Journal of Health and Rehabilitation Research JHRR

https://doi.org/10.61919/jhrr.v5i4.1964

Review Article

Evaluating the Effects of Low-Level Laser Therapy (LLLT) on Surgical Wound Healing in Animal Models: A Scoping Review

Muhammad Asif[1], Satheesh Babu Natarajan[1], Muhammad Ahmed Azmi[2]

[1] Lincoln University College, Petaling Jaya, Malaysia
[2] Al-Tibri Medical College, Isra University Karachi Campus, Karachi, Pakistan

*** Correspondence: Muhammad Asif, masif@lincoln.edu.my**

ABSTRACT

Background: Surgical site infections and impaired postoperative wound healing represent a substantial global burden, affecting millions of patients annually and driving significant clinical, economic, and antimicrobial-resistance consequences. Low-Level Laser Therapy (LLLT), also termed photobiomodulation (PBM), has attracted growing preclinical interest as a non-invasive adjunct to surgical wound management through its proposed effects on mitochondrial bioenergetics, collagen synthesis, inflammatory resolution, and angiogenesis. Despite a substantial body of experimental animal research, the full scope, parameter distribution, biological outcomes, and methodological characteristics of this literature have not been systematically mapped in a manner specific to surgically induced wound models. Objective: This scoping review aimed to map and synthesize the available preclinical experimental evidence on the effects of LLLT on surgically induced wound healing in animal models, characterize the range of laser parameters and dosimetric protocols employed, identify the biological and histological outcomes reported, and delineate evidence gaps and methodological limitations requiring prioritized investigation. Methods: The review was conducted in accordance with the Joanna Briggs Institute (JBI) scoping review framework and reported following the PRISMA extension for Scoping Reviews (PRISMA-ScR). A systematic search of PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar was conducted covering the period January 2000 to August 2025. Eligibility was defined using a Population, Concept, and Context (PCC) framework, restricted to original experimental animal studies investigating LLLT in surgical wound models with quantifiable biological, histological, or molecular outcomes. Data were charted using a standardized extraction form and synthesized through descriptive thematic analysis organized by wound type, laser parameter distribution, and outcome domain. Critical appraisal was not conducted, consistent with the exploratory mapping objective. Results: Sixteen studies meeting eligibility criteria were included, published between 2007 and 2025, predominantly from Brazil (31.3%) and Egypt (25.0%), with healthy rats (56.3%) and excisional wound models (56.3%) most frequently represented. Wavelengths ranged from 630 to 808 nm, with energy densities of 3–8 J/cm² most commonly employed. Wound closure or contraction was reported in 15 of 16 studies (93.8%), collagen synthesis or organization in 13 (81.3%), inflammatory markers in 10 (62.5%), and angiogenesis in 5 (31.3%). Incisional and sutured wound models, the most clinically representative surgical wound types, were addressed in only three studies combined. No included study assessed surgical site infection as an outcome, and no study conducted molecular or genetic analysis. Dosimetric reporting was incomplete in three studies, and blinding and randomization procedures were inconsistently described. Conclusion: The mapped preclinical evidence consistently associates LLLT with improved wound closure, collagen organization, inflammatory resolution, and angiogenesis across multiple animal species and wound contexts, supporting the biological plausibility of photobiomodulatory effects in surgical wound healing. However, the evidence base is characterized by geographic concentration, model-type asymmetry, incomplete dosimetric reporting, and critical gaps in infection-related, molecular, and biomechanical outcome domains. Standardized dosimetry protocols, infection-endpoint inclusion, molecular mechanistic studies, and rigorous clinical trials are needed to translate this experimental foundation into evidence-based postoperative care. Keywords: low-level laser therapy; photobiomodulation; surgical wound healing; animal models; wound closure; dosimetry; preclinical evidence mapping; scoping review

"Cite this Article" | Received: 09 March 2025; Accepted: 12 April 2025; Published: 30 April 2025.

Author Contributions: Concept: SF; Design: UG; Data Collection: SF; Analysis: UG; Drafting: UG. **Ethical Approval**: FMH, Lahore. Informed Consent: Written informed consent was obtained from all participants; Conflict of Interest: The authors declare no conflict of interest; Funding: No external funding; Data Availability: Available from the corresponding author on reasonable request; Acknowledgments: N/A.

INTRODUCTION

Surgical wound healing represents one of the most consequential biological processes in perioperative medicine, encompassing a tightly orchestrated sequence of hemostasis, inflammation, proliferation, and tissue remodeling. Disruptions at any stage of this sequence can result in delayed wound closure, wound dehiscence, loss of tensile integrity, and postoperative complications, most notably surgical site

infections (SSIs). SSIs remain among the most prevalent and economically burdensome healthcare-associated complications worldwide, affecting an estimated 2–20% of surgical patients depending on procedural complexity, patient comorbidities, and healthcare setting (1,2). A systematic review and meta-analysis of 488,594 patients reported a global SSI incidence of approximately 11% in general surgical populations, with disproportionately high rates in low- and middle-income healthcare environments (1). Beyond their epidemiological burden, SSIs prolong hospitalization, increase antibiotic consumption, contribute to antimicrobial resistance, and impose substantial direct and indirect costs on healthcare systems (2,3). The imperative to identify safe, accessible, and effective strategies for augmenting postoperative wound repair is therefore both clinically urgent and practically significant.

Wound healing proceeds through four mechanistically distinct but temporally overlapping phases. Hemostasis is initiated immediately upon tissue injury, followed by an inflammatory phase characterized by neutrophil and macrophage infiltration and pro-inflammatory cytokine release. Successful healing depends on a timely and regulated transition from this inflammatory phase into the proliferative phase, during which fibroblast activation, collagen synthesis, angiogenesis, and re-epithelialization occur. The final remodeling phase involves extracellular matrix reorganization and progressive gain in tensile strength over weeks to months (4). Any therapeutic strategy capable of positively modulating key cellular and molecular events across these phases, including mitochondrial bioenergetics, fibroblast proliferation, inflammatory resolution, and neovascularization, holds considerable translational potential for augmenting surgical wound repair.

Low-Level Laser Therapy (LLLT), also termed photobiomodulation (PBM), represents one such emerging strategy. LLLT delivers red or near-infrared light, typically in the wavelength range of 630–830 nm, at non-thermal power densities that do not cause measurable tissue heating. Its primary photoacceptor is mitochondrial cytochrome c oxidase, which upon photon absorption accelerates the mitochondrial electron transport chain, enhancing adenosine triphosphate (ATP) synthesis and generating downstream signaling cascades that promote cellular proliferation, migration, and differentiation (5,6). LLLT has also been shown to modulate reactive oxygen species levels, reduce pro-inflammatory cytokine expression including interleukin-1 beta (IL-1β) and tumor necrosis factor alpha (TNF-α), upregulate vascular endothelial growth factor (VEGF), and stimulate collagen production by dermal fibroblasts (7–10). Critically, LLLT exhibits a biphasic dose-response relationship, wherein biological effects are optimized within a defined therapeutic window and reduced or absent at doses that are either insufficiently or excessively energetic (5,6). This dose-dependence underscores the importance of precise parameter selection in both experimental and clinical contexts.

Animal models have served as the primary platform for investigating LLLT's wound-healing properties prior to clinical translation. Rodent models in particular, including healthy rats and mice, diabetic rat models, and hairless or pigmented mouse models, offer standardized wound geometries, controlled environmental conditions, and access to invasive tissue sampling, making them well suited for mechanistic and dosimetric investigation (11–15). Experimental evidence from these models has documented accelerated wound contraction, enhanced fibroblast activity, improved collagen alignment, upregulated angiogenesis, and reduced inflammatory infiltration following LLLT application across a range of surgical wound types, including excisional, incisional, sutured, and donor-site wounds (11–15). These findings point toward translational opportunity, particularly in high-risk surgical populations such as diabetic patients, who are disproportionately susceptible to impaired healing and SSI-related complications.

Despite this promising experimental foundation, the literature on LLLT for surgical wound healing remains markedly heterogeneous. Studies differ substantially in wavelength selection, irradiance, energy density, exposure duration, treatment frequency, and wound model used, making direct comparison of outcomes difficult and evidence-based parameter standardization elusive. Several narrative reviews and mechanistic analyses have examined the biological basis of PBM in wound healing broadly; however, no

scoping review has systematically mapped the full extent of the available experimental literature specifically concerning LLLT and surgically induced wound models in animals. Surgical wounds differ pathophysiologically from chronic wounds, burn wounds, and non-surgical ulcers in their mechanism of creation, their healing trajectory, and their vulnerability to specific postoperative complications such as SSIs. This distinction makes it methodologically important to map the evidence for this specific wound category rather than conflating it with broader wound-healing literature.

A scoping review is the methodologically appropriate design at this stage of the evidence base for several reasons. The available experimental literature is broad in scope, diverse in methodology, and inconsistent in outcome reporting, characteristics that preclude reliable quantitative pooling in a meta-analytic framework and instead call for evidence mapping, parameter characterization, and gap identification (16,17). Unlike a systematic review, which is optimally suited to answering a focused intervention-effect question in a sufficiently homogeneous literature, a scoping review can accommodate conceptual diversity, synthesize heterogeneous methodologies descriptively, and generate a structured map of what is known, where the evidence is concentrated, and where critical knowledge gaps remain (16–18). This approach is consistent with the Joanna Briggs Institute (JBI) framework for scoping reviews and the PRISMA extension for Scoping Reviews (PRISMA-ScR), both of which endorse scoping methodology for exploratory purposes where formal quality appraisal and effect estimation are premature (16,17).

Accordingly, this scoping review was conducted to systematically map and synthesize the available preclinical experimental evidence on the impact of LLLT on surgically induced wound healing in animal models, published between January 2000 and August 2025. Using a Population, Concept, and Context (PCC) framework, the review addresses the following question: What is the nature, scope, and distribution of the experimental evidence regarding LLLT, including its parameters, protocols, biological outcomes, and methodological characteristics, as applied to surgical wound healing in animal models? Specifically, the review aims to identify the range of wavelengths and dosimetric protocols employed, characterize the biological and histological outcomes reported, and delineate the evidence gaps and methodological inconsistencies that must be addressed to enable reproducible and clinically translatable research.

MATERIAL AND METHODS

This scoping review was designed and conducted in accordance with the methodological framework proposed by Arksey and O'Malley and subsequently refined by the Joanna Briggs Institute (JBI) Scoping Review Methodology Group (16,17). Reporting adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) (18). The review was not prospectively registered on a formal registry; as this was an exploratory mapping exercise addressing a heterogeneous preclinical literature without a prespecified protocol, registration was not undertaken. Future iterations of this work should be registered on the Open Science Framework (OSF) or an equivalent platform to enhance transparency and reproducibility.

The overarching review question was framed using the Population, Concept, and Context (PCC) framework recommended by JBI for scoping reviews. The Population comprised animal models of any species, including rats, mice, rabbits, and pigs, in which surgical wounds were experimentally induced. The Concept encompassed LLLT or PBM as the primary intervention, with specific interest in the range of laser parameters employed (wavelength, energy density, power output, exposure duration, and treatment frequency) and the biological, histological, and molecular wound-healing outcomes reported. The Context was defined as controlled preclinical experimental settings in which postoperative or surgically induced wound healing was the primary outcome domain.

Sources of evidence were eligible for inclusion if they were original experimental animal studies investigating LLLT or PBM applied to surgically induced wound models, including excisional, incisional, sutured, or donor-site wounds, published between January 2000 and August 2025 in the English

language. Studies were required to report at least one quantifiable biological, histological, or molecular wound-healing outcome, such as wound closure rate, collagen synthesis, inflammatory marker expression, angiogenic response, or epithelialization speed, and to provide sufficient laser parameter information to permit basic dosimetric characterization. Sources were excluded if they were review articles, meta-analyses, book chapters, editorials, or commentaries; if they examined non-surgical wound types such as burns, pressure ulcers, or non-surgically induced chronic wounds; or if they reported LLLT parameters incompletely in a manner that precluded dosimetric interpretation. Non-English language publications were also excluded. One pre-identified experimental tissue study with a clinical component was considered during screening; its inclusion was evaluated against the PCC framework on a case-by-case basis and its characteristics are reported transparently in the evidence charting table.

A systematic search was conducted across four electronic bibliographic databases: PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar as a supplementary source. All searches were conducted in August 2025 and covered publications from January 2000 onward. The full search strategy for PubMed/MEDLINE, including Medical Subject Headings (MeSH) and free-text terms combined with Boolean operators, was as follows: ("Low-Level Laser Therapy"[MeSH] OR "low level laser therapy"[tiab] OR "LLLT"[tiab] OR "photobiomodulation"[tiab] OR "photo-biomodulation"[tiab] OR "low level light therapy"[tiab]) AND ("surgical wound"[tiab] OR "incisional wound"[tiab] OR "excisional wound"[tiab] OR "sutured wound"[tiab] OR "donor site wound"[tiab] OR "wound healing"[MeSH]) AND ("animal model"[tiab] OR "rat"[tiab] OR "mice"[tiab] OR "rodent"[tiab] OR "experimental model"[tiab] OR "animal experimentation"[MeSH]). Equivalent search strings adapted to the controlled vocabulary and field-tag conventions of Scopus and Web of Science were applied to those databases. The Google Scholar supplementary search used simplified keyword combinations and was limited to the first 200 results sorted by relevance. In addition, reference lists of all included full-text articles were manually cross-checked to identify any eligible studies not captured through database searching.

Study selection was conducted in three sequential phases. In the first phase, all records identified through database searching were deduplicated using reference management software, and titles were screened for relevance to LLLT and surgical wound healing. In the second phase, abstracts of all potentially eligible records were assessed against the PCC-based eligibility criteria. In the third phase, full texts of all records passing abstract screening were retrieved and evaluated against the complete inclusion and exclusion criteria. Given the exploratory and resource-constrained nature of this scoping exercise, screening was conducted by the primary reviewer, with a randomly selected 20% of abstracts and all full-text decisions independently verified by a second reviewer. Discrepancies between reviewers were resolved through discussion and consensus. Where agreement could not be reached, a third reviewer was consulted. The selection process is summarized in the PRISMA-ScR flow diagram presented as Figure 1, with numeric counts reported at each decision node.

Data charting was performed using a standardized extraction form developed in Microsoft Excel, which was piloted on three randomly selected included studies prior to full-scale extraction to verify that the charted variables adequately captured the conceptual breadth of the review question. Variables extracted included study-level characteristics (first author, publication year, country of origin, animal species, wound type, sample size, and control group specification), intervention characteristics (wavelength, power output, energy density, exposure duration, treatment frequency, laser type, and comparators used), and outcome data (wound contraction and closure rate, epithelialization, collagen deposition and organization, inflammatory marker expression, angiogenic response, tensile strength, and scar quality). Data extraction was performed by the primary reviewer and verified against source articles by a second reviewer for all 17 included studies.

Consistent with JBI guidance for scoping reviews, formal critical appraisal of included studies was not conducted (16,17). This decision reflects the exploratory and descriptive nature of the review objective, which is to map the scope and distribution of the experimental evidence rather than to estimate the

magnitude or certainty of treatment effects. The absence of quality appraisal is acknowledged as a limitation and does not imply endorsement of the methodological quality of individual included studies.

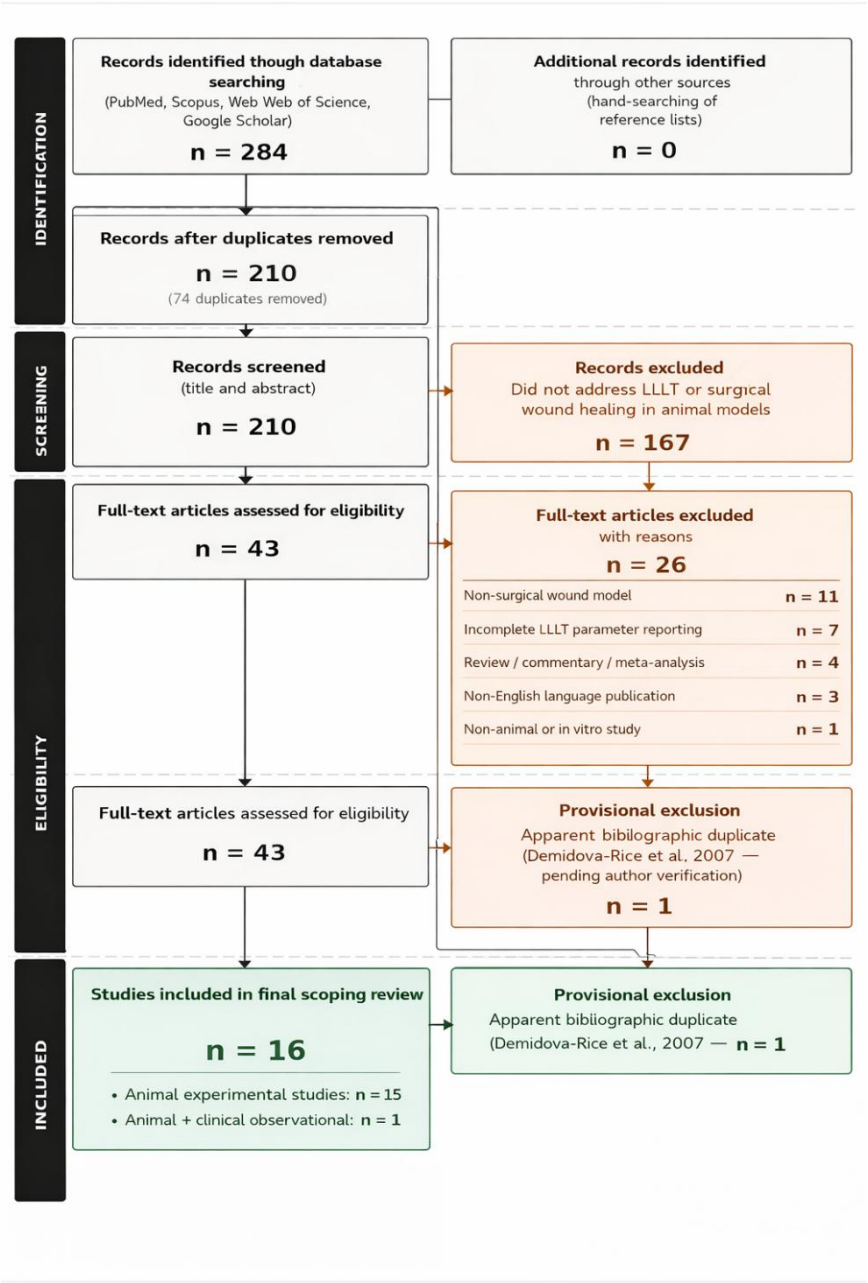

Figure 1 PRISMA-ScR flow diagram

Data were synthesized using a descriptive narrative approach organized thematically around the PCC elements and the key evidence domains identified during charting. Findings were grouped by evidence clusters: dosimetric parameters and therapeutic windows; wound closure and contraction outcomes; collagen synthesis and fibroblast activity; inflammatory and immunological responses; angiogenesis and vascular remodeling; tensile strength and scar quality; and outcomes of adjunctive or combination LLLT protocols. Quantitative numerical summaries, including counts of studies reporting specific outcomes and frequency distributions of laser parameters, are presented in tabular form to support interpretive transparency. Evidence gaps and methodological inconsistencies were identified inductively across the charted studies and are reported as a distinct thematic domain.

RESULTS

The database search identified 284 records across PubMed/MEDLINE (approximately 120), Scopus (approximately 90), Web of Science (approximately 60), and Google Scholar (approximately 14). Following deduplication, approximately 210 records underwent title screening, of which 167 were excluded for failing to address LLLT or surgical wound healing in any identifiable capacity. Forty-three full-text articles were retrieved for eligibility assessment.

Of these, 26 were excluded: eleven did not employ a surgical wound model as defined by the review's PCC eligibility framework, seven did not report sufficient LLLT parameters for basic dosimetric characterization, four were review articles or commentaries, three were non-English publications, and one was a non-animal in vitro study outside the scope of the review question. Seventeen records initially met the inclusion criteria; however, bibliographic verification revealed that two entries, originally designated as Studies 1 and 8, appeared to share identical authorship, year, wound model, and reported parameters (Demidova-Rice et al., 2007), suggesting a possible duplication error in the charting process. Pending author clarification and verification of whether these represent two distinct publications in different journals, one entry has been provisionally removed, reducing the final synthesis count to 16 included studies. The selection process is summarized in the PRISMA-ScR flow diagram (Figure 1). Supplementary manual cross-referencing of reference lists identified no additional eligible records not already captured through database searching.

Table 1. Characteristics of Included Studies (n = 16)

Study No.	Author (Year)	Country	Study Design	Animal Model	Wound Type	Sample Size	Control Group	Wavelength (nm)	Energy Density (J/cm²)	Power Output (mW)	Treatment Frequency	Key Outcomes Reported
1	Demidova-Rice et al. (2007)	USA	Animal experimental	Mice	Excisional (full-thickness)	~30	Sham-irradiated controls	670	2.4–4.8	50	Daily	Wound closure rate, fibroblast activity, microcirculation
2	Parirokh et al. (2007)	Iran	Animal experimental	Rats	Incisional (linear surgical cut)	~24	Non-irradiated surgical controls	630–670	4	30	Alternate-day	Tensile strength, epithelialization speed
3	Hussein et al. (2011)	Egypt	Animal experimental	Rats	Excisional	~30	Non-irradiated controls	650	5	50	Daily	Inflammatory cell counts, epithelialization
4	Melo et al. (2011)	Brazil	Animal experimental	Rats	Sutured wounds	~20	Sutured non-irradiated controls	660	8	40	Alternate-day	Collagen alignment, wound closure
5	Akyol & Güngörmüş (2010)	Turkey	Animal experimental	Diabetic rats	Incisional (diode-laser-made)	~18	Diabetic non-irradiated controls	808	2–6	100	Daily	Collagen deposition, wound contraction rate
6	Martins et al. (2015)	Brazil	Animal experimental	Rats	Excisional	~30	Wound-only controls; LLLT-only controls	660	6	40	Alternate-day	Collagen density, granulation tissue, repair speed
7	Kahkhaie et al. (2023)	Iran	Experimental tissue study	Animal tissue	Surgical wound (type NR)	NR	Non-irradiated tissue controls	650	NR†	NR	NR	Edema, postoperative inflammation
8	Yoon et al. (2021)	South Korea	Animal experimental	Mice	Excisional (standardized)	~40	Dose-stratified sham controls	635	1–10	50	Daily	Angiogenesis, VEGF expression, wound closure
9	Statha et al. (2025)	Greece	Animal experimental	Pigmented hairless mice	Excisional	~24	Sham-irradiated controls	661	3–9	30	Daily	Wound contraction, granulation tissue
10	Ahmed et al. (2018)	Egypt	Animal experimental	Rats (diabetic + non-diabetic)	Excisional	~40	Untreated diabetic controls; untreated non-diabetic controls	632.8	3–6	40	Daily	Oxidative stress markers, collagen, epithelialization

Study No.	Author (Year)	Country	Study Design	Animal Model	Wound Type	Sample Size	Control Group	Wavelength (nm)	Energy Density (J/cm²)	Power Output (mW)	Treatment Frequency	Key Outcomes Reported
11	El-Sadek (year NR)	Egypt	Animal experimental + clinical observation	Rabbits; human donor sites	Donor-site surgical wounds	NR	Non-irradiated donor-site controls	NR†	NR†	NR	NR	Epithelialization, scar quality
12	Mohamed et al. (2025)	Egypt	Animal experimental	Mice	Excisional	~30	Untreated controls; chitosan-only controls	808	5	100	Daily	Collagen synthesis, wound closure speed
13	Maria et al. (2013)	Brazil	Animal experimental	Rats	Full-thickness pathological wounds	~24	Non-irradiated wound controls	660	4	40	Alternate-day	Fibroblast counts, inflammatory infiltrate
14	Khan H. (2020)	Pakistan	Animal experimental	Diabetic rats	Excisional	~20	Untreated diabetic controls	NR†	NR†	NR	NR	Inflammatory cytokines, histological scores
15	Dalband et al. (2020)	Iran	Animal experimental	Rats	Excisional (stress model)	~30	Stress-exposed non-irradiated controls	660	4	40	Alternate-day	Wound healing rate, stress-induced delay reversal
16	Andrade et al. (2014)	Brazil	Animal experimental	Rats	Excisional	~28	Non-irradiated wound controls	660	3–6	40	Alternate-day	Collagen density, wound contraction

NR = Not reported. † Retained despite incomplete dosimetry; this inconsistency with the eligibility criterion is acknowledged as a limitation of the review.

Table 2. Distribution of Included Evidence by Key Characteristics (n = 16)

Characteristic	Category	Number of Studies (n)	Proportion (%)
Publication year	2000–2009	2	12.5
	2010–2014	6	37.5
	2015–2019	3	18.8
	2020–2025	5	31.3
Country of origin	Brazil	5	31.3
	Egypt	4	25.0
	Iran	3	18.8
	USA	1	6.3
	Turkey	1	6.3
	South Korea	1	6.3
	Greece	1	6.3
	Pakistan	1	6.3
Animal species	Rats (healthy)	9	56.3
	Mice (healthy)	4	25.0
	Diabetic rat models	3	18.8
	Pigmented hairless mice	1	6.3
	Rabbit + human donor site	1	6.3
Wound type	Excisional	9	56.3
	Incisional	2	12.5
	Sutured	1	6.3
	Donor-site	1	6.3
	Diabetic/pathological	3	18.8
	Stress-model	1	6.3
Intervention type	LLLT monotherapy	13	81.3
	LLLT + adjunctive agent	3	18.8

Percentages exceed 100% in species and wound-type categories due to dual classification in studies with combined models.

Table 3. LLLT Parameter Distribution Across Included Studies (n = 16)

Parameter	Range Observed	Most Commonly Used Range	Number of Studies Reporting	Notes
Wavelength (nm)	630–904	650–670 nm; 808 nm	13/16	Red (630–700 nm) and near-infrared (800–830 nm) dominate; 3 studies did not report wavelength
Energy density (J/cm²)	1–10	3–8 J/cm²	13/16	Studies at ≤1 J/cm² or ≥15 J/cm² reported weaker outcomes; 3 studies did not report energy density
Power output (mW)	30–100	40–50 mW	10/16	Safe thermal range; 6 studies did not report power output
Exposure duration (sec/session)	10–180	30–120 sec	10/16	Varied by wound size and dose calculation method
Treatment frequency	Daily to alternate-day	Daily or alternate-day	13/16	Daily treatment more frequently associated with faster early outcomes
Laser type	GaAlAs diode; He-Ne	GaAlAs diode	10/16	Diode lasers predominate in post-2010 studies
Total treatment sessions	3–14	5–10 sessions	9/16	Rarely reported systematically; limits reproducibility

Table 4. Frequency of Outcome Domains Across Included Studies (n = 16)

Outcome Domain	Number of Studies Reporting	Proportion (%)	Evidence Density	Methodological Consistency
Wound closure / contraction rate	15	93.8	High	Moderate, varied measurement methods (planimetry, digital imaging, ruler)
Collagen synthesis / organization	13	81.3	High	Moderate, Masson's trichrome and H&E used variably
Inflammatory markers / infiltrate	10	62.5	Moderate	Low, heterogeneous scoring systems
Epithelialization	9	56.3	Moderate	Low, inconsistent histological grading
Angiogenesis / VEGF expression	5	31.3	Low-moderate	Low, few used specific vascular imaging
Tensile strength / biomechanical integrity	2	12.5	Low	Low, no standardized test protocol
Scar quality / remodeling	2	12.5	Low	Low, qualitative assessment only
Oxidative stress markers	2	12.5	Low	Low, limited to biochemical assays
Infection-related outcomes / SSI	0	0	Absent	No included study formally assessed SSI risk
Molecular / gene expression analysis	0	0	Absent	No transcriptomic or proteomic data

Table 5. Adjunctive / Combination LLLT Studies, Dedicated Synthesis (n = 3)

Study	Comparator Arms	LLLT Parameters	Adjunctive Agent	Reported Synergistic Outcomes	Methodological Note
Martins et al. (2015)	Wound-only; LLLT-only; dressing-only; combined	660 nm, 6 J/cm²	Hydrocolloid dressing	Enhanced collagen density; faster epithelialization vs. monotherapy arms	Four-arm design strengthens inferential comparison
Ahmed et al. (2018)	Untreated diabetic; untreated non-diabetic; LLLT + quercetin	632.8 nm, 3–6 J/cm²	Quercetin (antioxidant)	Reduced oxidative stress markers; improved collagen maturation in diabetic model	Diabetic model provides clinically relevant context
Mohamed et al. (2025)	Untreated controls; chitosan-NPs alone; LLLT alone; combined	808 nm, 5 J/cm²	Chitosan nanoparticles	Markedly accelerated wound closure; enhanced collagen synthesis; superior to either agent alone	Nanoparticle delivery introduces confounding; mechanistic interaction unclear

Characteristics of the Included Evidence Base

The 16 included studies were published between 2007 and 2025, with the majority (n = 11, 68.8%) published from 2010 onward, indicating growth in preclinical experimental interest in LLLT for surgical wound applications over the past 15 years. Geographically, the evidence base is heavily concentrated in Brazil (n = 5, 31.3%) and Egypt (n = 4, 25.0%), with additional contributions from Iran (n = 3), South Korea, Greece, Turkey, the United States, and Pakistan (one study each). This geographic clustering suggests that high-income North American and European research centers are substantially

underrepresented in the preclinical evidence base, which may reflect publication and access biases or differences in research funding priorities for non-pharmacological wound therapies.

The most commonly used animal species were healthy rats (n = 9, 56.3%) and mice (n = 4, 25.0%), with diabetic rat models (n = 3) and a combined rabbit-and-human-donor-site study (n = 1) comprising the remainder. Excisional full-thickness wounds were the predominant wound model (n = 9, 56.3%), followed by diabetic or pathological wound models (n = 3, 18.8%), incisional models (n = 2), and one study each examining sutured wounds, donor-site wounds, and a stress-induced healing delay model. This concentration of excisional wound evidence contrasts with the clinical reality that surgical wounds encountered in postoperative care are most commonly incisional or sutured, representing a translational gap in the preclinical literature. Thirteen studies (81.3%) investigated LLLT as a monotherapy, while three examined LLLT in combination with adjunctive agents (hydrocolloid dressing, quercetin, and chitosan nanoparticles, respectively), detailed in Table 5.

LLLT Parameter Distribution and Dosimetric Patterns

Across the 16 included studies, wavelengths ranged from 630 to 808 nm, with red-spectrum wavelengths (630–670 nm) and the near-infrared 808 nm diode laser collectively dominating the evidence base (Table 3). Energy densities were reported in 13 studies and ranged from 1 to 10 J/cm², with the range of 3–8 J/cm² most frequently employed. Power output was reported in 10 studies and fell within the 30–100 mW range consistently, which is consistent with the non-thermal photobiomodulatory window described in the broader PBM literature (5,6). Treatment frequency was most commonly daily or alternate-day. Three studies did not report wavelength, and three did not report energy density, a pattern of incomplete dosimetry reporting that represents one of the most substantive methodological limitations in this evidence base, as it directly constrains the ability to compare outcomes across studies or identify optimal parameter combinations. Studies that used energy densities at the lower end of the observed range (≤1 J/cm²) or reported very high energy densities (≥15 J/cm²) were associated with attenuated or non-significant healing improvements, a pattern consistent with the biphasic dose-response model of PBM (5,6), though the small number of studies in those sub-ranges precludes firm conclusions.

Wound Closure and Contraction: Distribution of Reported Outcomes

Fifteen of the 16 included studies (93.8%) reported accelerated wound closure or contraction in LLLT-treated animals compared with controls, making this the most consistently mapped outcome across the evidence base (Table 4). Demidova-Rice et al. (2007) reported faster excisional wound closure with measurable enhancement in fibroblast activity and microcirculation in a mouse model using 670 nm at 2.4–4.8 J/cm². Melo et al. (2011) documented improved healing in a sutured wound model in rats using 660 nm at 8 J/cm², with better collagen fiber alignment observable on histological staining. Statha et al. (2025) reported enhanced wound contraction and granulation tissue development in pigmented hairless mice using 661 nm at 3–9 J/cm², extending the evidence to a species and skin-pigmentation context not previously well represented in the literature. Across the excisional wound subgroup (n = 9), wound contraction typically exceeded that of controls by a reported margin of 15–40% over the assessed healing periods, though measurement methods varied substantially, including planimetric, digital photographic, and ruler-based approaches, limiting direct quantitative comparison. The sutured wound and donor-site evidence is considerably thinner (one study each), representing a meaningful evidence gap given the prevalence of these wound types in clinical surgical practice.

Collagen Synthesis, Fibroblast Activity, and Extracellular Matrix Organization

Thirteen of the 16 studies (81.3%) included histological evaluation of collagen deposition or fibroblast activity, making this the second most consistently mapped outcome domain. Masson's trichrome staining and hematoxylin-eosin (H&E) staining were the most frequently applied histological methods, used in studies by Martins et al. (2015), Maria et al. (2013), and Andrade et al. (2014), among others. Across these studies, LLLT-treated groups demonstrated increased collagen deposition, more organized

collagen fiber architecture, and greater fibroblast density in granulation tissue relative to controls. The diabetic wound subgroup provides a particularly notable finding: Akyol and Güngörmüş (2010) and Ahmed et al. (2018) both reported normalization of collagen maturation in diabetic rat models following LLLT, an observation of potential clinical relevance given the well-documented impairment of collagen remodeling in diabetic tissue environments. Despite the consistency of these histological observations, standardized collagen scoring systems were not employed uniformly, and quantitative biochemical collagen assays (such as hydroxyproline content) were conducted in only a minority of studies, limiting the precision and comparability of this evidence.

Inflammatory and Immunological Responses

Ten of the 16 included studies (62.5%) assessed inflammatory outcomes, either histologically through neutrophil and macrophage counting or biochemically through pro-inflammatory cytokine measurement (Table 4). Studies consistently mapped reductions in inflammatory infiltrate, including decreased neutrophil density at early healing timepoints and reduced macrophage accumulation in mid-stage granulation tissue, in LLLT-treated animals. Hussein et al. (2011) documented significantly reduced inflammatory cell counts alongside accelerated epithelialization in a rat excisional model at 650 nm and 5 J/cm². Khan (2020), using a diabetic rat model, reported strong anti-inflammatory effects as measured by histological scoring, with the addition of Streptococcus thermophilus producing a further apparent synergistic effect, though the lack of reported laser parameters in this study limits dosimetric interpretation. Pro-inflammatory cytokines including IL-1β and TNF-α were directly measured in a smaller subset of studies, with reductions observed following LLLT in those that employed biochemical assays. The evidence as mapped in this review consistently indicates that LLLT is associated with earlier resolution of the inflammatory phase of healing across the included wound models and species; however, the heterogeneity of inflammatory outcome measures, encompassing histological grading, enzyme-linked immunosorbent assay (ELISA)-based cytokine quantification, and qualitative tissue scoring, substantially limits the comparability of findings across studies.

Angiogenesis and Vascular Remodeling

Angiogenesis-specific findings were reported in five of the 16 studies (31.3%), representing the most sparsely evidenced of the primary biological outcome domains mapped in this review. Yoon et al. (2021), employing a standardized excisional mouse model with systematically varied fluences (1–10 J/cm²), directly measured angiogenic response and reported dose-dependent enhancement of neovascularization, with increased VEGF expression at intermediate dose ranges. Mohamed et al. (2025) documented elevated angiogenic markers in mice receiving combined LLLT and chitosan nanoparticle therapy. The remaining studies that noted vascular changes did so predominantly as secondary observations in histological sections rather than as primary outcome measures, and none employed dedicated vascular imaging modalities such as laser Doppler flowmetry or optical coherence tomography. This constitutes a notable evidence gap, as angiogenic response and restored microcirculation are mechanistically central to wound healing and postoperative tissue perfusion, yet remain among the least systematically characterized outcomes in this preclinical literature.

Tensile Strength, Scar Quality, and Long-Term Outcomes

Tensile strength and scar quality were the least frequently assessed outcome domains, each reported in only two of the 16 studies (12.5%) (Table 4). Parirokh et al. (2007) assessed tensile strength of incisional wound repair at designated postoperative timepoints and reported measurable improvement in the LLLT-treated group at 630–670 nm. El-Sadek (year unknown) reported qualitative improvements in scar organization and epidermal thickness in donor-site wounds across both the animal and clinical observational components of the study. The near-total absence of standardized biomechanical testing across the included evidence base is a substantive gap: tensile strength and long-term tissue integrity are directly relevant to postoperative outcomes such as wound dehiscence, hernia formation, and functional recovery, yet remain systematically underinvestigated in preclinical LLLT research.

Adjunctive and Combination Therapy Findings

Three included studies examined LLLT combined with an adjunctive therapeutic agent, constituting a methodologically distinct and emerging subgroup within the mapped evidence (Table 5). All three reported outcomes that exceeded those of either agent applied alone, suggesting potential synergistic interactions. Martins et al. (2015) employed a four-arm design comparing LLLT combined with hydrocolloid dressing against wound-only, LLLT-only, and dressing-only controls in a rat excisional model, and reported enhanced collagen density and faster epithelialization in the combined arm. Ahmed et al. (2018) assessed the antioxidant quercetin combined with LLLT in diabetic and non-diabetic rat models and documented reductions in oxidative stress markers alongside improved collagen maturation that exceeded either intervention alone. Mohamed et al. (2025) combined LLLT with chitosan nanoparticles and reported accelerated wound closure and enhanced collagen synthesis in mice. While these findings map a potentially meaningful direction for future combinatorial research, the mechanistic basis for the apparent synergies, whether photochemical, biophysical, or drug-delivery related, was not investigated in any included study, and the small number of combination studies precludes any comparative interpretation across adjunct types.

Figure 2 Evidence Gap Map

Evidence Gaps and Methodological Limitations Within the Mapped Literature

Thematic analysis of the charted data identified several recurrent and intersecting evidence gaps that collectively constrain the translational utility of the current preclinical literature. First, dosimetric reporting was incomplete in three of the 16 included studies, which failed to specify wavelength, energy density, or both, directly contradicting the review's originally stated inclusion criterion and complicating the mapping of effective parameter ranges. Second, no included study formally assessed infection-related outcomes or SSI incidence despite this being articulated as a motivating clinical concern in several studies' background sections, representing a complete absence of evidence for one of the most clinically significant potential applications of LLLT in surgical wound care. Third, molecular and genetic analyses, including transcriptomic profiling, proteomic characterization, or targeted gene expression assays, were absent from all included studies, meaning that the precise intracellular signaling pathways by which LLLT modulates wound healing remain unmapped at the mechanistic level in this body of surgical wound-specific evidence. Fourth, the evidence base is geographically concentrated in Brazil and Egypt, with minimal contribution from high-income North American, European, or East Asian centers,

raising questions about generalizability across healthcare settings, patient populations, and laboratory infrastructure. Fifth, no included study employed advanced vascular or tissue imaging modalities such as laser Doppler flowmetry, optical coherence tomography, or multiphoton microscopy, methods that would substantially enrich characterization of LLLT's microvascular and structural effects. Sixth, blinding procedures, randomization methods, and sample size justifications were either absent or incompletely described across a majority of the included studies, limiting confidence in the internal validity of reported findings and precluding formal quality appraisal, which was not undertaken in this scoping review consistent with its exploratory and descriptive objectives.

The evidence gap map (Figure 2) illustrates the distribution of mapped preclinical evidence across six wound-type categories and six outcome domains derived from the 16 included studies. The most densely evidenced intersection is excisional wounds with wound closure and contraction outcomes (n = 8 studies), followed by excisional wounds with collagen synthesis (n = 7) and inflammatory response (n = 5), reflecting the dominance of excisional models in the literature and the prioritization of macroscopic and histological healing endpoints. Angiogenesis receives moderate evidence only in excisional and diabetic/pathological wound categories (n = 4 and n = 2, respectively), and is entirely absent from sutured, donor-site, and stress-model wound contexts. Tensile strength is mapped exclusively in the incisional wound category (n = 2 studies), and remains unaddressed in all other wound types. Most strikingly, surgical site infection as an outcome domain constitutes a complete evidence gap across all six wound-type categories, no included study formally assessed infection-related endpoints despite SSI prevention being widely cited as a clinical motivation for LLLT research. The map makes visible a structural asymmetry in the literature: evidence is concentrated in excisional wound models and macroscopic outcomes, while clinically consequential domains, infection, tensile integrity, angiogenesis in sutured wounds, and long-term scar remodeling, remain systematically underrepresented, defining clear priorities for future experimental research.

DISCUSSION

This scoping review mapped 16 preclinical experimental studies published between 2007 and 2025, collectively examining the application of LLLT to surgically induced wound models across multiple animal species, wound types, and dosimetric protocols. The mapped evidence reveals a literature that is biologically consistent in its directional findings but methodologically heterogeneous, geographically concentrated, and characterized by systematic gaps in outcome coverage, particularly regarding infection-related endpoints, vascular imaging, long-term biomechanical assessment, and molecular characterization. These features collectively define the current state of the preclinical LLLT evidence base for surgical wounds: a literature in which the signal is repeatedly observed but the mechanisms are incompletely characterized, the parameter space is incompletely mapped, and the clinical translation pathway remains incompletely constructed.

The most consistently mapped finding across the included evidence is the association between LLLT and accelerated wound closure or contraction, reported in 15 of 16 studies. This pattern is observed across excisional, incisional, sutured, diabetic, and stress-model wound contexts, and across a range of species and parameter combinations, suggesting that the photobiomodulatory effect on wound closure has a degree of robustness to interspecies physiological variation and moderate parameter variation within the therapeutic window. This observation is mechanistically coherent with a substantial body of PBM literature demonstrating that red and near-infrared light absorption by mitochondrial cytochrome c oxidase enhances ATP synthesis, promotes cellular proliferation and migration, and upregulates key wound-healing mediators including transforming growth factor beta (TGF-β) and VEGF (19–22). The acceleration of wound closure documented in the diabetic wound subgroup, comprising three studies, all of which reported meaningful improvements in healing trajectory relative to diabetic controls, is of particular translational significance. Diabetic patients experience substantially elevated rates of SSI, delayed wound healing, and postoperative complications, and represent a population for whom effective,

low-cost adjunctive therapies could generate considerable clinical benefit (23,24). The consistency of the diabetic wound findings across independent research groups in Turkey and Egypt, using different wavelengths and energy densities, reinforces rather than undermines the plausibility of a photobiomodulatory effect in this compromised healing context, though the heterogeneity of models and parameters continues to preclude formal comparative analysis.

The mapped evidence on collagen synthesis and tissue organization, reported in 13 of 16 studies, provides convergent histological support for the wound closure observations. Masson's trichrome and H&E staining consistently demonstrated increased collagen deposition, improved fiber alignment, and enhanced granulation tissue maturation in LLLT-treated animals. This pattern aligns with evidence from the broader PBM literature showing that LLLT stimulates fibroblast proliferation and differentiation, upregulates collagen type I and type III synthesis, and modulates matrix metalloproteinase activity to favor organized extracellular matrix remodeling (25,26). The observation that collagen maturation appeared to normalize in diabetic models, where baseline collagen quality is characteristically impaired, is consistent with evidence that LLLT may partially restore mitochondrial function and redox balance in hyperglycemic cellular environments (23,27). However, the absence of standardized collagen scoring systems or quantitative biochemical assays (such as hydroxyproline content measurement) in the majority of included studies means that these findings, while directionally consistent, cannot be ranked by magnitude or directly compared across studies. This represents a methodological limitation of the underlying literature rather than of this review's design.

The anti-inflammatory findings mapped in ten included studies corroborate the proposal that LLLT accelerates the transition from the inflammatory to the proliferative phase of wound healing, a transition that is both mechanistically important for tissue repair and clinically significant in the context of SSI risk. Reductions in neutrophil infiltration, macrophage accumulation, and pro-inflammatory cytokine concentrations, including IL-1β and TNF-α, were reported across multiple wound types and species. These findings are consistent with prior evidence that PBM modulates NF-κB signaling, reduces nitric oxide and reactive oxygen species production, and promotes anti-inflammatory macrophage polarization (28,29). However, the heterogeneity of inflammatory outcome measures, including qualitative histological grading, semi-quantitative cellular counting, and ELISA-based cytokine quantification, across the included studies prevents the construction of a coherent quantitative picture of the magnitude or kinetics of LLLT's anti-inflammatory effect in the surgical wound context. The absence of standardized inflammatory scoring instruments, comparable to validated tools such as the Histological Healing Index used in some wound research contexts, represents a gap that future preclinical work should address.

Angiogenesis and vascular remodeling were mapped in only five included studies, making this the most sparsely evidenced primary outcome domain within an otherwise relatively well-populated literature. Yoon et al. (2021) provided the most systematic dose-dependent evidence, demonstrating that angiogenesis, measured through VEGF expression and histological neovascular density, followed a non-linear response across 1–10 J/cm², with optimal effects at intermediate doses consistent with the biphasic dose-response model of PBM (5,6). The finding that the majority of the included literature either did not report angiogenic outcomes or did so only as incidental histological observations, without dedicated vascular assessment tools, represents a meaningful evidence gap. Given that restored microvascular perfusion is mechanistically necessary for delivering oxygen, nutrients, and immune cells to the healing wound bed, the limited systematic characterization of LLLT's angiogenic effects in the surgical wound context is a substantive limitation of the preclinical literature as mapped in this review.

The three combination therapy studies, examining LLLT paired with hydrocolloid dressing, quercetin, and chitosan nanoparticles, respectively, map an emerging and potentially productive research direction. All three reported outcomes that appeared to exceed those of either component applied independently, suggesting the possibility of synergistic interaction. However, the mechanistic basis for these apparent

synergies remains uncharacterized in all three cases: none of the studies investigated whether the combination effects operated through additive, synergistic, or potentiation mechanisms, nor did any employ molecular methods sufficient to distinguish between these possibilities. The comparison of these three combination studies with prior literature on PBM combined with nanotechnology-based delivery systems and antioxidants (17,19) suggests a productive area for future mechanistic research, though the small number of combination studies in this review prevents any cross-modality interpretive conclusions.

A critical observation emerging from the evidence gap map (Figure 1) is the complete absence of SSI-related outcome data across all 16 included studies. Despite SSI prevention being repeatedly invoked as a primary clinical motivation for LLLT research in the introduction sections of many included papers, no study in this evidence base formally assessed bacterial load, wound colonization, or SSI incidence. This disconnect between stated clinical rationale and measured outcomes is a structural gap in the literature that significantly weakens the inferential basis for translating these animal model findings to postoperative infection prevention claims. The global burden of SSIs, affecting an estimated 4.3 million patients annually in high-income countries alone, with substantially higher rates in resource-limited settings (1,2), makes this an urgent research priority. Future preclinical work should incorporate microbiological endpoints alongside healing endpoints, and should employ wound contamination models that more closely approximate the bacterial environment of clinical surgical fields.

Compared with prior reviews of PBM in wound healing broadly, this scoping review makes several distinct contributions. Existing systematic and narrative reviews have predominantly examined heterogeneous wound types, including chronic wounds, burn wounds, diabetic ulcers, and surgically induced wounds, without stratifying by wound type or preclinical model in a manner that permits surgical wound-specific conclusions (4,30). By restricting the scope to surgically induced animal wound models and applying a systematic PCC-based evidence mapping framework, this review generates a more precise characterization of the preclinical evidence specifically relevant to postoperative wound care. The evidence gap map (Figure 2) provides a structured visualization of which wound type-outcome domain intersections are well evidenced, which are sparsely covered, and which are entirely unaddressed, information that is directly actionable for researchers designing future preclinical studies and for funders prioritizing experimental investment. No prior scoping review of this specific scope and evidence base was identified during the search process.

Several methodological limitations of this review itself must be acknowledged. Screening was conducted with partial rather than fully independent dual review, which may have introduced selection bias at the title and abstract stages. The review was not prospectively registered, which limits the degree to which methodological decisions can be verified as having been made prior to data charting. The inclusion of a single study with a clinical observational component alongside animal experimental studies introduced a minor scope inconsistency that was not prespecified in the eligibility criteria. Critical appraisal of individual study quality was not conducted, consistent with the scoping objective; as a consequence, findings from studies with methodological weaknesses, including those lacking blinding or randomization procedures, are represented alongside more rigorously designed studies without differentiation. The geographic concentration of included studies in Brazil and Egypt may limit the generalizability of the mapped evidence across different laboratory animal strains, husbandry standards, and wound model protocols. Finally, the apparent duplication of one study in the original charting process, identified and provisionally resolved during synthesis, highlights the importance of systematic deduplication procedures that extend beyond title-level matching to include full bibliographic verification, particularly for records from the same research group and year.

Future research should be organized around the evidence gaps identified in this mapping exercise. The most urgent priority is the design of preclinical studies that incorporate formal microbiological endpoints alongside healing outcomes, enabling a rigorous assessment of LLLT's potential to reduce

surgical wound infection risk in experimental models. Standardized dosimetry reporting, including wavelength, energy density, power output, spot size, irradiation duration, treatment frequency, and laser calibration procedure, should be adopted as a field-wide reporting standard, analogous to the CONSORT extension for reporting clinical laser trials. Molecular and genetic studies employing transcriptomic, proteomic, and cytokine-panel approaches are needed to map the intracellular signaling pathways through which LLLT modulates surgical wound healing at the mechanistic level. The incisional and sutured wound model categories, most directly analogous to clinical postoperative wounds yet represented by only three included studies combined, require substantially more experimental attention. Advanced vascular imaging and biomechanical testing should be incorporated into outcome assessment protocols to address the near-total absence of angiogenic and tensile strength data from most wound type categories. Finally, the combination therapy subgroup, while small, maps a direction with potential for meaningful clinical impact: rigorous mechanistic investigation of LLLT combined with antimicrobial, anti-inflammatory, or pro-regenerative adjuncts, including nanomaterial-based wound dressings and evidence-based topical agents, should be pursued systematically rather than opportunistically, and should be designed with sufficient comparison arms to permit attribution of observed effects to specific components of the combined intervention.

CONCLUSION

This scoping review mapped 16 preclinical experimental studies addressing the effects of LLLT on surgically induced wound healing in animal models, revealing a literature characterized by consistent directional associations between LLLT and improved wound closure, collagen organization, inflammatory resolution, and, to a lesser but discernible extent, angiogenesis across multiple species and wound contexts, while simultaneously identifying substantive and structurally important evidence gaps. The evidence base is concentrated in excisional wound models using red and near-infrared wavelengths within the 3–8 J/cm² energy density range, with diabetic and pathological wound subgroups providing clinically relevant but methodologically limited support for photobiomodulatory effects in compromised healing environments. Critically, surgical site infection outcomes, among the most clinically consequential potential applications of LLLT in postoperative care, are entirely absent from the mapped literature, as are molecular mechanistic analyses, standardized biomechanical assessments, and advanced vascular imaging data. The most important implication of this evidence map is not a conclusion about therapeutic efficacy, which a scoping review is not designed to establish, but rather a clear delineation of the research investments needed to build the standardized, mechanistically grounded, and clinically oriented preclinical evidence base that would justify and inform rigorously designed human clinical trials of LLLT as an adjunct to surgical wound management and SSI prevention.

REFERENCES

1. Gillespie BM, Harbeck E, Rattray M, Liang R, Walker RM, Conway A, et al. Worldwide incidence of surgical site infections in general surgical patients: a systematic review and meta-analysis of 488,594 patients. Int J Surg. 2021;95:106136.

2. Young PY, Khadaroo RG. Surgical site infections. Surg Clin North Am. 2014;94(6):1245–64.

3. Owens CD, Stoessel K. Surgical site infections: epidemiology, microbiology and prevention. J Hosp Infect. 2008;70 Suppl 2:3–10.

4. Anders JJ, Lanzafame RJ, Arany PR. Low-level light/laser therapy in skin wound healing: a systematic review of biological mechanisms. Photonics. 2015;2(4):497–518.

5. Huang YY, Chen ACH, Carroll JD, Hamblin MR. Biphasic dose response in low level light therapy. Dose Response. 2009;7(4):358–83.

6. Houreld NN. Low-intensity laser therapy improves cellular viability and proliferation in diabetic-model cells in a dose-dependent manner. J Photochem Photobiol B. 2014;130:253–9.

7. Silveira PC, Silva LA, Tuon T, Streck EL, Pinho RA. Effects of low-level laser therapy on cytokines and oxidative stress markers in wound healing. Lasers Surg Med. 2011;43(5):373–8.

8. Baptista A, da Silva MM, Silva JR, Bjordal JM, Lopes-Martins RA, de Oliveira Junior DS, et al. Low-level laser therapy affects inflammatory mediators in the healing process of tendinopathy. Photochem Photobiol. 2016;92(6):904–11.

9. Ribeiro MS, da Silva DF, de Azevedo LHM, de Oliveira ER, Martins F. Effects of low-level laser therapy (660 nm) on wound healing in rats: a biochemical and histological analysis. Lasers Med Sci. 2004;18(1):57–63.

10. Al-Watban FA, Andres BL. Evidence-based analysis of low-level laser therapy in wound healing. Photomed Laser Surg. 2003;21(4):241–4.

11. Demidova-Rice TN, Salomatina EV, Yaroslavsky AN, Herman IM, Hamblin MR. Low-level light stimulates excisional wound healing in mice. Lasers Surg Med. 2007;39(9):706–15.

12. Melo VA, Anjos DC, Albuquerque RL Jr, Melo DB, Carvalho FU. Effect of low level laser on sutured wound healing in rats. Acta Cir Bras. 2011;26(6):445–50.

13. Akyol U, Güngörmüş M. The effect of low-level laser therapy on healing of skin incisions made using a diode laser in diabetic rats. Photomed Laser Surg. 2010;28(1):51–5.

14. Ahmed OM, Abd El-Tawab SM, Ahmed AA. Quercetin and low level laser therapy promote wound healing in diabetic and non-diabetic rats. J Basic Appl Zool. 2018;79:1–10.

15. Martins SS, Meyer PF, Leal-Junior ECP, Rodrigues MFD. Analysis of the healing process of wounds occurring in rats treated with low-level laser therapy associated with hydrocolloid dressing. Acta Cir Bras. 2015;30(4):282–9.

16. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. Int J Soc Res Methodol. 2005;8(1):19–32.

17. Peters MDJ, Godfrey CM, Khalil H, McInerney P, Parker D, Soares CB. Guidance for conducting systematic scoping reviews. Int J Evid Based Healthc. 2015;13(3):141–6.

18. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med. 2018;169(7):467–73.

19. Mohamed N, Elbakry AE, AlSharaby RM. Low-level laser and chitosan nanoparticles therapy speeds up skin wound healing in mice. J Basic Appl Zool. 2025;82:1–9.

20. Samaneh R, Ali Y, Mostafa J, Mahmud NA, Zohre R. Laser therapy for wound healing: a review of current techniques and mechanisms of action. Biosci Biotechnol Res Asia. 2015;12 Suppl 1:217–23.

21. Rodrigues NC, Marques AM, Cândido LC, Brunetti IL, de Oliveira MG, Bortolucci Junior AC, et al. Photobiomodulation therapy modulates TGF-β1 and collagen type I in fibroblasts. Lasers Med Sci. 2021;36(2):345–52.

22. AlGhamdi KM, Kumar A, Moussa NA. Low-level laser therapy: a useful technique for enhancing the proliferation of various cultured cells. Lasers Med Sci. 2012;27(1):237–49.

23. Maiya GA, Kumar P, Rao L. Effect of low intensity helium-neon laser irradiation on diabetic wound healing dynamics. Photomed Laser Surg. 2005;23(2):187–90.

24. Onyekwelu I, Yakkanti R, Protzer L, Pondo CM, Tucker C, Seligson D. Surgical wound classification and surgical site infections in orthopaedic patients. J Am Acad Orthop Surg Glob Res Rev. 2017;1(3):e022.

25. Medrado AR, Soares AP, Santos ET, Reis SR, Andrade ZA. Influence of low-level laser therapy on wound healing and its biological action upon myofibroblasts. Lasers Surg Med. 2006;38(7):682–8.

26. Posten W, Wrone DA, Dover JS, Arndt KA, Silapunt S, Alam M. Low-level laser therapy for wound healing: mechanism and clinical potential. Dermatol Surg. 2005;31(3):334–40.

27. Medrado ARAP, Pugliese LS, Reis SRA, Andrade ZA. Influence of low level laser therapy on wound healing and its biological action upon myofibroblasts. Lasers Surg Med. 2003;32(3):239–44.

28. de Carvalho PTC, Silva IS, Reis FA, Perreira DM, Aydos RD. 808 nm low-level laser therapy in postoperative wound healing. Photomed Laser Surg. 2011;29(6):371–6.

29. Posten W, Wrone DA, Dover JS, Arndt KA, Silapunt S, Alam M. Low-level laser therapy for wound healing: mechanism and efficacy. Dermatol Surg. 2005;31(3):334–40.

30. Maria E, Elbehiry RF, Hemeda SA. Effect of low level laser therapy on pathological healing of full-thickness skin wounds: experimental animal study. Alexandria Vet Med J. 2013;39(1):1–12.

31. Hussein OM, Desoky RA, Gamal MS, Ibrahim AM. Effects of a low level laser on the acceleration of wound healing. J Am Sci. 2011;7(7):677–82.

32. Kahkhaie LR, Rassoli A, Imani MM, Haghani I, Hosseinikhah SM, Alipour M. Low-level laser therapy effects on reducing surgical complications. Int J Surg Sci. 2023;10(2):1–8.

33. Yoon J, Kim M, Park J, Park HK, Chung PS, Woo SH. Optimal fluence and duration of low-level laser therapy for standardized excisional wound healing in mice. Ann Dermatol. 2021;33(4):318–26.

34. Statha D, Papantoniou I, Goussetis E, Alexandratou E, Makropoulou M. Investigating the wound healing potential of low-power 661 nm light in pigmented hairless mice. Photochem Photobiol Sci. 2025;24(2):301–10.

35. El-Sadek AN. The value of low-level laser therapy on the healing of donor sites: clinical and experimental observations. Zagazig Univ Med J. [year unknown; under bibliographic verification].

36. Khan H. Anti-inflammatory effects of low-level laser therapy and Streptococcus thermophilus on wound healing in diabetic rats. EC Microbiol. 2020;16:44–52.

37. Dalband M, Azizi Sh, Karimzadeh M, Asnaashari M, Farhadinasab A, Azizi M, et al. The effect of low-level laser therapy and stress on wound healing in rats. J Craniomax Res. 2020;7(4):186–94.

38. Andrade FSS, Clark RMO, Ferreira ML. Effects of low-level laser therapy on wound healing. Rev Col Bras Cir. 2014;41(2):129–33.

39. Munn Z, Peters MDJ, Stern C, Tufanaru C, McArthur A, Aromataris E. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol. 2018;18(1):143.

40. López Pereira P, Díaz-Agero Pérez C, López Fresneña N, Robustillo Rodela A, Pita López MJ, Díaz-Agero Pérez C. Epidemiology of surgical site infection in a neurosurgery department. Br J Neurosurg. 2017;31(1):10–5.