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Review article

Illuminating the evidence: A comprehensive review of light-assisted in-office tooth bleaching

Márcia V.G.B. Queiroz [a], Rafael Dascanio [b], Vinicius H. Hutemma [a], Diogo A. Chiovetto [a], Adriano F. Lima [a], Jorge R. Soto-Montero [c], Matheus Kury [a,*]

[a] Dental Research Division, Graduate Program in Dentistry, Paulista University (UNIP), Rua Dr. Bacelar 1212, Vila Clementino, São Paulo, SP 04026-002, Brazil
[b] Restorative Dentistry Department, Piracicaba School of Dentistry, University of Campinas, Piracicaba, Brazil
[c] Graduate Program in Dentistry, Universidade de Costa Rica, San José, Costa Rica

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ABSTRACT

Objective: To critically synthesize evidence on the role of light sources in-office tooth bleaching, including high-power lasers, LEDs of different wavelength profiles, photocatalytic bleaching strategies, and photobiomodulation (PBM), focusing on their mechanisms, efficacy, and safety.
Study selection: A narrative review was conducted using a structured and comprehensive search strategy across PubMed, Scopus, Web of Science, and selected grey literature. After duplicate removal, title/abstract screening, and full-text evaluation, 242 studies were included (predominantly *in vitro* and randomized clinical trials - RCT). Only in-office bleaching protocols using lasers and LEDs were included, while studies based on at-home systems, halogen, xenon lamps, and plasma devices were excluded.
Conclusions: Evidence indicates that investigated visible-light sources did not consistently enhance bleaching efficacy of high-concentration hydrogen peroxide (HP). Wavelength-screening experiments show that meaningful photochemical enhancement occurs within the near-UV range, which is clinically undesirable. Violet LEDs (combined with low-concentration HP (6–15%) demonstrated improved efficacy and reduced sensitivity. When paired with photocatalysts, such as TiO_2, violet LED can further potentiate gel's efficacy while maintaining biocompatibility. Further RCT are necessary to confirm these findings. PBM (660–810 nm) does not activate peroxide but may modulate pulpal inflammation, although clinical analgesic effects remain inconsistent and protocol-dependent.
Clinical significance: Current evidence does not confirm the clinical necessity of light activation for high-concentration gels. The most promising emerging approach is the violet LED-assisted activation of low-concentration peroxide or photocatalytic systems and PMB for modulating tooth sensitivity.

1. Introduction

The combination of light sources with in-office tooth bleaching has been explored for several decades, as an attempt to accelerate peroxide decomposition and thereby increase the availability of reactive oxygen species (ROS) [1,2]. Theoretically, optical energy may facilitate bleaching through photothermal or photochemical pathways, enhancing chromophore oxidation within dental hard tissues [3,4]. A broad array of light-emitting technologies has been investigated for this purpose, including halogen lamps, plasma arc units, blue light-emitting diodes (LEDs), broad-spectrum lamps, and high-power lasers, each characterized by distinct emission properties and energy delivery characteristics [5–10].

Nonetheless, systematic reviews have consistently indicated that combination of high-concentration hydrogen peroxide (HP) with such light does not yield a clinically meaningful enhancement in bleaching efficacy [11,12]. Current evidence still suggests that certain light activation provides little or no additional benefit [13,14], with some high-intensity devices being associated with increases in pulp chamber temperature, depending on wavelength and exposure parameters, which may become clinically relevant when approaching the critical threshold of approximately 5.5 °C [15–17]. Despite these considerations, research has continued to investigate the use of high-power lasers in bleaching protocols [7,18–21], supported by claimed advances in wavelength

* Corresponding author.
E-mail address: matheus.rodrigues123@docente.unip.br (M. Kury).

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specificity and energy modulation.

However, the current interest is mostly focused on violet-light systems [4,22–24], as these shorter-wavelength systems provide higher photon energy and improved interaction with the physicochemical properties of bleaching gels, including their optical absorption profile, catalytic components, and ionization dynamics. This is particularly relevant when combining low-concentration HP with photocatalytic nanoparticles, *e.g.* titanium dioxide (TiO_2) [25,26]. In contrast, other light sources, such as high-power lasers, are predominantly associated with photothermal effects, in which light energy is converted into heat to supposedly accelerate peroxide decomposition. These emerging violet-light–based approaches, therefore, represent a shift from heat-driven to photochemically driven mechanisms, offering the potential to maintain bleaching efficacy while reducing peroxide concentration and improving patient comfort [27].

Parallel to these developments, increasing attention has been directed toward the application of photobiomodulation with low-level laser therapy as an approach for managing bleaching-related sensitivity [28]. Although the biological mechanisms underlying these responses remain under active investigation, photobiomodulation has been associated with analgesic and anti-inflammatory effects, which may contribute to the modulation of stimuli generated after bleaching procedures [29–31]. Importantly, PBM is not intended to enhance bleaching efficacy, but rather to act as an adjunctive strategy focused on sensitivity management [31].

In view of this scenario, the objective of this narrative review is to critically examine and synthesize contemporary evidence regarding light-based adjuncts in tooth bleaching after 2010. This includes the appraisal of high-power lasers, blue- and violet-light protocols, photocatalytic systems, and the role of photobiomodulation of bleaching-related sensitivity, with emphasis on their mechanisms, clinical performance, and implications for dental tissue responses.

2. Methods

This narrative review was conducted using a comprehensive and structured search, incorporating peer-reviewed studies and selected grey literature. Searches were performed in October 2025 in PubMed, Scopus, and Web of Science using a broad and inclusive strategy aimed at capturing the diversity of evidence in this field. Controlled vocabulary and free-text terms were used when available, without following a predefined systematic protocol. In each database, keyword combinations were applied independently, including "*tooth bleaching* AND *LED*," "*tooth bleaching* AND *laser*," or "*tooth bleaching* AND *light*," as well as their equivalents using *whitening*: "*tooth whitening* AND *LED*," "*tooth whitening* AND *laser*," or "*tooth whitening* AND *light*".

Grey literature was further explored using Google Scholar with the same keyword combinations. Only the most relevant results from the initial 50 search outputs were considered, and documents not previously identified in the primary database search and after 2010 were included when they met the eligibility criteria and were consistent with the scientific literature. Since this is not a systematic review, only one researcher conducted the search and screening of titles, abstracts, and full texts. When uncertainty regarding inclusion arose, a second researcher was consulted. Studies were excluded when full texts could not be obtained despite attempts to contact the authors, or when they consisted of clinical case reports, conference abstracts, letters to the editor, commentaries, narrative reviews, or pilot studies, due to their limited methodological robustness and reduced ability to provide consistent evidence.

Only articles written in English were included. Studies focused solely on resin materials were also excluded, as they did not address bleaching efficacy outcomes. Additionally, investigations involving plasma arc lamps, halogen, or xenon light sources were not included, because these technologies are not representative of contemporary in-office bleaching practice and have been largely replaced by LED- and laser-based systems, differing substantially in emission characteristics and clinical application, and are predominantly reported in earlier-generation studies rather than current clinical protocols. Furthermore, studies evaluating exclusively at-home bleaching protocols were excluded, since this review specifically focused on in-office procedures involving the interaction between light sources and peroxide-based agents.

A qualitative discussion of some studies was performed, focusing on key methodological aspects considered most relevant to the objectives of this review. For pertinent randomized clinical trials (RCTs), adherence to CONSORT-related principles was considered, including clarity of study design, group allocation, and outcome reporting. In addition, certain RCTs and *in vitro* studies were discussed qualitatively in terms of experimental design adequacy, group balance, and the use of contemporary colorimetric outcome measures. No formal risk-of-bias assessment using standardized tools was conducted, in line with the narrative nature of this review.

3. Results

3.1. Search outcomes

The initial search retrieved 7830 records. After automated removal of duplicates using EndNote 20 (Clarivate Analytics, Philadelphia, PA, United States), 2327 studies remained. Title screening excluded non-relevant publications. At this stage, articles published before 2010 were also excluded, yielding 1232 articles for abstract evaluation. Following abstract screening, 441 studies were selected for full-text assessment. After detailed assessment, 239 studies satisfied the eligibility criteria and were included in the final synthesis. Search in grey literature identified additional 3 studies to be included in this narrative review. These events are illustrated in Fig. 1. Additional supporting evidence was also incorporated in order to elucidate mechanistic approaches or future perspectives.

Across the included studies, the main light sources identified comprised diode lasers, Nd:YAG lasers, KTP lasers, erbium lasers, blue LEDs, hybrid LED/low-power laser systems, violet LEDs, and low-level lasers applied for photobiomodulation. Although the physical and optical characteristics of these light sources are discussed in detail throughout the respective sections of this review, a summary of their main properties and clinical applications is presented in Table 1.

3.2. High-power lasers used to activate bleaching gels

- *Diode (740–980 nm)*

Diode lasers display low absorption in water and dental mineral, with their near-infrared (NIR) energy interacting primarily with pigmented components of the bleaching gel and, when these are limited, propagating into enamel and dentin. Diode lasers under different wavelengths have been evaluated in both *in vitro* and *in vivo* studies (Table 2), generally by irradiating the bleaching gel during its application to enamel in varying power density and cycling times, showing no *in vitro* differences between 808 and 815 nm to 980 nm devices on the impact of bleaching [21,32–34]. Only one *in vitro* study evaluated the impact of a 740 nm diode laser, concluding that its use protected enamel surface in a time-manner with gain in brightness of the dental specimens [35].

When it comes to 810–815 nm, *in vitro* protocols frequently employed 40% HP gels, most often red-colored formulations activated using 2 W continuous-wave GaAlAs diode lasers positioned close to the surface [36,37]. Across these experiments, laser activation produced either no improvement or only modest increases in immediate color change values (ΔE_{ab}), and any early advantage disappeared after storage. Enamel microhardness loss and surface roughness remained *in vitro* equivalent to peroxide alone, indicating that 810 nm irradiation neither exacerbated nor prevented peroxide-induced changes [37–41]. When

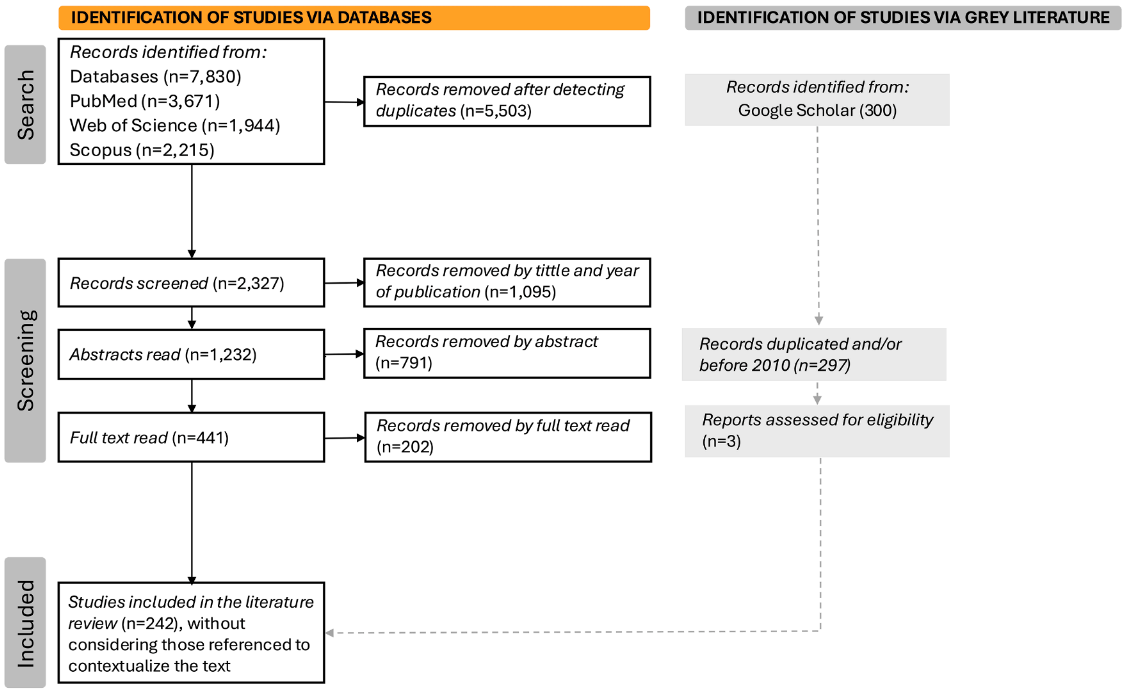

Fig. 1. Flow chart of the search strategy performed in the review.

different gels were tested, including red and blue formulations, some *in vitro* studies reported slightly higher color change (ΔE_{ab}) under laser activation [41,42]. Clinically, there was one non-randomized *in vivo* study using 810 nm lasers [43]. Although these investigations suggested that laser activation may enhance whitening, the dosimetry report is incomplete, preventing meaningful conclusions.

Diode lasers operating at 940 nm have been assessed generally following manufacturer-driven protocols. *In vitro* experiments typically used high-concentration HP gels - red, blue, or violet in the studies that specified gel color - activated up to 7 W in continuous-wave mode, usually for 30-s cycles repeated according to manufacturer recommendations, and with total gel-to-tooth contact times shorter than those of conventional chemical bleaching [41,44,45]. Across these models, laser activation did not increase bleaching efficacy and did not amplify or mitigate the morphological or mineral changes induced by HP. When milder alterations were observed *in vitro* on the surface, these were attributed primarily to the bleaching chemistry itself [44,46]. Clinical investigations using high-concentration HP gels photoactivated at 7 W for up to 30 s likewise reported immediate shade improvement [10,47]. On the other hand, a randomized study, using updated and digital colorimetric, revealed that 940 nm diode lasers were not able of increasing tooth color change (ΔE_{ab} and ΔE_{00}) [20].

Most *in vitro* studies employing 980 nm irradiation during bleaching reported no significant enhancement in tooth color change when compared with peroxide-only protocols, irrespective of power settings or irradiation time, and similarly failed to demonstrate protective effects on enamel microhardness or surface morphology [21,32–34,48,49]. In agreement with these findings, a randomized clinical trial with a three-month follow-up reported that light-activated bleaching units did not provide superior whitening efficacy or improved color stability compared with conventional chemical bleaching, reinforcing the limited clinical relevance of adjunctive light activation under controlled conditions [50]. Collectively, the available data indicate that diode lasers offered no consistent enhancement in bleaching efficacy and did not demonstrate stable protective or detrimental effects on enamel.

- *Neodymium (Nd, 1064 nm) and KTP (532 nm)*

Neodymium:YAG lasers (1064 nm), which exhibit low absorption in water and hydroxyapatite and, therefore, deliver energy deeply into dental tissues, have not demonstrated meaningful benefits in tooth bleaching. An *in vitro* study applying Nd:YAG irradiation when bleaching with a 35% HP gel (using two 60-s exposures at 1 W and 15 Hz) found no improvement in ΔE_{ab} compared with peroxide alone [51]. Similarly, a non-randomized clinical split-mouth study evaluated Nd:YAG activation applied after placement of a red-colored 35% HP gel, delivering 30 s of irradiation per tooth. Although all teeth exhibited whitening after two sessions, no additional color change could be attributed to the laser, whereas postoperative sensitivity increased [9]. Even though one study has shown that Nd:YAG activation did not make enamel surface more susceptible to caries development [52], the evidence indicates that Nd:YAG irradiation does not alter bleaching efficacy, limiting its clinical value as an adjunct to in-office peroxide bleaching.

In this context, KTP lasers (532 nm) are generated by passing the Nd:YAG beam (1064 nm) through a potassium titanyl phosphate crystal, which halves the wavelength while preserving many of the parent laser's optical characteristics. As a result, KTP radiation exhibits low absorption in water and dental mineral, as well as medium penetration in hard tissues, and high absorption in red color present in commercial HP gels [53]. One *in vitro* study reported that KTP activation produced the highest immediate ΔE_{00} among all tested light sources, outperforming Nd:YAG irradiation [54]. Another investigation showed that the relative performance of KTP depended on the type of staining, suggesting a chromophore-wavelength interaction influencing bleaching responsiveness [55]. Gao et al. demonstrated that KTP activation, particularly when combined with the red gel, yielded the greatest immediate color change. However, this advantage reduced markedly after 15 days despite remaining superior to Nd:YAG at early time points [53]. Therefore, evidence is not sufficient to support the activation of HP with both laser types, whose protocols used in the studies are depicted in Table 3.

- *Erbium (Er, 2400 - 2780 nm)*

Erbium lasers used for dental applications [Er:YAG (2940 nm) and

Table 1
Optical and physicochemical characteristics of light sources in dental bleaching and their interaction with dental tissues.

Light source	Definition	Typical wavelength range	Typical output power	Predominant physical mechanisms	Interaction with dental tissues	Main Effects Reported on Bleaching
High-power lasers	Coherent, monochromatic, and collimated light sources delivering high irradiance and energy density	~445–2940 nm (Diode: ~445–980 nm KTP: 532 nm Nd:YAG: 1064 nm Er,Cr:YSGG: 2780 nm Er:YAG: 2940 nm)	~1.0–10 W or higher (depending on emission mode)	Predominantly photothermal, but it may also induce photoablation effects depending on wavelength, pulse duration, and fluence	Strongly wavelength-dependent interaction. Diode and neodymium exhibit deeper penetration, while erbium wavelengths are highly absorbed by water and hydroxyapatite, resulting in superficial interaction and potential ablation	Photothermal interaction with bleaching gel occur, possibly enhancing ROS formation. Most tests occurred with high-concentration HP, and esthetic outcomes were not improved
Low-level lasers	Coherent, monochromatic, and collimated light sources used at low power densities to induce biological modulation	~630–980 nm	~10–500 mW	Photophysical and photochemical cellular signaling (photobiomodulation), with dose-dependent stimulatory or inhibitory effects	Deeper penetration with minimal temperature rise (infrared mode). The interaction occurs mainly through absorption by cells, with no structural alteration of enamel or dentin	Photobiomodulation is expected in pulp tissue, decreasing tooth sensitivity. Therefore, no effect on esthetic outcome is expected
Light-emitting diodes (LEDs)	Non-coherent, non-collimated light sources emitting narrow spectral bands in the visible region	Violet: 400–415 nm Blue: 450–480 nm	~500–2000 mW (device-dependent)	Primarily photophysical, with possible photochemical interactions depending on absorbers. There is limited photothermal contribution	More superficial interaction compared to lasers, with limited penetration into enamel and dentin. The effects are largely dependent on absorption by pigments, bleaching gels, or photocatalytic components	Current evidence indicates that violet LEDs potentiate the bleaching efficacy of low-concentration bleaching gels. The photochemical interaction with catalytic incorporated into gels further enhances this effect

Er,Cr:YSGG (2780 nm) – Table 4] are mid-infrared solid-state systems characterized by high absorption in water and hydroxyapatite, with low penetration into hard tissues. Regarding bleaching efficacy, one *in vitro* study evaluated Er,Cr:YSGG activation (0.72 J/s total, irradiation time: 30 s, 21.6 J per tooth) of a commercial 35% HP gel containing a violet dye. In this study, ΔE_{ab} was similar to the non-activated protocol, even 1 month after bleaching [56]. Across the available literature, erbium activation does not appear to exacerbate the structural alterations already expected from high-concentration HP. However, Er,Cr:YSGG-assisted bleaching produced *in vitro* reductions in enamel microhardness comparable to those of conventional in-office bleaching [57,58]. SEM analyses consistently revealed *in vitro* morphological changes, such as increased porosity, after high-concentration bleaching, but Er:YAG or Er,Cr:YSGG did not intensify these effects relative to protocols performed without laser activation [57–59].

A prospective non-randomized clinical study also evaluated an Er,Cr:YSGG-assisted in-office bleaching protocol using a red-colored 35% HP gel, with laser irradiation applied for a total of 30 s, delivering 21.6 J at a rate of 0.72 J/s. Although this protocol produced perceptible improvements in tooth color and whiteness indexes without detrimental effects on tooth sensitivity, the effect was not consistently observed across all teeth [18]. Another clinical study using Er,Cr:YSGG (2780 nm) for in-office bleaching - applying 1.25 W, 10 Hz, 700 μs pulses with a specialized 2.5-cm-distant bleaching tip - showed that this protocol achieved similar whitening to 35% HP only and diode-activated techniques over 12 months, while uniquely avoiding postoperative sensitivity, reinforcing the notion that erbium lasers remain superficial energy absorbers that do not transmit heat deeply into dental tissues [60]. Hence, there is no agreement if Erbium enhances efficacy of highly concentrated agents and sufficient evidence to encourage its use during in-office tooth bleaching.

- *Impact of high-power lasers on Intrapulpal Temperature*

- Diode, Nd:YAG, and KTP lasers

One of the main concerns of using NIR and mid-infrared wavelengths is their impact on temperature. Diode lasers produced power-dependent increases in intrapulpal temperature during bleaching [16,61]. In an 808 nm model, irradiation at 1.0–3.3 W (10.9–36.7 W/cm^2) in 30 and 60 s resulted in proportional ΔT rises, with 16.1 W/cm^2 identified as the highest setting within safety limits (ΔT $<$ 5.5 °C) for pulp tissue [62]. Likewise, 810 nm (1.5 W, 30 s) generated temperature elevations still below critical thresholds [63]. On the other hand, a 980 nm laser (6 W, 30 s) has surpassed the critical ΔT thresholds [64]. The same was found under 3 W and 1.5 W for 20 s [65]. Similarly, 980 nm diode (4 W, continuous mode) and Nd:YAG (4 W, 60 Hz), for 20 s also increased temperature above 5.5 °C. However, the combination of a reddish gel with either Nd:YAG or KTP lasers (800 mW, 5-mm spot size, 4.2 W/mm^2, 180 s) increased temperature below the threshold [53].

A recent study evaluating different diode lasers and power density showed that the only bleaching protocols below the 5.5 °C limit were at 445 nm (0.3 W), 940 nm (1.5 W), and at 970 nm (0.5 W) [66]. In this regard, the use of blue diode laser (445 nm) has been recently indicated for tooth bleaching, without gain to bleaching efficacy [67–70]. Papadopoulou et al. (2023) pointed out that blue diode laser at 0.5, 1, 1.5 W (10 to 60 s) did not increase temperature in pulp chamber above the ΔT thresholds, while increased the surface temperature of bleaching gel [71]. However, further studies are necessary to attest its gain on bleaching efficacy.

- Influence of tip geometry and spot size on diode and erbium laser performance

An Er,Cr:YSGG (2780 nm) at 1.25 W with a pulse duration of 700 μs (below 0.5 J/cm^2 to avoid ablation) activated through 6-mm wide

Table 2
Bleaching protocols using diode light extracted from the studies included in this review.

Authors (Year)	Type of Study	Light Source	Wave-length (nm)	Time of Laser Activation	Parameters Informed by the Authors	Bleaching Gel %	Gel's coloration	Gel's Time	Number of Sessions
Son et al. (2012) [35]	*In vitro*	Diodent II, HOYA	740	0, 30, 60, 120, or 180 s	Power: 300 mW	35% HP	n.i.	30 min	1
Kiomars et al. (2016) [21]	*In vitro*	Gigaa dhang, China	810–815	4 × 30 min at 1-min intervals	Power: 1.5 W in continuous wave (cw)	30% or 46% HP	Transparent	≈ 8.5 min	1
Azarbayjani et al. (2018) [33] Saeedi et al. (2019) [34]	*In vitro*	Cheese TM Wuh Giga Opt Tech Co Ltd. China	810–815	3 × 30 s	Power: 1.5 W; Energy: 45 J/30 s = 135 J per tooth; 2-mm distant	40% HP [33] HP 35% [34]	Red [33] or Ultramarine Violet [34]	≈ 10 min	1
Ahrari et al. (2015) [36] Ghanbarzadeh al. (2015) [38]	*In vitro*	ARC Lase GmbH, Nuremberg, Germany	810–815	4 × 15 s	Power: 2 W in continuous wave (cw)	HP 40% [36] 15% CP or 40% HP [38]	Red	≈ 10 min	3 among home bleaching
Fekrazad et al. (2017) [37]	*In vitro*	n.i.	810–815	Intervals of 7 e 4 min	n.i.	HP 35%	Red	n.i.	1
Anaraki et al. (2015) [39]	*In vitro*	Denlase, China	810–815	3 × 15 s	Power: 1.5 W; Energy: 22.5 J	n.i.	Red	n.i.	1
Yusof et al. (2020) [40] Quran et al. (2011) [43]	*In vitro* [40] *In vivo* [43]	LaserSmile, Biolase, *CA*, USA	810–815	8 × 10 s [40] or n.i. [43]	n.i.	35%HP	Ultramarine Violet [40]	n.i.	1 [40] 1 or 2 [43]
Goenka et al. (2021) [41]	*In vitro*	n.i.	810–815	3 × 20 s at 20-s intervals	Power: 2.5 W	35%, 37.5%, or 40% HP	Red or Blue	n.i.	1
Sayooet al. (2024) [42]	*In vitro*	Photon Zolar Technology Canada	810–815 and 940	2 × 30 s	Power: 2 W	35% or 40% HP	Red	15 min	1
Ardekani et al. (2018) [10]	*In vivo*	InGaAsP Ezlase, Biolase, USA	940 nm	30 s per quadrant	Power: 7 W; 210 J per tooth, scan mode and 1 mm distant; 400 µm uninitiated fiber optic tip	38% HP	Red	10 min per quadrant	1
Tekce et al. (2022) [20] Saeedi et al. (2019) [34] Maiya et al. (2024) [44] Radwan et al. (2021) [45] Suresh et al. (2020) [46] Al-Maliky (2019) [47]	*In vivo (RCT)* [20] *In vivo* [47] *In vitro* [34, 44–46]	Epic10 BIOLASE, USA	940 nm	12 min [20] 3 x of 30 s [34,44] 2 x of 30 s [45,47] 3 min [46]	Power: 7 W [20,45, 46] Power: 7 W; ED = 210 J [44,47]	35% HP [20,34,44] 38% HP [45, 47] 45% HP [46]	Ultramarine Violet	16 min [20] ≈10 min [34] 17 or 24 min [44] 30 min [45] 24 min [46] 20 min [47]	1
Goenka et al. (2021) [41]	*In vitro*	n.i.	940 nm	3 × 20 s at 20-s intervals	Power: 2.5 W	35%, 37.5%, or 40% HP	Red or Blue	n.i.	1
Kiomars et al. (2016) [21] Saluja et al. (2022) [32] Azarbayjani et al. (2018) [33] Saeedi et al. (2019) [34] Valizadeh et al. (2022) [48] Sadeghi et al. (2024) [49]	*In vitro*	Wiser/Doctor Smile, Italia	980 nm	3 x of 30 s [21,33,34, 48,49] and 2.5 to 5 min [32]	Power: 1.5 W in continuous wave (cw) [21,34] Power: 1.5 W; Energy: 45 J/30 s = 135 J per tooth; 2-mm distant [33 Power: 2 W [49] Power: n.i. [48] Power: 5 W [32]	30% or 46% HP [21] 15%, 20%, or 30% CP [32] 35% HP [34, 48] 40% HP [33, 49]	Transparent [21] Red [33,48, 49] Ultramarine Violet [34] n.i. [32]	≈ 8.5 min [21,48]; ≈10 min [32–34, 49]	1 [21,33, 34,48,49] 2 [32]
Polydorou et al. (2013) [50]	*In vivo (RCT)*	GENTLErayKaVO GmbH, Biberach, Germany	980 nm	4 x of 30 s	Power: 6 W	38% HP	n.i.	60 min	1

acrylic tip was shown to be safe for pulp [72]. These findings highlight that the thermal behavior of laser-assisted bleaching is strongly influenced not only by wavelength and power, but also by the geometry of bleaching handpieces and their resulting spot size, which substantially modifies fluence and heat distribution. Er:YAG at 2940 nm (0.4 W, 10 Hz, 40 mJ, 1000 µs) through a 3-mm bleaching tip (0.29 cm^2) for 20 s produced the highest ΔT within the gel, yet maintained a very small intrapulpal increase, remaining far below the critical 5.5 °C threshold [73]. In the same study, the 810 nm diode (4 W, continuous mode, 5.85 cm^2 bleaching tip, 20 s) showed the opposite pattern, with a lower gel temperature but higher pulpal rise, reflecting deeper penetration of NIR energy through the gel and into the tooth. Importantly, in both systems, the use of bleaching-specific handpieces with enlarged spot sizes markedly reduced fluence and played a central role in keeping ΔT

Table 3
Bleaching protocols and parameters for both Nd:YAG and KTP devices used in the studies.

Authors (Year)	Type of Study	Light Source	Wave-length (nm)	Time of Laser Activation	Parameters Informed by the Authors	Bleach-ing Gel %	Gel's Coloration	Gel's Time	Number of Sessions
Borse et al. (2022) [51]	*In vitro*	*Nd:YAG* - AT S LightWalker®; Fotona, Slovenia	n.i.	2 × 1 min without interruption before treatment	Power = 1 W, Frequency = 15 Hz; 1-cm distant from the samples	35% HP	Blue	16 min	1
Strobl et al. (2010) [9]	*In vivo*	*Nd:YAG* - Fidelis Plus II, Fotona d.d., Slovenia	1064 nm	3 × 10 s on each tooth and without interruption	Energy = 1,4 J/cm2; Power = 4 W; Frequency = 10 Hz; Beam diameter= 6 mm; Pulse duration= 320 μs	35% HP	Red	1 min 45 s	2
Ashnagar et al. (2017) [52]	*In vitro*	*Nd:YAG* -FIDELISTM, Fotona, Slovenia	1064 nm (pulsed mode)	3 × 30 s at 1-min intervals	Power = 2,5 W; Fiber tip = 320 μm; Irradiation distance = 6 mm	40% HP	Red	20 min	1
Gao et al. (2020) [53]	*In vitro*	*Nd:YAG* - n.i.	1064 nm	20 s	Power: 800 mW; Power density: 4,2 W/cm2; Energy density: 84 J/cm^2.	35% or 38% HP	Red	15 min	n.i.
Shahabi et al. (2018) [54]	*In vitro*	*Nd:YAG* -QSwitched Fotona, Slovenia	1064 nm	4 × 30 s at 1-min intervals	Frequency= 20 Hz; Pulse width = 20 ns, Energy = 100 mJ; Beam diameter = 3 mm; Pulse power = 50 mW.	40% HP	Red	n.i.	n.i
Gao et al. (2020) [53]	*In vitro*	*KTP* – n.i.	532 nm	20 s	Power: 800 mW; Power density 84 J/cm2.	35% or 38% HP	Red	15 min	1
Shahabi et al. (2018) [54]	*In vitro*	*KTP* - Starline Lambda Physik, Germany	532 nm	4 × 30 s at 1-min intervals	Energy:4 mJ; pulse width:20 ns; power: 4/20 (0,2 × 10^6) W; repetition rate: 10 Hz; Beam diameter = 1.5 mm.	HP 40%	Red	60 min (3 cycles of 20 s each)	1
Lagori et al. (2014) [55]	*In vitro*	*KTP* - LaseMar 500 Eufoton, Italy	532 nm	3 × 30 s at 1-min intervals	Power: 1.5 W	HP 30%	NI	30 min	1

Table 4
Protocols of the studies using high-power Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm) lasers.

Authors (Year)	Type of Study	Light Source	Wave-length (nm)	Time of Laser Activation	Parameters Informed by the Authors	Bleach-ing Gel %	Gel's Coloration	Gel's Time	Number of Sessions
Tsaltampasi et al. (2025) [18] Dionysopoulos et al. (2017) [56] Dionysopoulos et al. (2017) [57] Dionysopoulos et al. (2015) [59] Surmelioglu et al. (2020) [60] Strakas et al. (2017) [72]	*In vitro* [56,57, 59,72] *In vivo* [18] *In vivo (RCT)* [60]	Waterlase MD Turbo, BIOLASE, Irvine, *CA*, USA	2780 nm	2 × 15 s [56,59,60] 60 s [72]	Energy = 21.6 J with a rate of 0,72 J/s; Power = 1.25 W; Frequency = 10 Hz; Pulse = 700μs (S-mode); 2.5 cm distant from the samples [18, 56] Power = 0.4 W; Frequency = 10 Hz (VLP mode); Spot size = 5 mm; Pulse = 1000μs; 2 cm distant from the samples [58] Power = 1.25 W; Frequency = 10 Hz; Pulse = 700μs (S-mode); 2.5 cm distant from the samples [60,72]	35% HP [56,59, 60,72] 38% HP [72] 40% HP [18,58]	Ultramarine Violet [56,59] Red [18] Yellow [58,72] Purple [60,72]	2 × 15 to 20 min [56,58] 3 × 15 min [59] 2 × 20 min [18] 20 min [60]	1 [18,56,58, 59] 2 [60]
Hou et al. (2021) [58] Sari et al. (2015) [73]	*In vitro*	LightWalker, Fotona, Slovenia	2940 nm	20 s	Power = 0.4 W; Frequency = 10 Hz (VLP mode); Spot size = 5 mm; Pulse = 1000μs; 2 cm distant from the samples [578 Energy = 40mJ; Pulse = 1.000 μs; Power = 0,4 W; Frequency = 10 Hz; 5 mm distant from the samples [73]	35% HP [73] 40% HP [58]	Red	8 min [58]	1 [58]

within safe limits [73]. Overall, tip geometry and spot size were key determinants of energy distribution, whereas gel-related factors, including color and composition, influenced light absorption and heat generation, thereby affecting the thermal behavior during bleaching procedures.

3.3. LEDs used to activate bleaching gels

- *Blue LEDs (440–480 nm)*

Even though often grouped with lasers in commercial bleaching systems, LEDs operate on fundamentally different physical principles. LEDs emit non-coherent, non-collimated, poly-chromatic light over a relatively broad spectral band, while lasers deliver coherent, monochromatic, and highly collimated radiation with precisely defined optical penetration and tissue-interaction behaviors. As a result, blue LEDs have markedly lower power (≅ 1500 mW), lower irradiance, minimal tissue penetration, and limited capacity for targeted photothermal effects compared with laser sources [74].

In vitro, three studies demonstrated mixed outcomes: low-irradiance blue LEDs (45–55 mW/cm^2) specifically for tooth bleaching, or high-irradiance (≈1,200 mW/cm^2) indicated for light curing, improved color change (ΔE_{ab}) when used with gels lacking photocatalysts [7,75], not increasing surface mineral changes [76], and failed to enhance whiteness index when applied to violet- or blue-colored 35% HP gels [77]. Clinically, one trial compared 40% and 35% HP protocols with or without blue LED activation and reported greater shade improvement with LED [78]. Other clinical reports found only modest color changes and noted slight increases in sensitivity and gingival irritation [79,80]. The heterogenous light-assisted bleaching protocol with blue LEDs are depicted in Table 5. Moreover, it is important to emphasize that blue LED curing lights typically operate at higher irradiance levels than light sources specifically developed for tooth bleaching. In addition to their unfavorable design for standardized light delivery across multiple teeth, prolonged use of these devices may lead to an increase in intrapulp temperature [81]. Up to this moment, there is not enough evidence to support use of blue light-systems on activation of bleaching gels.

- *Blue LED/Laser (440–480 nm; 808–830 nm)*

In addition to blue LED-only systems, a substantial proportion of bleaching devices evaluated in the literature are hybrid platforms, which were specifically produced for tooth bleaching purposes, that combine blue LED illumination of the entire upper and/or lower arches with 3 to 6 beam lights of low-level infrared diode laser (≅ 300 mW), often without clear specification of whether both wavelengths were simultaneously activated during treatment. *In vitro* investigations showed that repeated 1-min activation cycles using a commercial LED/ laser unit did not increase whitening effect compared with HP alone [82] and that mineral alterations were dependent on the gel formulation, with LED/laser activation increasing calcium loss after application of certain commercial peroxide gels [83]. An *in situ* study reported no improvement in bleaching efficacy and no additional microhardness loss when 15% or 35% hydrogen peroxide gels were photoactivated [84].

Some clinical studies have evaluated hybrid blue LED/infrared laser devices in combination with high-concentration HP (35–38%). As shown in Table 6, light activation generally followed manufacturer-standardized cycles composed of multiple applications of a few minutes each, separated by defined intervals, yielding a total irradiation time consistent with the manufacturers' recommendations. Even though few clinical trials suggested reduced treatment time and lower sensitivity with hybrid activation [85,86], examiner-blinded randomized clinical trials (RCT) demonstrated that hybrid activation did not enhance bleaching efficacy of 35% HP and that the laser component failed to reduce bleaching-related sensitivity or even increased its levels [87–91], maintaining the enamel temperature lower than the critical ΔT threshold [92]. In addition, a triple-blind, long-term clinical trial [93] confirmed that hybrid activation provided no additional bleaching immediately or after 36 months, though it allowed a reduced gel contact time and yielded lower immediate postoperative sensitivity.

- *Violet LEDs (400–410 nm)*

Violet LEDs (≈405 nm, ≅ 1200 mW) differ from conventional blue LEDs (440–480 nm) not only in wavelength but also in photon energy, which is higher and, therefore, may facilitate more efficient interactions with intrinsic dental chromogens and commonly encountered staining compounds. Because of this higher-energy profile, violet LEDs (Table 7) have been proposed both as standalone bleaching sources and as activators for low-concentration peroxide gels. Manufacturers also recommend their use in combination with low-dose HP or high-concentration carbamide peroxide (CP), although experimental and clinical studies have additionally examined their association with high-concentration gels (35–38% HP) [94].

- Use of violet LED alone (without gels' combination)

The use of violet LED alone has been extensively investigated *in vitro*, consistently demonstrating its capacity to degrade pigments through direct photolysis after repeated exposure, particularly in teeth stained with coffee, tea, red wine, or tobacco smoke [95–99]. Despite producing perceivable whitening, these effects were markedly inferior to those achieved with high-concentration HP gels [99–105], likely due to its low penetrability [95]. Randomized clinical trials confirmed these findings: violet LED used alone produced modest ΔE_{ab}, ΔE_{00}, and/or ΔWI_D values that remained significantly below those of peroxide-based protocols, with limited clinical relevance and differences in satisfaction of patients [24,106–110]. On top of that, one major drawback of this approach is the extended number of sessions (up to 10), discouraging clinicians to offer such a treatment for their patients. Also, the irradiation cycling is extensive, with twenty 1-min light activation cycles with consecutive 30-s intervals, which exhibited a gradual decrease in the LED irradiance over time in an *in vitro* study [95].

Table 5
Use of blue LED and their parameters during light-assisted tooth bleaching.

Authors (Year)	Type of Study	Light Source	Wave-length (nm)	Time of LED Activation	Parameters Informed by the Authors	Bleach-ing Gel %	Gel's Coloration	Gel's Time	Number of Sessions
Oommen et al. (2024) [7]	*In vitro*	Woodpecker ILED Plus Curing Light, Mumbai, India	385 to 515 nm	3 × 20 s	Power density: 1250 mW/cm²	35% HP	Green	8 min	3
Qi et al. (2021) [75]	*In vitro*	WE light Class II, White Essence, Tokyo, Japan	460 nm	10 min	High intensity: 55 mW/cm²; Low intensity: 45 mW/cm²	35% HP	Transparent	6 × 10 min	1
Silva et al. (2014) [76] Alvarez et al. (2021) [77]	*In vitro*	LED RADII SDI, Bayswater, VI, Australia	440–480 nm	2 × 20 s 2- min intervals [76] 8 min [77]	Power density: 1400 mW/cm² [76] Power density: 1200 mW/cm² [77]	35% HP	Red-to-green [76] Blue or Purple [77]	3 × 15 min [76] 3 × 8 min or 1 × 40 min [77]	3 [76] 1 to 3 [77]
Savaliya et al. (2014) [78]	*In vivo*	n.i.	n.i.	n.i.	n.i.	35% or 40% HP	Red-to-green or red	n.i.	n.i.
Hayward et al. (2012) [79]	*In vivo*	BriteWhite® Inc, Jasper, Alabama, USA	450–500 nm	3 × 10-min	n.i.	35% or 44% CP	n.i.	3 × 10 min	Three in-office followed by home
Lo Giudice et al. (2012) [80]	*In vivo*	WS25-Kroma Ogna™, Valais, Switzerland	495 nm	n.i.	Output power: 60 W; Light intensity: 30,000 mW	35% HP	Red	3 × 1 min	3

Table 6
Protocols information regarding the use of hybrid blue LED/laser platforms for in-office tooth bleaching.

Authors (year)	Type of Study	Light Source	Wavele-ngth	Time of Source Activation	Parameters Informed by the Authors	Bleaching Gel %	Gel's coloration	Gel's Time	Number of Sessions
Mahounak et al. (2024) [49]	*In vitro*	Blue-LED: Whiten MAX, Taiwan; Laser: Wiser, Doctor Smile, Italy	LED: 420–490 nm; Laser: 980nm	LED: 20 min Laser: 30 s at 2-min intervals	LED power density: 3 W/cm^2; Laser power density: 2 W/cm^2	40% HP	n.i	2 × 2 min	2
Roberto et al. (2011) [82] Loiola et al. (2016) [84] Mena-Serrano et al. (2016) [89] Kossatz et al. (2011) [90]	*In vitro* [82] *In situ* [84] *In vivo (RCT)* [89,90]	Whitening Lase Light Plus, DMC Equip. Ltda, São Carlos, SP, Brazil	LED: 470 nm; Laser: 830nm	Three 60-s cycles at 2-min intervals [82] 15% HP: 5 × 90-s at 90-s intervals; 35% HP: 3 × 60 s at 60-s intervals [84] 9 × 1 min [89,90]	Laser power: 0.2 W [82] Laser power: 0.6 W [84] Light intensity: 200 mW/cm^2 [89,90]	15%-20% HP [84,90] 35% HP [84,85,89,90]	Red-to-green [82] Orange [84] Red-to green [89,90]	2 × 10–15 min [84] 1 × 40 min [82] 3 × 15 min [89,90]	1 [82] 2 [84,89,90]
Berger et al. (2010) [83]	*In vitro*	Ultrablue Laser System, DMC Equip. Ltda	LED:470 nm; Laser: 810–830nm	3 × 2 min	Laser power: 0,2 W; Energy density: n.i.	35% HP	Green, blue or red	3 × 10 min	1
Bortolatto et al. (2013) [85] Farhat et al. (2014) [87] Mondelli et al. (2012) [88] Moncada et al. (2013) [91] de Freitas et al. (2017) [92] Mondelli et al. (2017) [93]	*In vivo (RCT)*	Whitening Lase II, DMC, Equip. Ltda	LED: 425–480 nm; Laser: 810 nm	4 × 1 min [85] 9 × 1 min [88] 9 × 3 min [88] 5 min per arch (1-min cycle at 30-s intervals) [90] 3 × 1 min (total 3 min per gel application) [92] 3 × 2 min (6 min total per gel application) [93]	LED power: 1.8 W (total); Laser power: 0.6 W (total); Energy density: 300 mW/cm^2 LED power: 300 mW (6 chips); Laser power: 200 mW (3 beans); Irradiance: ~300 mW/cm^2 per tooth	35% HP [85,88,93,94] 38% HP [88] 15% HP [90]	Orange [87,88,91–93] Red [88]	3 × 15 min [85] 3 × 10 min [88] 3 × 1 min [89] 30 to 45 min [91] 3 × 8 min [92] 3 × 2 min at 7.5-min intervals [93]	1 [88,91–93] 2 [87]
Sabbagh et al. (2015) [86]	*In vivo (RCT)*	MeToo Deluxe, Acteon, Pierre Rolland, Lebanon	LED: 450–480 nm; Laser: 835–865 nm	3 × 15 min	LED optical power: 5 W; IR optical power: 1.5W	30% HP	Orange	3 × 15 min	1 followed by home

- *Use of violet LED combined with high concentration HP gels*

Studies have also evaluated violet LED sources combined with high-concentration HP, using predominantly a commercial two-bottle gel whose color is carmine immediately after its mixing that turns into transparent in approximately 5 min. Findings have been heterogeneous, with some *in vitro* studies reporting short-term improvements and others showing no meaningful enhancement in whitening compared with 35% HP alone [111–113]. Importantly, violet LED did not reduce the prevalence or intensity of tooth sensitivity associated with conventional in-office bleaching in RCTs [106,114,115]. Nevertheless, *in vitro* investigations and RCTs demonstrated a practical benefit: the combination allowed a substantial reduction in chairside time, with traditional 45-min peroxide protocols shortened to approximately 15 min, without the need for gel replenishment [116–119]. This has positioned violet LED primarily as a workflow-optimizing adjunct rather than an efficacy-enhancing technology when paired with high-concentration peroxide.

- *Use of violet LED combined with low-concentration HP gels or high-concentration CP*

The most compelling evidence emerges from protocols combining violet LED with lower concentration peroxide formulations than 35–40% HP, such as 6% or 15% HP or 37% CP. Across multiple *in vitro, in situ,* and randomized clinical studies, this combination consistently produced significant improvements in bleaching efficacy, approaching the outcomes achieved with high-concentration HP [97,106,107,120–124]. Notably, *in vitro* studies also showed that violet LED, regardless of HP combination, did not produce detrimental changes to enamel surface morphology and mineral content [8,125–128], and was not associated with increased pulpal cytotoxicity; in some instances, it may even reduce cytotoxic effects [117,129] by enabling the use of lower peroxide concentrations. Some laboratory studies reported temperature increases exceeding critical thresholds with violet LED [130–132]. However, no clinical trial has documented persistent or clinically relevant sensitivity when violet LED is combined with low-concentration peroxide protocols, or even when is used isolated. In fact, these protocols have consistently shown lower sensitivity incidence and intensity compared with traditional in-office bleaching using ≥35% hydrogen peroxide (HP), according to a systematic review [22].

- *Evidence regarding ZOOM system*

As shown in Table 8, it is important to note that the ZOOM system is in some studies described as an LED-based device, although other studies have stated as a mercury metal-halide lamp emitting a broad spectrum centered around 350–400 nm, within the near-UV/violet range [15,133,134]. This distinction is clinically relevant: metal-halide sources can generate more heat than blue or violet LEDs and exhibit different optical behavior, including deeper penetration of high-energy photons [135]. Consistently, *in vitro* and *in vivo* studies using ZOOM typically in combination with 25% hydrogen peroxide gels have shown no meaningful enhancement in bleaching efficacy compared with chemically activated protocols [136–139]. Moreover, due to its near-UV output described in the literature, ZOOM has been associated with higher *in vitro* surface temperature rises than both 405-nm LEDs and defocused lasers [15], underscoring the need for

Table 7
Information on the use of violet LED source combined or not with in-office bleaching gels.

Authors (year)	*Type of Study*	Light Source	Wave-length	Time of LED Activation	Parameters Informed by the Authors	Bleaching Gel %	Gel's coloration	Gel's Time	Number of Sessions
Kury et al. (2022) [95] Kobayashi et al. (2021) [96] Kury et al. (2020) [97] Clemente et al. (2022) [98] Fernandes et al. (2021) [99] Gallinari et al. (2019) [100] Nogueira et al. (2021) [101] Palandi et al. (2023) [102] Marques et al. (2023) [103] Silva et al. (2023) [104] Kury et al. (2020) [106] Kury et al. (2022) [107] Mayer-Santos et al. (2022) [108] Santos et al. (2021) [109] Sobral et al. (2021) [110] Vardasca et al. (2024) [111] Oliveira et al. (2021) [112] Silva Daltro et al. (2020) [113] Zanin et al. (2025) [114] Ferreira et al. (2023) [115] Bachiega-Silva et al. (2023) [116] Ribeiro et al. (2022) [117] Oliveira et al. (2021) [120] Menezes et al. (2022) [121] Brugnera et al. (2020) [122] Gallinari et al. (2020) [123] Eugenio et al. (2020) [125] Leite et al. (2023) [126] Kury et al. (2020) [127] Pin et al. (2022) [128] Silva et al. (2022) [129] Najar et al. (2023) [130] Guanaes et al. (2022) [131] Resende et al. (2025) [132]	*In vitro* [95–104,111–113,116,117,120,121,124–128,130–132] *In vivo (RCT)* [106–110,114,115,122,123] *In vivo* [129]	Bright Max Whitening, MMOptics, São Carlos, Brazil	405 nm ± 10 nm	20 × 1 min at 30-s intervals [95–97,99–104,106–111,113,114,116,120,122,125–127,131,132] 3 × 20 min at 10-min intervals [98] 10 × 1 min [112] 3 × 3 min [115] 15, 30, or 45 min [117] 15 × 1 min at 60-s intervals [121] 30 min [123] 20 min [129] 10, 20, and 30 min or 20 × 1 min at 30-s intervals [132]	Power: 1202 mW (total) and 350 mW (per chip); Power density: 910 mW/cm^2 (total)	Only light [95–98,104,106–110,114,115,120,123,125,127,132] 10–22% CP [99,102,113,126] 37% CP [95,96,103,106,107,109,127,130,132] 45% CP [102] 6–10% HP [99,111,119,121,125] 17.5% HP [100,129] 35–40% HP [96,97,100,101,106–117,127,128,130–132]	Transparent [96,97,99,103,104,106,107,109,111,121,125,127,130,132] Red to green [100,111,131] Purple [110] Orange [115]	1 × 30 min [96,97,102,106–109,121,122,126–130,132] 1 × 40–45 min [110,112,116,131] 1 × 50 min [111] 1 × 60 min [99,125] 3 × 15 min [100,115,117]	7–10 (only light) [97–99,104,106,107,125,127,132] 1 (combined with gels) [97,103,117] 2 (combined with gels) [110,111,113,121–123] 3 (combined with gels) [96,97,99,102,106,107,114,115,126–128,130–132] 4 (combined with gels or only light) [108,109,113,116]
Almeida et al. (2023) [105]	*In vitro*	Twin Flex Evolution, MMO	405 ± 15 nm	20 × 1 min at 30-s intervals	n.i.	No gel or 35% HP	Transparent	2 × 15 min	3
Youssef et al. (2021) [118]	*In vivo*	Whitening Plus LED Violet, DMC	405 nm ± 5 nm	3 × 2.5 min	Power: 375 mW (the authors reported the use of only violet LED)	35% HP	n.i.	1 × 15 min or 3 × 5 min	3
Klaric et al. (2014) [119]	*In vitro*	LED Engin Inc, San Jose, USA	405 nm	30 min	Energy density: 400 mW/cm^2	10% to 38% HP	Varying	30 min	n.i.

Table 8
Information collected from the studies which evaluated the ZOOM light during in-office tooth bleaching.

Authors (year)	Type of Study	Light Source	Wave-length	Time of Source Activation	Type of Light Reported by the Authors	Bleaching Gel %	Gel's coloration	Gel's Time	Number of Sessions
Klaric et al. (2015) [133]	*In vitro*	ZOOM2, Philips Discus Dental, Culver City, USA	350–400 nm	2 × 15 min	Mercury metal halide light	10, 16, or 30% CP; 25 or 38% HP	Transparent	2 × 15 min	n.i.
Bennett et al. (2015) [134]	*In vitro*	ZOOM2, Philips Discus Dental	n.i.	30 min	Blue LED	n.i.	Transparent	30 min	n.i.
AlSheikh et al. (2018) [135]	*In vitro*	ZOOM2, Philips Discus Dental	n.i.	15 min	Ultraviolet Light	n.i.	Transparent	15 min	n.i.
Ugurlu et al. (2022) [136]	*In vitro*	ZOOM2, Philips Discus Dental	n.i.	15 min	LED	25% HP	Transparent	15 min	1
Nutter et al. (2013) [137]	*In vivo (RCT)*	ZOOM2, Philips Discus Dental	400–505 nm	3 × 15 min	n.i.	25% HP	Transparent	3 × 15 min	1
Alomari et al. (2010) [138]	*In vivo (RCT)*	ZOOM2, Philips Discus Dental	n.i.	3 × 20 min	Mercury metal halide light	35% HP	n.i.	3 × 20 min	1
Kabil et al. (2019) [139]	*In vivo (RCT)*	Philips ZOOM!, Discus Dental	365 nm	n.i.	Ultraviolet Light	25% HP	n.i.	n.i.	3
Marto et al. (2022) [141]	*In vitro*	Zoom, Discus Dental	n.i.	45 min	LED	25% HP	Transparent	n.i.	1

caution regarding thermal effects and soft-tissue safety [140–142]. Therefore, despite superficial similarity in color output of the equipment, caution should be taken when grouping ZOOM within LED-based devices.

• *Combination of LEDs with Gels Containing Photocatalysts*

An additional focus of research in the present field over the last decade has been the combination of light sources and photocatalytic particles, most prominently titanium dioxide (TiO_2), incorporated into experimental or commercial bleaching gels and that can be doped with other elements [4,143]. TiO_2 is a wide-bandgap semiconductor capable of absorbing photons and promoting electron-hole pair formation. Under irradiation, these charge carriers can accelerate the decomposition of hydrogen peroxide into ROS or even generate longer-lived species such as hydroperoxyl radicals ($HO_2\bullet$) and superoxide anions ($O_2\bullet$) [144], which diffuse further than hydroxyl radicals and may contribute to enhanced oxidative bleaching [145,146]. This photochemical behavior has been proposed as a strategy to increase the efficacy of low-concentration hydrogen peroxide (6 to 15% HP) for in-office use while simultaneously reducing peroxide-related cytotoxicity and the associated risk or intensity of tooth sensitivity [143].

- *Blue LEDs (hybrid or non-hybrid) and N_TiO_2-enriched gels*

Only a limited number of studies (Table 9), in the early 2010s evaluated TiO_2-containing gels in combination with blue LED and blue LED/laser, including randomized clinical trials showing that color change did not approach the outcomes achieved with 35% HP [147–149], despite the reduced sensitivity typically associated with low-peroxide formulations incorporated with N_TiO_2 [150–155]. Since blue LED spectrum is energetically distant from the near-UV absorption peak of TiO_2, this fact may have reduced photocatalytic activation in this scenario. The commercial gels used in those studies rarely confirmed the presence of the anatase crystalline phase of TiO_2 [156] as well as its catalytically active form [144,157].

- *Violet LEDs (hybrid or non-hybrid) and N_TiO_2-enriched gels*

The emergence of violet LEDs (≈405 nm), closer to TiO_2's activation range while remaining safe for oral soft tissues, has appeared as an alternative in the field [95,155]. The literature search revealed bleaching gels with titanium dioxide nanoparticles predominantly from one manufacturer, at concentrations of 6%, 15%, and 35%, containing TiO_2, reportedly doped with nitrogen to turn the metal-oxide sensible to visible light. Notably, this same manufacturer also produces a light device used for gel activation, which consists of a hybrid system combining violet LED and low-level laser irradiation [8,124,158–165], as also seen in Table 9. Only one study, a RCT, has tested color change and tooth sensitivity using commercial TiO_2-enriched gels with a non-hybrid violet LED source from a unpaired manufacturer [166]. Randomized clinical trials have shown that commercial available low-concentration gels with N_TiO_2 nanoparticles, not characterized in the literature, exhibit significant increases in bleaching efficacy when paired with violet LED devices, whether hybrid or non-hybrid [155,165]. These protocols consistently produced substantially lower sensitivity compared with in-office bleaching using ≥ 35% HP [165,166]. Studies have shown no isolated effect of low-level infrared laser on the photochemical interaction of light and titanium dioxide [167,168].

- *Other Photocatalytic Systems*

Literature also reports the development of nanostructured, doped, or surface-modified TiO_2 nanoparticles [27,169–173] as well as TiO_2 nanotubes [174–177], These modified nanomaterials have demonstrated promising results when used with 6% HP or 37% CP gels, including both experimental formulations and commercially available peroxide gels enriched with these advanced structures in experimental designs. *In vitro*, experimental systems achieved bleaching efficacy comparable to 35% HP [27,178–180], along with preservation or enhancement of enamel surface and mineral content [181] and a marked reduction in cytotoxicity to odontoblast-like cells [182,183]. Very recently, a randomized controlled clinical trial demonstrated that an experimental 6% hydrogen peroxide (HP) gel incorporating TiO_2 nanoparticles co-doped with nitrogen and fluorine achieved whitening efficacy and patient satisfaction comparable to a commercial 35% HP protocol after a 6-month follow-up, while significantly reducing both the risk and intensity of tooth sensitivity [184].

Emerging photocatalytic approaches have been explored for low-peroxide bleaching, such as nanofiber scaffolds combined with enzymatic primers under violet LED irradiation, which improved esthetic outcomes in a 15-min only session while reducing trans-amelodentinal cytotoxicity [185–187] and tooth sensitivity in a recent randomized clinical trial [188]. Similarly, formulations with 6% HP enriched with manganese-based photocatalysts demonstrated *in vitro* enhanced ROS production and reduced oxidative stress in odontoblast-like cells

Table 9
Protocols using commercial bleaching gels enriched with N_TiO_2 nanoparticles and irradiated with a hybrid blue (450–470 nm) or violet (405 nm) LED/laser (808–830 nm) platforms.

Authors (year)	Type of Study	Light Source	Wavelength	Time of Source Activation	Parameters Informed by the Authors	Bleaching Gel %	Gel's coloration	Gel's Time	Number of Sessions
Bersezio et al. (2019) [147] Fernández et al. (2017) [148] Bortolatto et al. (2014) [150] Martín et al. (2013) [152]	*In vivo (RCT)*	Whitening Light Plus DMC Equip. Ltda.	LED: 470 nm ± 15 nm; Laser: 810 nm	2 × 15 min [147,148] 6 × 1 min [150] 5 × 1.5 min per arch [152]	LED power: 1500–1800 mW; Laser power: 300mW	6% and 35% HP [147, 148,150] 15% HP [152]	Red [152]	2 × 12 min [150] 2 × 15 min [147,148] 3 × 15 min [152]	1 [152] 2 [150] 3 [147, 148]
Martín et al. (2015) [151] Vildósola et al. (2017) [154] Bersezio et al. (2021) [149]	*In vivo (RCT)*	Bleaching Lase Plus DMC Equip. Ltda	LED: 450 nm ± 15 nm; Laser: 808 nm	2 × 12 min [151,154] 24 × 2 min [149]	Total power: 1500 mW; Laser total power: 300 mW	6% HP	Yellow [149]	2 × 12 min [151,154] 2 × 36 min or 1 × 72 min [149]	1 [151] 3 [154, 149]
Dias et al. (2013) [153]	*In vivo (RCT)*	Twin Flex II, MMOptics	450 nm; Laser: 660 and 780 nm	n.i.	LED power: 300 mW; Laser power: 300mW	6% HP	Yellow	2 × 12 min	1
Oliveira et al. (2024) [155] Costa et al. (2021) [8] Costa et al. (2022) [158] Manzoli et al. (2022) [159] Costa et al. (2021) [160] Costa et al. (2022) [161] Costa et al. (2022) [124] Manzoli et al. (2023) [162] Takeuchi et al. (2024) [163] Costa et al. (2023) [164] Trevisan et al. (2022) [165]	*In vitro* [8,124, 158–165] *In vivo (RCT)* [155,165]	Whitening Light Plus DMC Equip. Ltda.	LED: 405 nm ± 15 nm; Laser: 810 nm	10 × 1.5 min at 1.5-min intervals [155] 15 × 60 s at 60-s intervals [8,124,158, 160–162] 12 × 60 s at 60-s intervals [158] 10 × 60 s at 60-s intervals [163] 15 min [164] 8 × 1 min [165]	LED power: 2400 mW; Laser power: 300 mW; Energy density: 600 mW/cm^2	6% HP [8,124,155, 158, 162–165] 15% HP [155,161, 163,164] 35% HP [155,159, 161–164]	Orange (HP 35%); Red (HP 15%); Yellow (HP 6%) [124, 162–165] Purple (35% HP); Red (15% HP) [161]	2 × 15 min [155] 1 × 30 min [8,158, 162–164] 3 × 16 min [165] 3 × 8 min or 1 × 24 min [159]	1 [155] 2 [158–162] 3 [8,160, 165] 6 [159] 10 [163]
Castro et al. (2024) [166]	*In vivo (RCT)*	Bright Max Whitening, MMO	405–410 nm	20 × 1 min at 30-s intervals	Power density: 112 mW/cm^2; Energy density: 134 *J*/cm^2; Total energy/session of 1440 *J*	6% HP	Yellow	1 × 30 min	3

[189–191], achieving bleaching results comparable to 35% HP [192]. The protocols tested experimentally are presented in Table 10. However, up to this moment, TiO_2-enriched bleaching gels appears as the available clinical protocols, directed to be used in conjunction with violet LED equipment.

3.4. Low-Level Laser (650 nm -810 nm) Used for Photobiomodulation (PBM)

PBM, also referred to as low-level laser therapy (LLLT), has been investigated as an adjunctive approach not to activate bleaching gels, but to be applied directly to dental tissues in order to modulate the biological response to peroxide exposure and reduce post-bleaching sensitivity. During in-office bleaching, HP and its reactive by-products readily diffuse through enamel and dentin to reach the pulp chamber, and even though the light sources discussed in previous sections do not seem to increase peroxide diffusion *in vitro* [193–196], the presence of high-concentration HP alone is sufficient to trigger pulpal inflammation and transient cytotoxic effects [190,191]. Red and NIR irradiation have been extensively studied, under LLLT, on their effect on photo-modulating inflammatory responses occurring in the pulp tissue due to the arrival of unreacted HP on the pulp chamber.

In this context, an *in vitro* study showed that repeated irradiations with low-power semiconductor lasers (30 mW, 650 nm, 40 s per point = 2.4 J/cm^2) stimulated proliferation and odontoblastic differentiation of human dental pulp stem cells, out of the tooth bleaching context, indicating that PBM can promote beneficial cellular activity under chemically stressful conditions [197]. An *in vitro* research involving tooth bleaching demonstrated that PMB (40 mW, 660 or 780 nm, various times - up to 10 J/cm^2) was capable of counteracting the cytotoxicity produced by substances released from 35% HP gels, restoring the viability of pulp fibroblasts to levels comparable to non-stressed controls [29]. On the other hand, when a 780 nm (0.025 W) was applied, but for longer time (300, 800 and 1200 s - up to 15 J/cm^2), no beneficial effect

Table 10
Experimental photocatalytic strategies found in the literature in combination with light devices.

Authors (year)	Type of Study	Light Source	Wavelength	Time of Activation	Parameters Informed by Authors	Bleaching Gel %	Type of Photocatalystic	Gel's coloration	Gel's Time	Number Sessions
Kury et al. (2022) [27] Matos et al. (2019) [169] Kury et al. (2024) [172] Benati et al. (2025) [178] Kury et al. (2025) [181] Benati et al. (2025) [182] Melo et al. (2026) [183] Melo et al. (2025) [184]	*In vitro* [27,169, 172,178, 181–183] *In vivo (RCT)* [184]	Bright Max Whitening, MMO	401 nm	20 × 1 min at 30-s intervals	Power: 1202 mW; Power density: 910 mW/cm²	1.5% HP [178,182] 6% HP [27, 169,172, 178, 181–184] 15% HP [27] 35% HP [27,172, 181]	NF_TiO_2 nanoparticles (5% or 10%)	Transparent	1 × 30 min	3
Thacker et al. (2017) [170]	*In vitro*	Litex 686, Dentalamerica Asia Inc, Taipei, Taiwan	n.i.	1 × 1 min	n.i.	10% CP	N_TiO_2 nanoparticles (1%)	n.i.	1 × 5 min	1
Hu et al. (2021) [171]	*In vitro*	n.i.	808 nm	n.i.	0.2, 0.3, and 0.4 W/cm²	12% HP	TiO_{2-x} nanoparticles (2 mg/mL)	n.i.	3 × 20 min	1
Sürmelioglu et al. (2013) [173]	*In vitro*	WhitenMAX-BR800, Monitex, China	420–490 nm	n.i.	n.i.	6% HP	TiO_2 with or without chitosan	n.i.	3 × 15 min	2
Antunes et al. (2023) [174] Carlos et al. (2023) [175] Guedes et al. (2023) [176] Dacoreggio et al. (2025) [177]	*In vitro*	Valo, Ultradent, Utah, USA [174] Bright Max Whitening, MMO [175,177] Whitening Plus DMC Equip. Ltda [176]	400–460 nm [174] 405 nm [175,177] LED: 405 nm; Laser: 808 nm [176]	8 × 15 s at 5-min intervals [174] 20 × 1 min at 30-s intervals [175,177] 1 min at 1-min intervals [176]	Power: 1000 mW/cm² [174] Irradiance: 112 mW/cm²; total energy/ session: 1440 J [175,177] LED total power: 390 mW; Laser power: 100 mW [176]	35% HP [175,176] 7% HP [176] 35% HP [175–177] 40% HP [174]	TiO_2 nanotubes (1, 5, or 10%)	Red [174] Transparent [175,177]	1 × 40 min [174] 1 × 30 min [175, 177] 1 × 18 min [176]	3
Cheng et al. (2024) [179]	*In vitro*	Uvgo, China	405 nm ± 5 nm	20 × 1-min at 1-min intervals	Power: 5 W	40% HP	TiO_2 (1, 3, or 5%; 20 or 100 nm)	n.i.	2 × 20 min	2
Lee et al. (2019) [180]	*In vitro*	n.i.	306 nm or 405 nm	15 min	Illumination intensity: 2.1 mW/cm²; Spot size: 10 mm	3.5% HP	TiO_2	n.i.	15 min	n.i.
Martins et al. (2022) [185] Ribeiro et al. (2024) [186] Ribeiro et al. (2024) [187] Esteves et al. (2025) [188]	*In vitro* [185–187] *In vivo (RCT)* [188]	Bright Max Whitening, MMO	405 nm	15–20 min [185–187] 8 × 1 min at 30-s intervals [188]	Power: 1202 mW; Power density: 910 mW/cm²	10–20% HP [185] 35% HP [186–188]	Scaffold + heme peroxidase primer before gel	Red [189]	1 × 15 min [187, 188] 1 × 45 min [185, 186]	1 [185–187] 3 [188]
Dias et al. (2022) [189]	*In vitro*	Bright Max Whitening, MMO	405 nm ± 10 nm	1 × 20 min	Output power: 350 mW; optical power: 1.5 W; Irradiance: 140.2 mW/cm²	6%, 10%, and 35% HP	Manganese oxide – MnO_2 (10 mg/mL)	n.i.	1 × 45 min	1
Dascanio et al. (2026) [192]	*In vitro*	Bright Max Whitening, MMO	401 nm	20 × 1 min at 30-s intervals	Power: 1202 mW; Power density: 910 mW/cm²	6% HP	Biosilicate ® doped with 2.5% MnO_2	Transparent	1 × 30 min	3

was verified on pulp cells previously exposed to extracts containing the diffused 35% HP through dentinal discs [198].

Animal studies, however, further corroborate the protective potential use of LLLT. Infrared PBM applied after bleaching (100 mW, 808 nm, 30 s) significantly reduced acute pulpal inflammation in rat molars, limiting necrosis and attenuating the immunolabeling of pro-inflammatory mediators such as IL-23 in comparison with bleaching alone. Although PBM did not substantially alter HIF-1α expression, which plays a role in survival and improving cell resistance during the inflammatory process, it consistently resulted in milder inflammatory scores and more organized tissue architecture in the early post-operative period [199]. Additional histological evidence has shown that both red (660 nm) and infrared (808 nm) protocols (100 mW, 15 or 30 s) can reduce inflammatory infiltrate and influence collagen fiber maturation during initial healing, even though neither modality was able to prevent the long-term deposition of tertiary dentin [200].

In one randomized clinical trial using 40% HP gel, infrared LLLT (810 nm - 200 mW, 3 J, 15 s per area = 12 J/cm2) significantly reduced tooth sensitivity at 24 h compared with both red (660 nm) PBM and placebo, although all groups showed similar pain levels by 48 h, and bleaching efficacy remained unaffected [201]. Another RCT comparing PBM (808 nm - 100 mW, 2 J, 20 s per point = 70J/cm^2) applied before or after bleaching with 35% HP showed that both strategies reduced pain relative to control, with superior outcomes when PBM was applied after gel removal, though again no enhancement in whitening was observed [202]. Conversely, a placebo-controlled study using PBM (780 nm - 40 mW, 0.4 J, 10 s per point = 10 J/cm^2) failed to demonstrate any reduction in sensitivity, highlighting that dose and irradiation regimen might critically influence the analgesic effect [203]. More recent high-rigor trial tested PBM (808 nm - 100 mW, 3 J, 30 s per point = 100/Jcm^2) immediately after each bleaching session using 35% HP and found no reduction in either the risk or intensity of TS compared with placebo [30]. Notably, a clinical trial employing PBM delivered via a device described as a 940-nm "LED" (160 mW; 14 J/cm^2) modulated significantly tooth sensitivity [204]. These findings suggest that although PBM can modulate inflammatory responses and cellular stress

Table 11
Protocols found in the literature using low-lever power for photobiomodulation during bleaching therapies.

Authors (year)	Type of Study	Light Source	Wavelength	Dosimetry Informed by the Authors	Parameters Informed by the Authors	Bleaching Gel %	Gel's Time	Moment of Irradiation
Dantas et al. (2010) [29]	*In vitro*	Twin Laser, MMOptics	660 nm (AlGaInP) or 780 nm (GaAlAs)	4 J/cm^2 (0.16 Jm, 4 s, 10 mW/s) or 6 J/cm^2 (0.24 Jm, 6 s, 6.6 mW/s), or 10 J/cm^2 (0.4 Jm, 10 s, 4.0 mW/s)	Output power: 40 mW, spot size: 0.04 cm^2, punctual and continuous mode	0.2 g of 35% HP/1 mL culture medium	40 min	After bleaching exposure
Lima et al. (2014) [198]	*In vitro*	InGaAsP diode laser prototype	780 ± 3 nm	300, 800 and 1200 s, for 4, 10 and 15 J cm^{-2}	Power: 0025 W; Energy: 4, 10 and 15 J cm^{-2}	35% HP (diffused through dentin)	15 min	After bleaching exposure
Silva et al. (2022) [199]	*In vivo* (rat model)	GaAlAs; MMOptics	808 nm	30 s	Power: 100 mW; Beam exit area: 3 mm^2	35% HP	30 min	After bleaching exposure
Terayama et al. (2020) [200] Vochikovsk et al. (2022) [30]	*In vivo* (rat model) [200] *In vivo (RCT)* [30]	Laser Duo (GaA1As InGaAlP); MMOptics	660 nm (RL) or 808 nm (IRL)	15 s (RL) or 30 s (IRL) per session; 3 J (IRL) / 1.5 J (RL) [200] 3 J, 30 s per point = 100/Jcm^2 [30]	Power: 100 mW; Beam exit area: 3 mm^2	35% HP	30 min [200] 1 × 50 min [30]	After bleaching exposure
Moosavi et al. (2016) [205]	*In vivo (RCT)*	Thor DD2 Control Unit (InGaAlP and GaAlAs), Thor, London, UK	660 nm (RL) or 810 nm (IRL)	15 s per tooth; 3 J; 12 J/cm^2; 800 mW/cm^2	Power: 200 mW	40% HP	3 × 15 min	After bleaching exposure
Takeuchi et al. (2025) [202] Cardoso et al. (2024) [210]	*In vivo (RCT)*	Therapy EC, DMC	808 nm	20 s per point (2 points); 2 J per point; 70 J/cm^2 [202] 1 J per point; 100 mW/cm^2 [210]	Power: 100 mW	35% HP [202] 22% CP (home) [210]	3 × 15 min [202] 2h/day [210]	After bleaching exposure [202] Once a week (3 weeks) [210]
Calheiros et al. (2017) [203]	*In vivo (RCT)*	Name n.i., MMOptics	780 nm	10 s per point (2 points); 0.4 J per point; 10 J/cm^2;	Power: 40 mW; Spot size: 0.04 cm^2	35% HP	3 × 15 min	Before, before/after and after bleaching
Miranda et al. (2022) [204]	*In vivo (RCT)*	Custom LED device (16 spots)	940 nm	10 min; 16 mW/cm^2; 4 J/cm^2	Power: 160 mW; Irradiated area:1 cm^2	35% HP	3 × 15 min	Before bleaching exposure
Femiano et al. (2023) [205]	*In vivo (RCT)*	Soft Touch; 810 nm diode laser (Creation Medical Laser)	810 nm	30 s per tooth; 15 J/cm^2	Power: 5 W	38% HP	1 × 20 min	Before bleaching exposure
de Paula et al. (2019) [31] Alencar et al. (2018) [206] Pompeu et al. (2021) [209]	*In vivo (RCT)*	Photon Laser III (AsGaAl), DMC	808 nm	16 s per point; 1.7 J; 60 J/cm^2	Power: 100 mW; Spot size: 0.028 cm^2	35% HP	3 × 15 min	After bleaching exposure [31, 209] Before bleaching exposure [206]
Sadri et al. (2023) [207]	*In vivo (RCT)*	EpicTM 10, Biolase Tech., Irvine, USA	940 nm	30 s	Power: 10 W	35% HP	2 × 20 min	During bleaching exposure
Yahya et al. (2022) [218]	*In vivo (RCT)*	Diode laser, Hager& Werken	660–900nm	60 s, 1 mm-distant from the teeth	Power: 90 mW	40% HP	n.i.	After bleaching exposure

pathways, its clinical analgesic effect is not reliably reproduced, and appears sensitive to wavelength, fluence, timing (described in the protocols in Table 11), and possibly interindividual variability in pulpal physiology. Importantly, none of the trials reported improvements in bleaching efficacy attributable to PBM [202,205], reinforcing that its role is purely adjunctive for symptom modulation, not chemical activation of peroxide.

Several randomized clinical trials have also investigated whether combining PBM with established desensitizing agents - such as potassium nitrate [31], sodium fluoride (in dentifrice [206], foam [207], or varnish [208] forms), strontium chloride [209], or casein phosphopeptide-amorphous calcium phosphate fluoride pastes [210] - could produce a synergistic reduction in bleaching-induced tooth sensitivity. Across studies, however, the combined protocols consistently failed to demonstrate superior analgesic outcomes compared with the isolated use of each desensitizing strategy, indicating that PBM does not potentiate the effects of these agents and that their mechanisms of action likely operate independently. Taken together, the evidence suggests that combining PBM with chemical desensitizing agents does not enhance therapeutic outcomes.

4. Discussion

Across the literature, studies comparing different light-activated bleaching techniques, ranging from LEDs and hybrid LED/laser devices to diode, KTP, Nd:YAG, and Er:YAG laser systems, have produced inconsistent and often conflicting results. Despite frequent claims of accelerated whitening or enhanced gel activation, the heterogeneity in wavelengths, dosimetry, gel formulations, evaluation methods, and follow-up periods makes it difficult to identify any light source that reliably outperforms conventional chemically activated high-concentration peroxide [211]. Beyond critically appraising the available evidence, the intent of this literature review was to provide the reader with a clearer conceptual framework to understand the fundamental differences among the various light sources commonly promoted for tooth bleaching (Fig. 2). Even in the presence of conflicting and heterogeneous evidence, this discussion aims to equip clinicians and researchers with the tools necessary to distinguish these technologies more critically, moving beyond marketing claims toward an evidence-based interpretation.

When different light sources are directly compared, some clinical and *in vitro* investigations have suggested that diode laser activation can promote slightly greater immediate shade change than Er:YAG, Nd:YAG, and blue LED or purely HP [212–214]. On the other hand, studies attested that Er:YAG promoted better enamel bond strength following bleaching [215] and lower tooth sensitivity [60] when compared to diode activation. Studies with KTP and Nd:YAG reported superior initial color change values for KTP-associated protocols when combined with red-colored gels; although this advantage diminished due to shade regression [53,216–218]. Curiously, previous studies have demonstrated controversial results even when comparing all these laser sources during use of sodium perborate on non-vital tooth bleaching, yet the results are mostly *in vitro* [219–225].

Moreover, several *in vitro* experiments directly comparing mostly blue and violet LEDs, alone or in hybrid LED/low-level laser configurations, found no differences among lights and no clinically relevant improvements in color change, HP penetration, or cytotoxicity compared with 35% HP alone, and any early differences tended to converge during medium- to long-term follow-up, especially for blue LED [226–230]. Multiple systematic reviews with meta-analysis, none of which including violet LED-assisted protocols, have concluded that, blue LEDs, hybrid LED/laser devices, and high-power lasers (mostly diode- and erbium-based) do not provide clinically meaningful improvements in subjective (based on visual guide units) and objective (ΔE_{ab}) color changes compared with 25–40% HP alone [6,11,13,14,231,232]. In addition, a comprehensive network meta-analysis specifically comparing different light sources, also previously from violet LED studies, reported that no activation device outperformed another, and none was superior to peroxide alone when only well-designed RCTs were included in the statistical model [12].

However, such systematic reviews highlighted the marked heterogeneity of clinical protocols and the high or unclear risk of bias in most trials, resulting in a low certainty of evidence. Substantial methodological limitations (lack of randomization, absence of blinding, and reliance only on subjective VITA shade assessment) was confirmed by reading studies using diode laser [10,43,47,233], erbium laser [18,60], and blue LED [78–80,234]. Accordingly, up until this moment, data do not support the routine use of light sources in conjunction with highly concentrated HP. The continued promotion of light-activated systems as adjuncts to in-office bleaching, especially high-power laser devices adapted from other dental applications, would benefit from confirmation through well-designed, adequately powered randomized clinical trials that address the methodological limitations identified in the current evidence base.

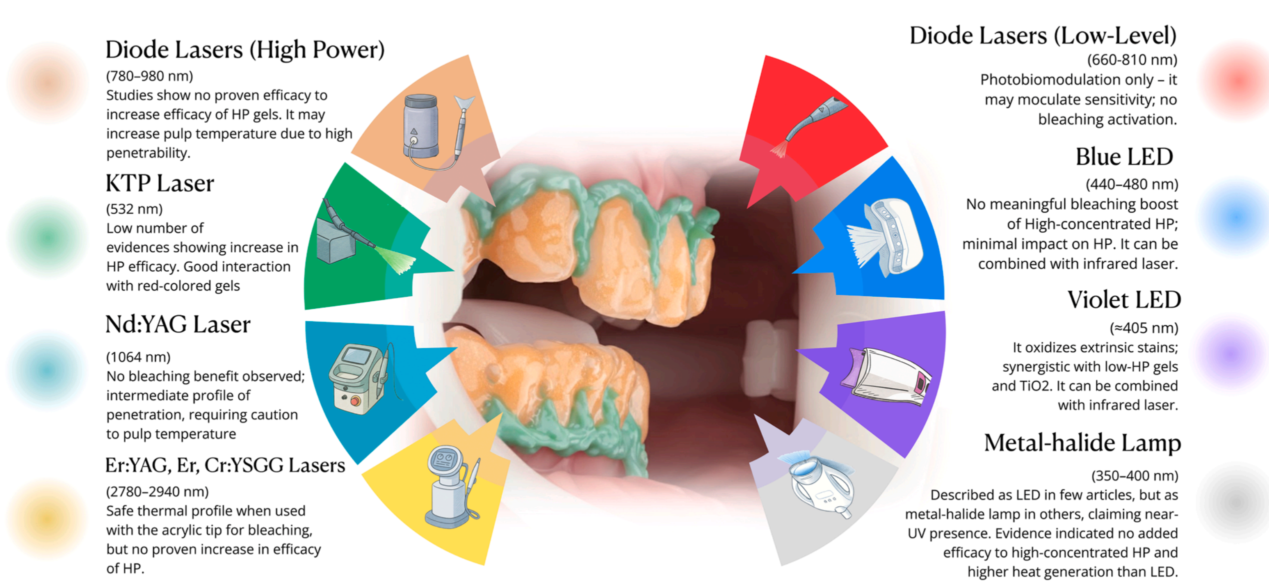

Fig. 2. Schematic illustration of different light sources used in dental bleaching (lasers and LEDs across various wavelengths) and their reported interactions with hydrogen peroxide–based gels.

Building upon these high-level syntheses, experimental wavelength-screening models further attempt to clarify why most chairside devices fail to potentiate peroxide chemistry. Studies evaluating the photochemical behavior of hydrogen peroxide in isolation or in the presence of transition-metal catalysts demonstrate that meaningful enhancement of bleaching kinetics occurs predominantly within the near-UV range (≈256–310 nm), where photon energy is sufficient to trigger Fenton-type and photo-Fenton reactions. These mechanisms generate highly ROS through metal-assisted photoredox cycling, markedly accelerating chromophore degradation [119,227,235,236]. As aforementioned, the only device in the dental literature emitting within (or close to) this UV domain would be the ZOOM2, being credited as a mercury-metal-halide lamp (≈350–400 nm) by some authors [133,138]. However, ultraviolet exposure is not desirable in clinical dentistry due to its side-effects, and no high-quality randomized clinical trials substantiate superior efficacy for this system [136–139,237]. Either way, if dentists use this specific light source, it is highly recommended to protect the entire surrounding oral soft tissues, because of the risks of UV exposure for epithelial tissues [238].

In practical terms, the light technology that most closely approximates these higher-energy interactions, without crossing into harmful UV radiation [95], is the violet LED (≈405 nm), commercially introduced nearly a decade ago for tooth bleaching purposes [22]. An *in vitro* evaluation concluded that violet LED exposure selectively elevated temperature and enhanced ionization dynamics in low-concentration peroxide gels (6% and 15% HP), altering their pH and electrical potential in a way that accelerates HP dissociation into ROS, an effect not observed with highly concentrated gels whose intrinsic ionic reactivity would be already maximal [124]. A substantial body of *in vitro* evidence and few well-designed RCTs have demonstrated that violet LED can enhance whitening when combined with low-concentration HP or high-concentration CP even in the absence of photocatalytic additives, as shown by Bessa et al. (2025) in a systematic review. However, these outcomes should be cautiously interpreted due to the moderate certainty of the evidence [239].

More recently, the literature has increasingly progressed toward combining violet-range light with semiconductor photocatalysts such as TiO_2, manganese oxides, and others [189,240,241], achieving meaningful improvements in bleaching efficacy due to reasons explored previously while maintaining enamel microstructural integrity, biocompatibility, and intrapulpal temperature within acceptable limits. For effective activation, the photocatalytic activity of TiO_2 requires photon energies close to its bandgap approximately 3.0 eV for rutile and 3.2 eV for anatase, which correspond to wavelengths within the violet region of the visible spectrum [145,167], encouraging the use of violet LED along with TiO_2-enriched gels. A multi-study clinical synthesis discussed, however, that infrared diode lasers are unlikely to play a meaningful role in TiO_2-driven photochemistry [167]. NIR wavelengths (*e.g.*, 810–980 nm) deliver photon energies around 1.25–1.53 eV, far below the threshold (3.0–3.2 eV) required to promote electron–hole pair formation in TiO_2 [167,168]. Consequently, when TiO_2-containing gels are irradiated with infrared lasers, in a hybrid light context, the interaction is predominantly thermal rather than photocatalytic, and any enhancement in bleaching efficacy is improbable to stem from semiconductor-mediated ROS generation. Therefore, when using a hybrid violet LED, the activation of low-laser infrared laser during gel contact with enamel would be unnecessary.

Although only a few commercial formulations currently incorporate these catalysts, reflecting a field still dominated by experimental development, the emerging data point toward a clear trend: violet-assisted photocatalytic systems represent one of the most promising low-HP in-office bleaching strategies under investigation. A recently published systematic review and meta-analysis [242] demonstrated that experimental or commercial gels incorporating TiO_2 promote significantly greater color change and whitening index values than peroxide-only formulations, particularly at low concentrations, supporting the translational relevance of these catalytic strategies. Nevertheless, the substantial heterogeneity observed among the included studies in the systematic review underscores the influence of methodological variability, including differences in gel formulation, TiO_2 physicochemical properties, light parameters, and outcome assessment protocols. These limitations highlight the need for well-designed, adequately powered randomized clinical trials with standardized protocols and longer follow-up periods to robustly define the clinical magnitude, durability, and safety profile of TiO_2-assisted low-peroxide bleaching approaches.

A fundamental optical principle underpinning the variable behavior of light-activated bleaching systems is that photon energy is inversely proportional to wavelength. Thus, shorter wavelengths (violet/blue) carry higher photon energy, interact more readily with the color pigments and additives within bleaching gels, and exhibit lower tissue penetrability [95]. Conversely, long-wavelength infrared lasers possess markedly lower photon energy, show minimal absorption by peroxide gels, and penetrate deeper into enamel and dentin, increasing the likelihood of pulpal heating rather than photochemical activation. The optical behavior of the gels themselves also plays a key role: a red-colored gel reflects red light (≈620–750 nm) and therefore absorbs it poorly, limiting the interaction with red/near-infrared diode lasers (810–980 nm) and Nd:YAG (1064 nm). In contrast, green KTP light (532 nm) lies near the complementary region of red pigments, resulting in strong absorption and more efficient photothermal coupling-consistent with studies showing enhanced early ΔE when KTP is paired with red gels [53]. Together, these optical principles clarify why short-wavelength sources tend to interact more effectively with bleaching gels, whereas infrared lasers, despite deeper penetrability, demonstrate limited activation potential and a higher propensity to raise pulpal temperature in a high power mode.

In parallel, PBM warrants distinct consideration, as its purpose is not to activate peroxide gels but to modulate the pulpal response triggered by the transenamel diffusion of HP itself. As demonstrated in some studies summarized in a systematic review on pulpal responses, the presence of peroxide, not the light source, is the primary determinant of inflammatory and cytotoxic changes [243]. At the mechanistic level, PBM appears to mitigate peroxide-related damage through converging mitochondrial and signaling pathways. Red and infrared wavelengths are largely absorbed by mitochondrial cytochrome C oxidase, leading to increased mitochondrial membrane potential, enhanced ATP synthesis, and upregulation of antioxidant and pro-survival signaling cascades [244]. NIR irradiation (≈780–1064 nm) can additionally modulate light-sensitive ion channels and intracellular Ca^{2+} dynamics, which in turn influence gene expression, cell proliferation, and tissue repair [244]. Secondary effects include modulation of ROS and nitrogen species, nitric oxide release, and activation of transcription factors related to inflammation resolution and extracellular matrix remodeling [245].

Across animal and *in vitro* studies, PBM using low-level red or infrared wavelengths (≈660–810 nm) did not increase intrapulpal temperature [246] nor independently injure the pulp, and in certain parameter ranges was capable of attenuating inflammatory scores, modulating neuropeptide expression, or influencing collagen-fiber maturation. Nonetheless, these effects were highly dependent on wavelength, fluence, exposure time, and substrate thickness, and were not consistently reproducible because of substantial methodological heterogeneity and incomplete reporting of laser parameters. Most available data derive from non-human models, further limiting clinical extrapolation [243,247].

A PRISMA-compliant review including six low-risk-of-bias RCTs concluded that PBM shows promising but inconsistent results in reducing TS after in-office bleaching, with insufficient evidence to establish optimal parameters [248]. A second systematic review evaluating six RCTs likewise found a tendency toward TS reduction, but emphasized the heterogeneity of protocols and the overall low certainty of evidence, calling for well-designed, adequately powered trials to define clinically meaningful protocols [28]. Therefore, current evidence indicates that PBM may mitigate bleaching-related discomfort under certain conditions, but its benefits are not universal, and no clinically validated standard protocol exists. It is important to reiterate that PBM is not effective for irradiating bleaching gels, as it does not improve gel efficacy, regardless of hydrogen peroxide concentration or the incorporation of photocatalysts.

Beyond peroxide-based strategies, several peroxide-free light-assisted approaches have been proposed to reduce pulpal irritation and enamel alterations inherent to HP diffusion. Photodynamic therapy (PDT) represents the earliest of these modalities, relying on photosensitizers such as bismuth oxychlorideor phthalocyanine to generate ROS under visible-light activation. Although PDT can degrade chromogens and disrupt biofilm, its whitening potential remains modest, limited by photobleaching, shallow penetration, and long irradiation times, which has restricted its clinical applicability [249–251]. More recently, non-peroxide formulations have become increasingly relevant, being combined with violet LED or diode laser *in vitro*. In this instance, plant-derived gels like Aloe vera [252], peroxide-free LED-activated whitening pens [253], PAP-based agents (phthalimidoperoxycaproic acid) [254,255], and TiO_2-only formulations [256,257] demonstrate improved biocompatibility and measurable color improvement, albeit generally inferior to high-concentration HP. These elements are discussed as forward-looking considerations, rather than being grounded in the herein gathered evidence. Despite the early stage of development and scarcity of well-designed clinical trials, these findings indicate the growing trend of emergent peroxide-free, light-responsive technologies, particularly those leveraging violet-range activation, are evolving as promising adjuncts or alternatives for patients seeking safer protocols.

This review has inherent limitations related to its narrative design. Additionally, the restriction to English-language publications and the substantial heterogeneity among study protocols may have influenced the comprehensiveness and comparability of the included evidence. In a clinical context, the evidence synthesized in this review suggests that light-assisted bleaching, regardless of the technology, offers limited and inconsistent additional benefit when compared with well-established protocols using high concentrations of HP. Predictability, safety, and longevity appear to be primarily influenced by peroxide concentration, gel formulation, soft-tissue protection, and adherence to controlled application times. Accordingly, reported advantages of light-based devices, such as enhanced efficacy or reduced sensitivity, remain variable and should be interpreted in light of the available scientific evidence.

5. Conclusion

Within the limitations of this review, the following conclusions could be drawn:

- Light-based adjuncts would not provide predictable or clinically meaningful improvements in the efficacy of high-concentration HP bleaching. Heterogenous studies pointed out that high-power lasers, blue and violet LEDs, and hybrid LED/laser devices show no consistent advantage and do not reliably reduce bleaching-related sensitivity when used to activate highly concentrated hydrogen peroxide gels.
- Violet-LED systems applied in combination with low-concentration HP, especially containing photocatalysts, such as TiO_2, have shown encouraging *in vitro* and early clinical results - often achieving improved whitening with reduced sensitivity and maintaining favorable enamel and biological outcomes. However, further high-rigor clinical studies are still necessary to confirm such findings.
- Photobiomodulation may modulate pulpal inflammation under specific parameters, but its effect controlling tooth sensitivity in clinical bleaching remains inconsistent and protocol dependent.
- Future investigations focusing on the optimization of light parameters, gel formulations, and photocatalytic strategies may contribute to improvements in both bleaching efficacy and tooth sensitivity, potentially enabling the reduction of hydrogen peroxide concentration or even its replacement when combined with light-based approaches.

CRediT authorship contribution statement

Márcia V.G.B. Queiroz: Writing – original draft, Methodology, Investigation, Data curation. **Rafael Dascanio:** Writing – review & editing, Software, Resources, Data curation. **Vinicius H. Hutemma:** Writing – original draft, Methodology, Investigation. **Diogo A. Chiovetto:** Writing – original draft, Methodology, Investigation. **Adriano F. Lima:** Writing – review & editing, Visualization, Validation. **Jorge R. Soto-Montero:** Writing – review & editing, Visualization, Validation, Conceptualization. **Matheus Kury:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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