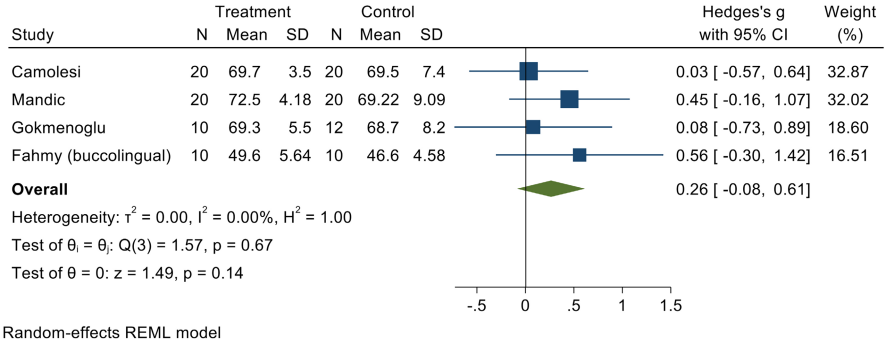


FIGURE 9 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 4 weeks post-implant insertion. Studies PBM wavelength: Camolesi[45]:630,808 nm, Fahmy[35]:660 nm, Mandic[43]:637 nm, Gokmenoglu[41]:626 nm.

Palled et al.'s 6-week follow-up analysis of the test group revealed that 80% of the implants had achieved moderate stability ranging from 60 to 69 ISQ, whereas 20% had achieved high stability above 70 ISQ. Conversely, all the implants in the control group displayed low stability at the end of 6 weeks of follow-up.[42]

A total of four studies assessed outcomes 2 months after implant insertion.[32,41,44,45] Camolesi et al. and Gokmenoglu et al. reported RFA in ISQ, found significant mean difference between laser and control groups ($z = 0.28$, $p = 0.78$, Hedges's g = 0.07, 95% CI: [−0.42, 0.56]) and no significant heterogenicity ($I^2 = 0.00\%$, $p = 0.84$)[41,45] (Figure 12). Two studies reported measurements in PTV.[32,44] PBM and control groups differ significantly with higher implant stability in laser groups ($z = -3.14$, $p < 0.001$, Hedges's g = −0.67 95% CI: [−1.09, −0.25]),

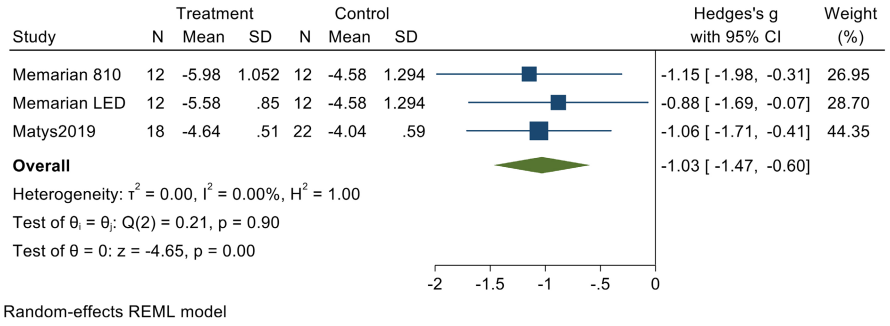


FIGURE 10 Forest plot comparing implant stability (PTV values) between laser-treated and control groups 4 weeks post-implant insertion. Studies PBM wavelength: Matys[44]:635 nm, Memarian[32]:626,810 nm.

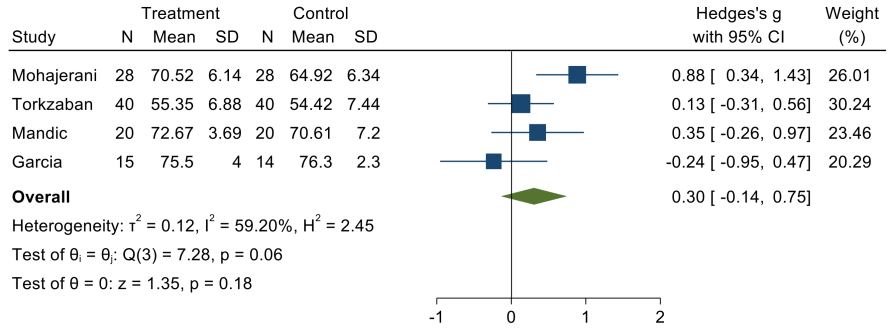


FIGURE 11 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 6 weeks post-implant insertion. Mohajerani[33]:832,830 nm, Torkzaban[34]:940 nm, Mandic[43]:637 nm, Garcia[37]:830 nm.

TABLE 5 Meta-regression results using restricted maximum likelihood (RELM) based on photobiomodulation characteristic variables to determine the source of heterogeneity (implant stability in ISQ values) 6 weeks post-implant insertion.

Meta estimate	Coefficient	Standard error	z	$p > \|z\|$	[95% confidence interval]	
Total exposure time	0.000764	0.000298	2.57	0.01	0.0001803	0.0013469
Constant	−0.02887	0.202477	−0.14	0.887	−0.4257226	0.3679733

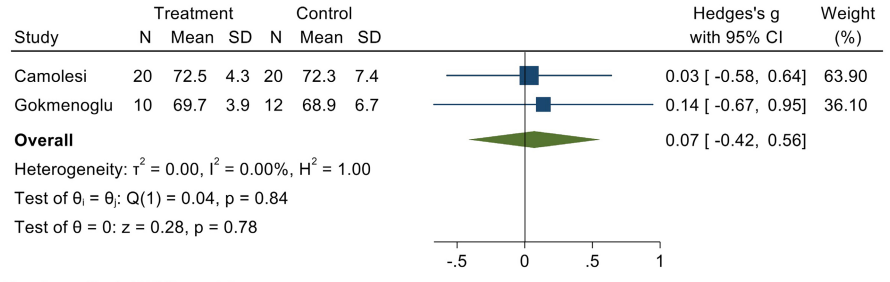


FIGURE 12 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 8 weeks post-implant insertion. Studies PBM wavelength: Camolesi[45]:630,808 nm, Garcia[37]:830 nm.

with no significant heterogeneity in the data. ($I^2 = 0.00\%$, $p = 0.54$)[32,44] (Figure 13).

After 9 weeks of implant insertion, Mohajerani et al. and Garcia et al. reported insignificant distinction between the laser and control groups ($z = 0.42$, $p = 0.68$, Hedges's g = 0.23, 95% CI: [−0.83, 1.28]).[33,37] There was a statistical difference in data heterogeneity ($I^2 = 82.20\%$, $p = 0.02$)[33,37] (Figure 14).

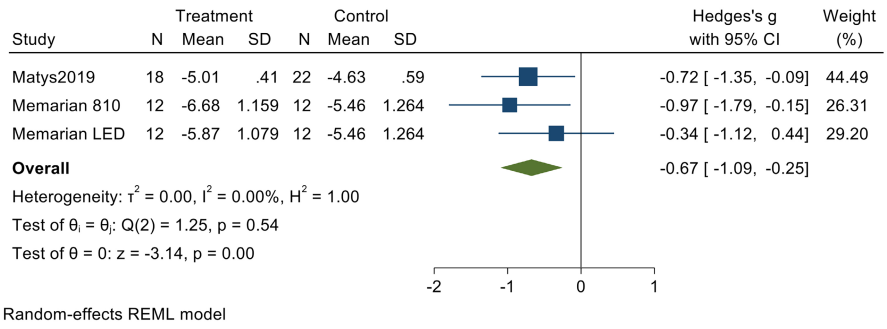


FIGURE 13 Forest plot comparing implant stability (PTV values) between laser-treated and control groups 8 weeks post-implant insertion. Studies PBM wavelength: Matys[44]:635 nm, Memarian[32]:626,810 nm.

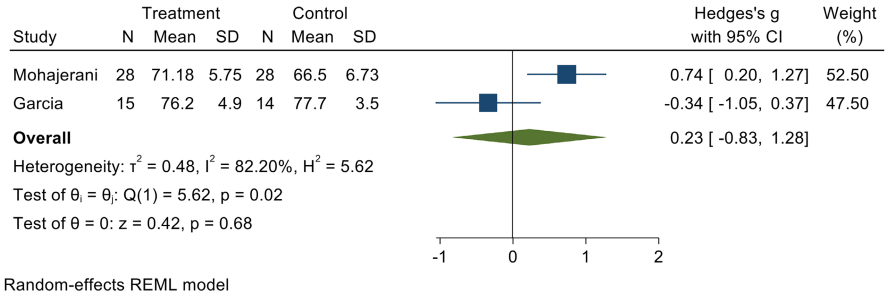


FIGURE 14 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 9 weeks post-implant insertion. Mohajerani[33]:832,830 nm, Garcia[37]:830 nm.

Stability measurement 3 months after implant insertion

After 3 months of implant insertion, seven RFA in ISQ evaluations were conducted. Among these, four studies were included in the meta-analysis[34,35,37,41] and three were excluded.[31,40,42] There was no significant statistical difference between the control groups and the PBM groups ($z=25.54$, $p=0.59$, Hedges's $g=0.17$, 95% CI: [−0.45, 0.80]), but there was significant heterogeneity among the studies ($I^2=68.97\%$, $p=0.03$).[34,35,37,41] (Figure 15) Based on the meta-regression analysis, the power density can be one of the sources of the heterogeneity (Table 6).

Stability measurement 6 months after implant insertion

Five studies reported implant stability 6 months after insertion,[22,23,36,38,39] and three reported ISQ.[22,38,39] The analysis revealed no significant difference between the PBM and control groups ($z=0.85$, $p=0.39$, Hedges's $g=0.29$, 95% CI: [−0.37, 0.95]) and high heterogeneity among the studies ($I^2=75.70\%$, $p=0.02$)[22,38,39] (Figure 16). Based on the meta-regression analysis, the total exposure time can be one of the sources of the heterogeneity (Table 7).

El Makaky et al. and ElSayad et al. reported implant stability in PTV, which showed no statistically significant difference between test and control groups ($z=-1.14$, $p=0.25$, Hedges's $g=-0.53$, 95% CI: [−1.44, 0.38]) and had high heterogeneity ($I^2=76.09\%$, $p=0.04$)[23,36] (Figure 17).

Stability measurement 12 months after implant insertion

El Makaky et al. and ElSayad et al. reported implant stability in PTV, which showed no statically significant difference between test and control groups ($z=-1.141$ $p=0.27$, Hedges's $g=-0.68$, 95% CI: [−1.88, 0.52]) and high heterogeneity ($I^2=85.52\%$, $p=0.01$)[23,36] (Figure 18).

DISCUSSION

In recent years, photobiomodulation has attracted considerable attention from researchers because of its many safe and effective potential clinical uses in dentistry.[47] This area must be evaluated through carefully planned clinical trials and systematic reviews to develop comprehensive practice guidelines.[47] Numerous systematic reviews and meta-analyses assessed the impact of PBM on

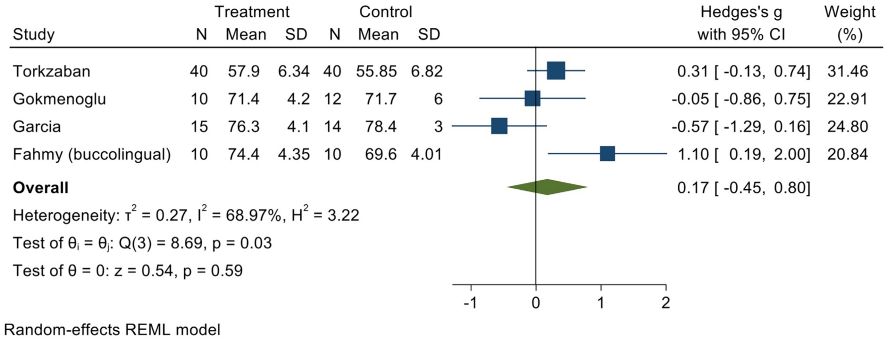


FIGURE 15 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 3 months post-implant insertion. Studies PBM wavelength: Fahmy[35]:660 nm, Torkzaban[34]:940 nm, Gokmenoglu[41]:626 nm, Garcia[37]:830 nm.

TABLE 6 Meta-regression results using restricted maximum likelihood (RELM) based on photobiomodulation characteristic variables to determine the source of heterogeneity (implant stability in ISQ values) 3 months post-implant insertion.

Meta estimate	Coefficient	Standard error	*z*	*p* > |*z*|	[95% confidence interval]	
Power density	0.002033	0.001104	1.84	0.066	−0.00013	0.004196
Constant	−6.9862	3.482534	−2.01	0.045	−13.8118	−0.16056

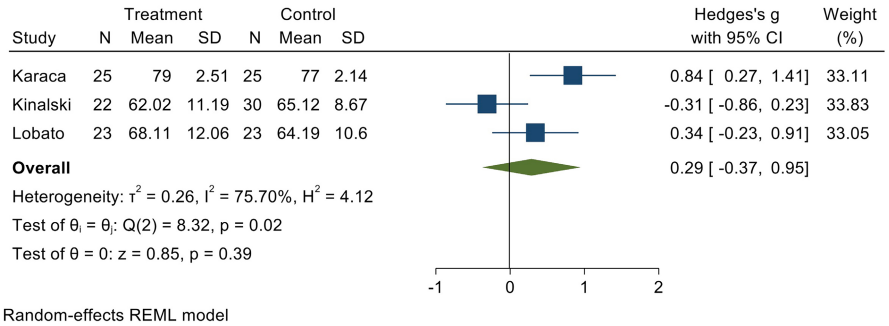


FIGURE 16 Forest plot comparing implant stability (ISQ values) between laser-treated and control groups 6 months post-implant insertion. Studies PBM wavelength: Kinalski[38]:808 nm, Karaca[22]:830 nm, Lobato[39]:808 nm.

TABLE 7 Meta-regression results using restricted maximum likelihood (RELM) based on photobiomodulation characteristic variables to determine the source of heterogeneity (implant stability in ISQ values) 6 months post-implant insertion.

Meta estimate	Coefficient	Standard error	*z*	*p* > |*z*|	[95% confidence interval]	
Total exposure time	−0.00218	0.001235	−1.77	0.077	−0.00461	0.000236
Constant	1.002014	0.469731	2.13	0.033	0.081359	1.922669

osseointegration, crestal bone loss, and as a surface treatment for dental implants.[39,44,48] Nevertheless, there are a limited number of meta-analysis reviews that precisely assess the effectiveness of PBM on implant stability. The prior goal of this systematic review and meta-analysis was to assess the impacts of photobiomodulation therapy on changes in implant stability during the healing period in humans. Multiple techniques, such as insertion torque values, reverse torque test, percussion test, ISQ, and PTVs, are employed to assess implant stability. ISQ and PTVs are regarded as the most dependable of these techniques, as evidenced by the studies incorporated in this study.

Various methods have been developed to improve the stability of dental implants during the healing period. These include coating with chemical agents such as calcium and growth factor, implant surface modification, ozone therapy, and PBM.[10,22,49,50]

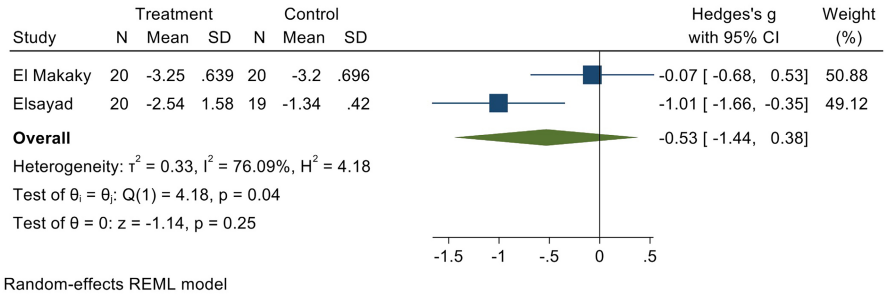


FIGURE 17 Forest plot comparing implant stability (PTV values) between laser-treated and control groups 6 months post-implant insertion. Studies PBM wavelength: El Makaky[23]:660 nm, ElSayad[36]:940 nm.

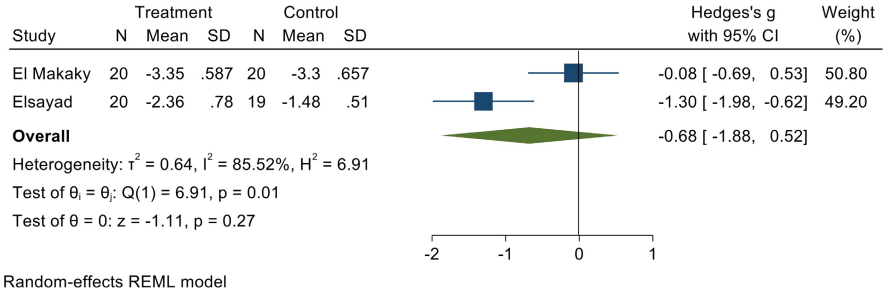


FIGURE 18 Forest plot comparing implant stability (PTV values) between laser-treated and control groups 12 months post-implant insertion. Studies PBM wavelength: El Makaky[23]:660 nm, ElSayad[36]:940 nm.

PBM exerts its photochemical effects on biological systems through non-thermal mechanisms, wherein the light is absorbed and induces a subsequent chemical alteration.[47] Numerous investigations have demonstrated the bio-stimulatory impacts of PBM on tissue growth and regeneration and explored the molecular biological processes underlying these effects.[51] These processes are closely linked to heightened ATP synthesis and improved mitochondrial activity. Additionally, photobiomodulation therapy using low-level laser (LLL) can reduce inflammation around implants by stimulating cellular processes that lead to decreased inflammation and improved healing.[52] The reduction of inflammatory processes during the healing phase decreased inflammatory factors such as PGE2 and IL-1B in both PBM and control implants. However, IL-1B and PGE2 levels were inflammatory factors in the case, and the control sides were not statistically different at all follow-up intervals.[32,41] By targeting specific wavelengths of light to the affected area, PBM therapy can modulate inflammatory responses and promote tissue regeneration.[53] The anti-inflammatory effects of PBM therapy using LLL are achieved through various cellular and molecular pathways, including the activation of mitochondrial respiratory chain components, the production of reactive oxygen species (ROS), and the modulation of inflammatory mediators. Additionally, PBM therapy can enhance cellular metabolism, increase blood flow, and promote tissue repair.[54] Camolesi et al. demonstrated that PBM plays a crucial role in reducing inflammation and improving the early healing of mucosal tissue but does not have effective results in increasing or accelerating the stability of implants.[45]

The present study's meta-analysis revealed that PBM positively influenced implant stability in the research participants. More precisely, improvements were observed in the second week of ISQ assessments and the fourth and eighth weeks of PTV assessments. In line with Kashefimehr et al., findings indicated that the use of laser led to a significant enhancement in ISQ values 3 months post-implantation.[31] Matys et al.'s research has shown a consistent increase in implant stability after 30 days using red and near-infrared laser wavelengths. Contrarily, Bozkaya et al. did not observe a considerable distinction in implant stability.[40] The results of our meta-regression analysis exhibited that factors such as laser wavelengths, total dose per implant (both in all session and one session), total exposure time, number of laser applications, laser output power, and power density could contribute to the heterogeneity.

Statistically insignificant variances were observed in implant stability and alkaline phosphatase (APL) activity surrounding dental implants reported by Mandić et al.[43] However, upon examination of the data collected in this

study, it was noted that the laser group displayed higher levels for both implant stability and ALP compared to control group after the 4th week of observation period. The reason behind this occurrence can be traced back to the connection between LLL stimulation and the reaction of stem cells in the tissue. Research indicates that LLL can significantly influence stem cell behavior by promoting their proliferation and differentiation. For example, studies have shown that LLL enhances the proliferation of stem cells derived from sources such as bone marrow, adipose tissue, and dental pulp. Specifically, LLL has been found to increase the expression of growth factors like Vascular Endothelial Growth Factor (VEGF) and Transforming Growth Factor beta 2 (TGFβ2), which are crucial for cell growth and tissue regeneration. Moreover, LLL appears to activate various intracellular signaling pathways that facilitate these processes. It has been suggested that LLL can enhance mitochondrial function, leading to increased adenosine triphosphate (ATP) production, which is vital for cellular energy and activity.[55,56] This reaction encourages soft tissue, bone regeneration, and recovery around the implant site. The study conducted by Torkzaban et al. also found comparable outcomes.[34] The combined findings of studies included in this meta-analysis indicated a beneficial impact of PBM on dental implant stability. Conversely, there is limited research on the effects of PBM on osteoporotic bones. De Vasconcellos et al. and Karakaya et al. reported a positive influence of PMBT on osteointegration in animal models with osteoporotic bones.[57–59]

El Makaky et al.[23] (laser wavelength 660 nm, 8 laser application sessions, 40s exposure time) reported that the peri-implant probing and modified gingival index of the PBM groups at all follow-up sessions did not reach significant statistical differences for the evaluation of clinical parameters and the secondary outcome measures. On the contrary, Palled et al.[42] (laser wavelength 1064 nm, 4 laser application sessions, 60s exposure time) documented that the peri-implant probing index and the modified plaque index were significantly lower in the laser group.

During El Makaky et al.'s[23] study period, no significant difference was observed between the modified plaque index of the PBM and control implants. The modified sulcus bleeding index was insignificantly lower in the El Makaky et al. laser group[23] and significantly lower in the Palled et al. study.[42] It has been shown in Lobato et al. and El Makaky et al.[23,39] that PBM did not affect pain levels, marginal bone loss, and radiographical peri-implant alterations (laser wavelength 808 nm, 2 laser application sessions, 442.8 s exposure time).

The healing cascade around titanium implants is a multi-stage biological process essential for successful osseointegration. Immediately following implantation, an inflammatory response occurs, attracting immune cells to prevent infection. This is followed by a proliferation phase where fibroblasts and endothelial cells form granulation tissue and new blood vessels. Osteoblasts then migrate to the titanium surface, depositing new bone matrix, which is critical for implant stability. The final remodeling phase involves the continuous breakdown and rebuilding of bone tissue to optimize the structure around the implant. Factors such as implant surface characteristics and patient health significantly influence this healing process, ultimately determining the success and longevity of the implant.[60]

Although it has been suggested that PBM therapy could be beneficial for improving implant stability in diabetic patients, the majority of the qualified studies in this systematic review excluded diabetic patients. To draw a dependable conclusion, clinical trials should be structured to evaluate the effects of photobiomodulation therapy in individuals with diabetes, other systemic illnesses, and smokers. Given the diverse age range for implant application, it is essential to assess the effectiveness of PBM therapy across different age groups. Moreover, area-specific research is necessary due to the significant variations in bone morphology and microstructure. All the previous systematic reviews[1,21,47] highlighted the need for higher quality and more standardized human clinical trials. The same need is concluded in this review.

The systematic review and meta-analysis encountered certain limitations. Initially, the small sample size may also lead to inter-subject variations, causing clinical heterogeneity. Furthermore, uncontrollable factors such as diverse dietary habits, oral hygiene status, and oral health awareness among patients were present. Additionally, only 14 studies were incorporated into the meta-analysis, which is limited for a review because of the topic's novelty and ongoing modifications. The small sample size may also lead to inter-subject variations, causing clinical heterogeneity. Furthermore, uncontrollable factors such as diverse dietary habits, oral hygiene status, and oral health awareness among patients were present. These variations could lead to inconsistent baseline parameters, affecting the collected data and analysis of implant stability. Moreover, variations in follow-up days among the evaluated studies could significantly impact the results.

CONCLUSIONS

Despite its limitations, the study suggests that PBM therapy benefits patients with dental implants at different periods. PBM therapy is particularly beneficial during the early phases of healing, making it a viable option for patients

with dental implants. However, various laser parameters and treatment protocols were used in the included studies. Further evaluation of photobiomodulation's impact on implant therapy results requires additional well-designed clinical trials with standardized protocols.

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How to cite this article: Arshad M, Mazidi Y, Chiniforush N, Shirvani A, Bassir SH. The effect of photobiomodulation therapy on implant stability: A systematic review and meta-analysis. *Photochem Photobiol*. 2024;00:1-19. doi:10.1111/php.14033