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Review article

Effect of transcranial photobiomodulation on electrophysiological activity of brain in healthy individuals: A scoping review

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ABSTRACT

Background objective: Transcranial photobiomodulation (tPBM) is a safe and non-invasive treatment that has recently emerged as an effective technique to apply near-infrared or red light to activate neural tissues. The objective is to review the literature on the effect of tPBM on electrophysiological activity in healthy individuals.

Methods: Literature was searched through PubMed, Scopus, Web of Science, Cumulated Index to Nursing and Allied Health Literature (CINAHL), Embase, and Ovid for transcranial photobiomodulation therapy in healthy individuals age group 18–80 years of either gender having electroencephalography as an outcome. Critical appraisal of included Randomized Controlled Trials and non-randomized experimental studies was done using Joanna Briggs Institute (JBI) critical appraisal tool.

Results: A database search yielded a total of 4156 results. After eliminating 2626 duplicates, 1530 records were left. 32 articles were considered for full-text screening after 1498 records were excluded through title and abstract screening. 10 articles were included in this review. tPBM has been found to increase the higher electrophysiological oscillations and there is inconclusive evidence targeting the lower oscillatory electrophysiological frequencies.

Conclusion: Transcranial photobiomodulation can have promising effects on the electrophysiological activity of the brain in healthy individuals.

1. Introduction

"Transcranial photobiomodulation (tPBM) is a type of light therapy that uses monochromatic visible and infrared light from non-ionizing radiation sources (lasers, LEDs) positioned on the scalp, forehead, or intranasally to project light directly to specific parts of the brain" [1]. tPBM is a safe and non-invasive intervention that has been found to regulate cerebral metabolism, cerebral oxygenation, and cognitive function [2–4]. It increases the metabolic efficiency of neurons and promotes synaptogenesis, neurogenesis, anti-apoptotic, anti-inflammatory, and antioxidant responses [5]. tPBM has been implemented and found beneficial in treating individuals with neurodegenerative and vascular brain diseases [1,3,6–10]. A beneficial effect of tPBM was also observed in the cognitive performance of young healthy adults [11].

Electroencephalography (EEG) has been employed to study a vast array of clinical and cognitive phenomena in recent years [12,13]. Clinical studies utilized EEG to examine the neural correlates of various psychological ailments, including depression and schizophrenia [14,15]. Additionally, EEG has been used to examine the neural mechanisms underlying cognitive activities like attention, perception, decision-making, and working memory [16–20]. Developments in EEG analysis techniques, such as machine and deep learning algorithms, have improved the accuracy and speed of data processing and interpretation [21,22].

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There is a significant decrease in alpha power and an increase in beta power with age, a decline in functional connectivity in the default mode network (DMN), a decline in event-related potentials (ERPs), a decrease in slow wave activity (SWA) is seen in older individuals as compared to young individuals [23–26]. Studies have shown age-related alterations in resting-state EEG connectivity, with older individuals showing decreased connectivity in some brain regions, particularly in the fronto-parietal network, and decreased coherence between different brain regions, mainly in the frontal and temporal lobes [27–29].

As mechanical modernization progresses, work-related stress increases significantly in the young and middle-aged population. It is important to understand when the decline in electrophysiological activity of the brain starts. Therefore, there is a necessity for early screening of brain function in this population. Photobiomodulation (PBM) is one of the preventive non-pharmacological tools for improving cognitive function and has been found useful in improving outcomes in diseased populations. A previous systematic review by Magkouti et al. 2023 did not provide a comprehensive search of various databases for existing literature on the effect of tPBM on EEG in healthy individuals. As a preventive strategy to avert further complications, there is a need to review the literature on the effect of tPBM on electrophysiological activity especially using EEG in healthy young and middle-aged individuals. Hence this review aims to scope existing literature on the effect of transcranial photobiomodulation on electrophysiological activity in healthy individuals.

2. Methods

This review used the Preferred Reporting Items for Systematic Reviews and meta-Analysis extension for Scoping Reviews (PRISMA-ScR) checklist for reporting [30].

2.1. Information sources

A data search was executed in March 2023. The following databases were used for the systematic search of relevant articles- PubMed, Scopus, Web of Science, CINAHL, Embase, and Ovid. Additional records were identified through citation searching.

2.2. Eligibility criteria

Inclusion criteria includes healthy individuals, age group 18–80 years of either gender, original study, interventional study design, studies on the effect of transcranial photobiomodulation therapy, comparator includes sham, placebo photobiomodulation, between different parameters of photobiomodulation, different treatment strategies, studies having electroencephalography as an outcome. Exclusion criteria include language other than English, animal studies, conference proceedings, book chapters, and unavailability of full text.

2.3. Search

Following terms and Boolean operators were used for the search: “healthy” OR “normal adult*” AND “laser therapy” OR “phototherapy” OR “transcranial photobiomodulation” OR tPBM OR “light-emitting diode” OR photobiomodulation OR “transcranial light therapy” OR “transcranial near-infrared light” OR “infrared laser” OR “low-level light therapy” OR “brain photobiomodulation” OR “transcranial laser stimulation” OR “low-level laser therapy” OR “near-infrared light” OR “pbm therapy” OR phototherapy OR “laser therapy” OR “transcranial infrared laser” OR “transcranial light stimulation” AND “electroencephalography” OR “eeg” OR “functional connectivity” OR “imaginary part of coherence” OR “graph theory” OR “singular value decomposition” OR eLORETA OR “default mode network” OR “executive control network” OR “frontal-parietal network”.

2.4. Selection of sources of evidence

Three reviewers (SSJ, SS, VP) independently searched the literature. All the records retrieved from databases were uploaded to Rayyan software [31]. Duplicates were resolved by VP. Two reviewers (SS and DS) independently screened the title and abstract. Any conflicts regarding the selection of articles were resolved by another reviewer (SSJ). Full-text screening of selected articles was carried out by VP, SS, DS, and SSJ independently and the data was retrieved from relevant articles.

2.5. Data charting process

A data extraction sheet was developed after analyzing the contents of the included articles. The data extraction sheet was finalized after discussion with other authors (AGM, SS, VP, SSJ, DS). Finalized data extraction sheet was used to retrieve the data from included articles. Two authors retrieved data in duplicate and the other three authors helped in resolving disagreement of extracted data.

2.6. Data items

Following data items were included in the data extraction sheet-Authors; year of publication; Country where the study was conducted; the objective of the study; population characteristics such as age and gender; study design; sample size; Intervention; photobiomodulation parameters such as wavelength, power, duration, number of sessions, area; comparator group; outcomes; EEG parameters; and results.

2.7. Critical appraisal

Randomized Controlled Trials (RCTs) examine the causal linkages between interventions and outcomes to determine causality and quantify the effectiveness of interventions while minimizing bias [32]. Critical appraisal of included RCTs was done using Joanna Briggs Institute (JBI) critical appraisal tool for assessment of the risk of bias for Randomised Controlled Trials and Non-Randomized Experimental studies were assessed using the JBI checklist for Quasi-Experimental Studies (Non-Randomized Experimental studies) [33,34].

JBI critical appraisal checklist is a tool to evaluate the methodological quality of the study and to identify how well a study addressed the possibility of bias in its design, methodology, and analysis [33]. For the interpretation of critical appraisal, the percentage of the number of “yes” answered to the questions was considered. Studies were categorized as having a “low risk of bias” if their score was greater than or equal to 70 %, a “moderate risk of bias” if it was between 50 % and 69 %, and a “high risk of bias” if it was <49 % [35].

3. Results

A thorough search was done in six databases: PubMed, Scopus, Web of Science, CINAHL, Embase, and Ovid and a total of 4156 records were obtained. There were 1530 records left after 2626 duplicates were eliminated. After 1498 records were eliminated through title and abstract screening, 32 articles were taken into consideration for full-text screening. Additionally, 2 records were obtained through back-referencing of articles. During the full-text screening, 24 records were excluded for the following reasons: book chapters (n = 1), conference proceedings (n = 6), outcomes other than EEG (n = 13), and unavailability of full-text (n = 4). Finally, 10 studies were included in this scoping review [4,36–44]. (see Fig. 1). Among the 10 included studies, three studies [42–44] were conducted by the same research group having the same group of healthy participants and differed in terms of objectives and data analysis methods.

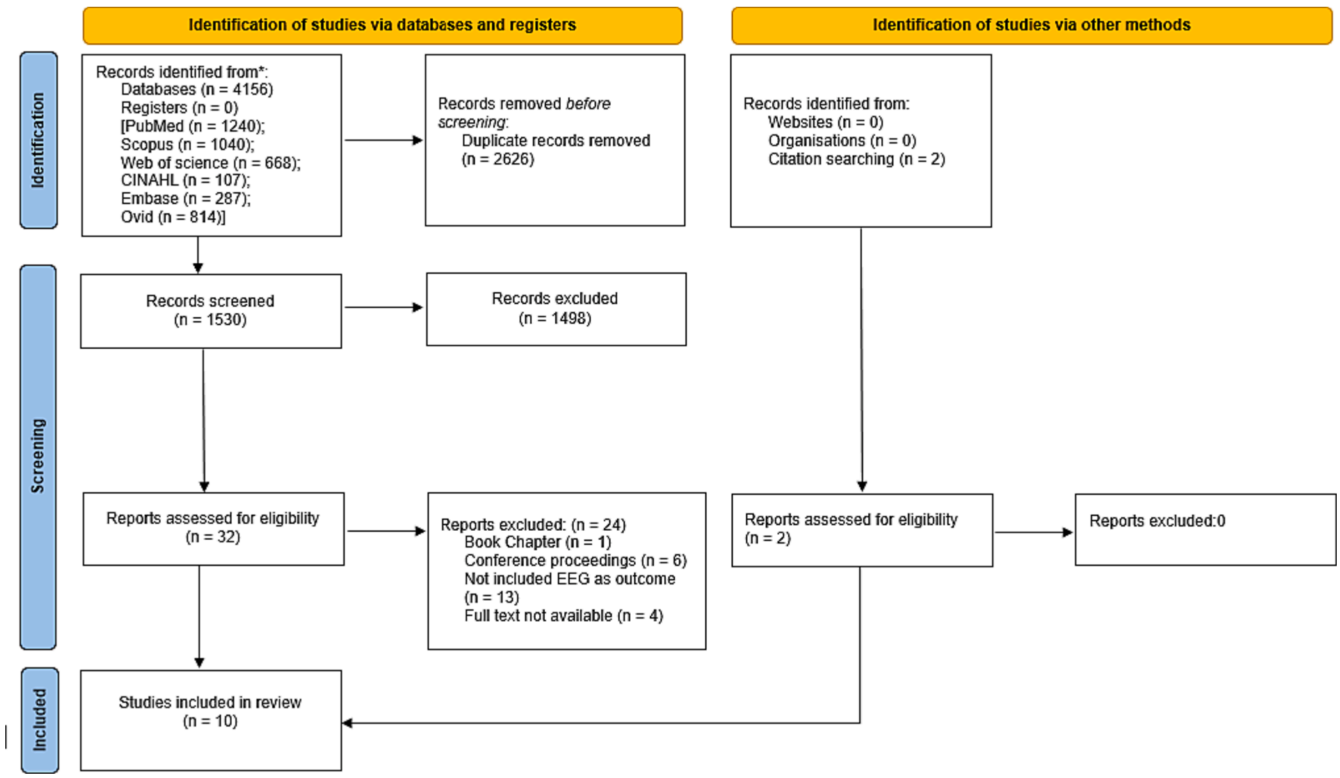

Fig. 1. PRISMA 2020 Flowchart.

3.1. Study characteristics

The studies were conducted in the USA (n = 5), Iran (n = 2), China (n = 2), and Canada (n = 1) [4,36–44]. The included articles' sample sizes ranged from 10 to 90 individuals. There were four RCTs [4,36,38,40], two single-blind cross-over studies [42,43], one single-blind sham-controlled pilot study [41], a sham-controlled experiment [44], one experimental design [39], and one within-subject sham-controlled design [37]. (see Table 1).

3.2. Participants

The age range of the participants in the 10 studies was 18–70 years. Out of these, eight studies had included younger and middle-aged individuals with an age range of 18–41 years [4,36,37,39,40,42–44], and one study had included older individuals with an age range of 61–74 years [38] and one study had a wider age range of 18–70 years [41]. Nine studies had included both males and females but 1 study has not disclosed the sex [39].

3.3. Intervention

Different transcranial photobiomodulation devices were employed to deliver the intervention. Among the ten included studies, four studies used Model CG-5000 photobiomodulation, TX, USA [37,42–44], two studies used InGaAIP LED (Iranbargh, Tehran, Iran) [36,40], one study used Lite Cure-TPBM-1000 [41], one study used Vielight Neuro Gamma' (Neuro Gamma) [38], and two studies didn't mention any details of the PBM device [4,39].

The wavelength of PBM was 1064 nm in five studies [4,37,42–44], 850 nm in two studies [36,40], 810 nm in two studies [38,39] and 830 nm in one study [41]. In one study, two different wavelengths such as 1064 nm and 852 nm of tPBM were compared to find its effect on working memory capacity [4]. 1064 nm is considered to have good penetration whereas 852 nm is a good absorber therefore authors tried to find the optimal wavelength of tPBM by comparing these wavelengths [4]. The power density in two studies was 250 mW/cm^2 [42,43], two studies is 285 mW/cm^2 [36,40], whereas one study mentioned 257.4 mW/cm^2 [44]. The rest of the five studies, three studies documented the power density between 100 and 200 mW/cm^2 which is 167 mW/cm^2, 162 mW/cm^2, and 100 mW/cm^2 [4,37,38]. The remaining two studies reported below 100 mW/cm^2, that is 30.65 mW/cm^2 and 54.8 mW/cm^2 [39,41].

Treatment duration varied from a minimum of 2.5 min to a maximum of 30 min. Three studies had given tPBM for 8 min [42–44]. Two studies mentioned the treatment time as 2.5 min [36,40] and two other studies documented it as 20 min [38,41]. The remaining three studies applied tPBM for 11 min, 12 min, and 30 min [4,37,39]. Nine studies delivered only one session of active tPBM [4,36–40,42–44], whereas one study documented three sessions of tPBM including continuous, sham, and pulsed tPBM [41].

Five studies applied tPBM on the forehead of which four were on the right forehead [37,42–44] and one was at the center [39]. In two studies tPBM was applied on the right frontopolar area [36,40], one study applied PBM transcranially and intranasally [38], one study delivered NIR light to four EEG sites targeting frontal poles and dorsolateral prefrontal cortex [41] and one study delivered tPBM only to the prefrontal cortex [4]. The forehead was the preferred location for tPBM application by many authors as it is found to improve cognitive function and local oxygen metabolism [37,44]. (see Table 2).

3.4. Comparator

Nine studies had sham-controlled comparators [4,36–38,40–44], and one study had four experimental groups (having different frequencies of tPBM) and one control group as a comparator [39].

3.5. Adverse events

Seven articles have not mentioned adverse or side effects

Table 1
Characteristics of the study.

Author	Year	Country	Objectives	Age	Sex	Study Design	Sample Size
Ali Jahan et al. [36]	2019	Iran	To investigate the possible electrophysiological changes of the brain associated with transcranial LED PBM by using qEEG in healthy people	21 ± 2 years of age	15 males 15 females	Experimental design	30
Wang et al. [37]	2019	USA	To investigate if transcranial photobiomodulation with 1064-nm laser modulates brain electroencephalogram rhythms	26.8 ± 8.8 years of age	13 males 7 females	Within-subject, sham-controlled design	20
Reza Zomorrodi et al. [38]	2019	Canada	To analyze objective data to understand the effect of a selected pulse frequency of 40 Hz and other PBM parameters on neural activity	Mean age 68.00 ± 5.94 years of age Range 61–74 years of age	9 males 11 females	randomized, sham-controlled, double-blinded trial	20
Liuye Yao et al. [39]	2020	China	To determine whether and how different frequencies of the NIR LED light affect brain activity by evaluating the relative energy and gravity frequency of EEG signals	22 to 26 years of age	Not reported	Experimental design	50
Amirhossein Ghaderi et al. [40]	2021	Iran	Effects of transcranial neuromodulation on synchrony and complexity of functional brain networks	Sham: 21.31 ± 2.21 years of age Test: 21.21 ± 2.57 years of age	20 males 20 females	Experimental design	40
Vincenza Spera et al. [41]	2021	USA	To assess whether transcranial photobiomodulation with near-infrared light modulates cerebral electrical activity through EEG and CBF	18–70 years of age	4 males 6 females	Single-blind sham-controlled pilot study	10
XinlongWang et al. [42]	2021	USA	This study hypothesized that tPBM-induced and heat-induced alterations in EEG power topography were significantly distinct	Sham-controlled tPBM condition: 26 ± 8.8 years of age sham-controlled thermo_stim condition: 29 ± 8.8 years of age	Sham-controlled tPBM condition: 30 males 19 females sham-controlled thermo_stim condition: 8 males 6 females	Single-blind, cross-over study	Sham-controlled tPBM condition: 49 sham-controlled thermo_stim condition: 14
Sadra Shahdadian et al. [43]	2022	USA	To identify key cortical regions that present significant changes caused by tPBM in the EEG oscillation powers and functional connectivity in the healthy human brain	26 ± 8.8 years of age	30 males 19 females	Single-blind cross-over study design	49
Xinlong Wang et al. [44]	2022	USA	Hypothesized that gSVD in conjunction with eLORETA enabled to identify (a) human EEG networks on the 2D sensor and 3D source space and (b) their responses to the 1,064-nm tPBM on the right forehead of healthy humans	Females of 27.4 ± 6.1 years of age Males of 28.7 ± 4.7 years of age	30 males 19 females	Sham-controlled experimental protocol	49
Zhao et al. [4]	2022	China	To investigate whether individual visual working memory capacity and related neural response could be modulated	Experiment 1: 22 years Experiment 2: 22.753 ± 3.750 years Experiment 3: 22.655 ± 4.050 years Experiment 4: 22.808 ± 3.95 years	Experiment 1: 22 females, 5 males Experiment 2: 7 males Experiment 3: 8 males Experiment 4: 7 males	Active and sham, randomized, double-blind design	Total: 90 Experiment 1: 27 Experiments 2–4: 21

qEEG quantitative electroencephalography, **nm** nanometers, **Hz** hertz, **NIR** near-infrared, **LED** light emitting diode, **EEG** electroencephalography, **CBF** cerebral blood flow, **tPBM** transcranial photobiomodulation, **thermo stim** thermal stimulation, **gSVD** group singular value decomposition, **eLORETA** exact low-resolution brain electromagnetic tomography.

[4,36,37,40,42–44]. Two articles have reported no adverse events [38,39]. However, one article has reported adverse events among three subjects which were drowsiness, weakness, trouble concentrating, blurred vision, and nausea/vomiting [41].

3.6. Outcomes

EEG measures described in the included studies:

3.6.1. Delta

Delta waves have frequencies ranging from 1 to 4 Hz. These waves are found in deep sleep conditions. Uncontrolled delta waves are commonly observed in brain disorders, learning problems, and severe attention deficit hyperactivity disorder (ADHD) [45].

Eight studies have reported the effects of tPBM on delta waves [36–40,42–44]. One study found a significant decrease in the absolute and relative power of the delta band after receiving 850 nm transcranial near-infrared PBM on the right prefrontal cortex ($p < 0.05$) [36]. One study found significant differences between tPBM and sham group ($t = -3.513$, $p < 0.01$) [38]. In the other two studies, a significant reduction was seen in delta power during tPBM session and the recovery period but there was no difference found in delta power between tPBM and thermo stimulation [42,43]. There was no significant modulation seen in delta power with tPBM treatment in the other four studies [37,39,40,44].

3.6.2. Theta

Theta waves are a kind of brainwave that is frequently recorded in EEG. They are distinguished by their frequency range, which spans from 4 to 8 Hz. Theta waves are mostly seen in the hippocampus, a brain area important for learning and memory [46,47]. It has been connected to cognitive functions like working memory, attention, and spatial navigation [47–49]. Additionally, abnormalities in theta wave activity have

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Table 2
Effect of transcranial photobiomodulation on EEG.

Author, year	Photobiomodulation parameters						Comparator group information	Outcomes	EEG parameters	Results
	Device name	Wavelength	Power	Duration	Number of sessions	Area				
Ali Jahan et al. 2019 [36]	Iranbargh, Tehran, Iran	850 nm	power density was 285 mW/cm^2.	2.5 mins	Single	Fp2 (According to the 10/20 international standard system)	Sham 5 s light irradiation for each 1-min of the treatment	EEG Parametric Go/No-Go task	Ten-minute eyes-open resting EEG was recorded from electrodes in the linked-ears referential montage. The sampling rate was 256 Hz and a band-pass filter was applied between 0.5 and 30 Hz on the signal. Impedances of all electrodes were kept below 5 kΩ	There was a decrease seen in the delta band after real-PBM irradiation in all regions ($p = 0.02$). Also, posthoc analysis showed a significant increase in the absolute power of the delta band in all regions after sham-PBM ($p = 0.04$)
Wang et al. 2019[37]	Continuous-wave laser (Model CG-5000 Laser, Cell Gen Therapeutics LLC, Dallas, Texas)	1064 nm	2200 mW Power density: 0.162 W/cm2 Energy density: 107 J/cm2	11 min	2 sessions - both active and sham stimulations on the same day, with sham taken first, followed by active stimulation	13.6 cm2 Right forehead	Within-subject sham control	EEG	64-channel scalp electroencephalogram	The effect size map showed tPBM increases the strength of electrophysiological oscillations (alpha (8–13 Hz) and beta (13 to 30 Hz) bands) with a very large size effect. No significant change was found in the delta and theta bands
Reza Zomorrodi et al. 2019 [38]	'Vielight Neuro Gamma' (Neuro Gamma)	810 nm	The power density of LED on the anterior band is 100 mW/cm^2 (transcranial)	20 min	1 session	Transcranial and intranasal	Sham tPBM	**EEG-** power spectrum analysis, Brain functional connectivity and synchrony	The EEG signals were recorded using the DISCOVERY 24E (Brainmaster Inc.) at a 256 Hz sampling rate and a bandwidth of 0.43–80 Hz. 19-Channel EEG free-cap set was used (Institut für EEG-Neurofeedback), which allows EEG to be recorded during tPBM delivery	A comparison between the active and sham groups presented significant differences in delta ($t = -3.513p < 0.01$), theta ($t = -3.736p < 0.01$), alpha ($t = 4.455p < 0.01$), beta ($t = 3.221p < 0.01$), and gamma ($t = 2.658$, $p < 00.1$) frequency bands After active tPBM treatments, the global efficiency of the network changed mostly in the alpha band for 50–60 %, 75 %, and 85–90 % sparsity levels, and in the gamma band for 15 %, 50–60 %, 70–75 %, and 90 % sparsity levels. The global efficiency in sham conditions did not change in any frequency band
Liuye Yao et al. 2020 [39]	–	810 nm	Power density 30.65 mW/cm2	30 min	Single	Forehead	Four experimental groups The LED flicker frequencies of the four stimulation experiments were 0 Hz, 5 Hz,	EEG - gravity frequency (GF), the relative energy, and sample entropy	Thirty-two channels of Ag/AgCl electrodes were placed on the scalp according to the expanded international 10–20 montage system for EEG measuring and recording.	The amplitude of alpha waves' relative energy increased ($p < 0.001$), while theta waves decreased remarkably in the experimental groups ($p < 0.02$), and the extent of increase/decrease was larger at higher stimulation

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Table 2 (*continued*)

Author, year	Photobiomodulation parameters						Comparator group information	Outcomes	EEG parameters	Results
	Device name	Wavelength	Power	Duration	Number of sessions	Area				
							10 Hz, and 20 Hz, respectively. 1 control group			frequency, compared to that of the control. A larger frequency of the NIR LED light would cause more distinct brain activities in the stimulated areas
Amirhossein Ghaderi et al. 2021 [40]	InGaAlP LED (Iranbargh, Tehran, Iran)	850 nm	Power density 285 mW/cm^2 The energy density of 42.75 J/Cm^2	2.5 mins	Single	Right frontopolar area (Fp2 according to the 10/20 international standard system)	Sham	EEG	via 19 EEG channels, according to the 10/20 EEG standard system	The false discovery rate analysis did not show any significant difference between the two groups in relative changes of alpha, delta, and beta1 bands. A significant difference in eigenvector centrality was observed in the right hemisphere electrodes ($t = 2.21$, $p = 0.030$) in the beta2 band
Vincenza Spera et al. 2021 [41]	TPBM-1000	830 nm	54.8 mW/cm^2	20 min	Three sequential sessions, separated by at least one week	Frontal poles and dorsolateral prefrontal cortex	Sham	EEG, Cerebral blood flow, and DCS (diffuse correlation spectroscopy)	Twenty-channel monopolar EEG	c-tPBM significantly increased gamma ($t = 3.02$, $p < 0.02$) and beta ($t = 2.91$, $p < 0.03$) EEG spectral powers in eyes-open recordings and gamma power ($t = 3.61$, $p < 0.015$) in eyes-closed recordings. Differences were not significant in the alpha and beta bands
XinlongWang et al. 2021 [42]	Model CG-5000 Laser, Cell Gen Terapeutics LLC, Dallas, TX, USA	A continuous-wave (CW) 1064-nm laser	Power of 3.5 W	Consisted of a 2-min baseline, an 8-min tPBM, and a 3-min recovery period	Each subject took both active and sham tPBM within 1 week, with a minimum of 3 days between two measurements	Right forehead	Sham controlled tPBM	EEG	64-channel time series	Baseline-normalized, sham-subtracted tPBM neuromodulated delta, alpha, and beta oscillations in an eyes-closed resting state
Sadra Shahdadian et al. 2022 [43]	Model CG-5000 Laser, Cell Gen. Therapeutics LLC, Dallas, TX, USA	1064 nm	On scalp : 250 mW/cm^2 On cortex: ~2.5 mW/cm^2	2 min baseline (pre), an 8 min stimulation (tPBM or sham), and a 3 min recovery (post) period	Single session Each subject completed both sham and active tPBM experiments in a random order.	Right forehead, with an aperture of 4.2 cm in diameter	Sham	EEG	64-channel EEG instrument	There was an increase in alpha ΔmPowers seen in the bilateral frontal and left parietal-occipital regions and an increase in beta ΔmPowers was mainly seen in the central/parietal region of the scalp. There was a reduction in delta power in the frontal, left temporal, and occipital regions during tPBM, and in the right frontal region during recovery

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Table 2 (*continued*)

Author, year	Photobiomodulation parameters						Comparator group information	Outcomes	EEG parameters	Results
	Device name	Wavelength	Power	Duration	Number of sessions	Area				
Xinlong Wang et al. 2022 [44]	(Model CG-5000, Cell Gen Therapeutics LLC Dallas, TX, United States)	1064 nm	257.4 mW/cm2	8 min	Single	tPBM or sham was delivered on the right forehead above the eyebrow and below the hairline	Sham	EEG	A 64-electrode 10–10 EEG system (Biosemi Inc., Barcelona, Spain) was employed to non-invasively record EEG readings	tPBM-induced increases in alpha powers occurred at the default mode network, executive control network, frontal parietal network, and lateral visual network. It was found that the right forehead, 1,064-nm tPBM could neuromodulate the alpha and gamma powers on several of the gSVD-derived EEG brain networks
Zhao et al. 2022 [4]	Not mentioned	Experiment 1: 1064 nm Experiment 3: 852 nm	2271 mW Power density: 167 mW/cm2	12 min	2 different sessions of tPBM separated by a week between sessions, with sham or active tPBM	13.57 cm2 Prefrontal cortex	Sham control	Classical change detection task along with EEG	EEG amplifier and the Curry 8.0 package (NeuroScan, Inc.) from a Quick-cap with 64 silver chloride electrodes arranged according to the international 10–20 system.	1064 nm tPBM applied on the right prefrontal cortex can improve visual working memory capacity

Fp2 right frontal pole EEG, **EEG** electroencephalography, **tPBM** transcranial photobiomodulation, **c-tPBM** continuous transcranial photobiomodulation, **GF** gravity frequency, **NIR** near-infrared, **FDR** false discovery rate, **DCS** diffuse correlation spectroscopy, **ΔmPowers** mean percent changes in power.

been linked to several neurological and psychiatric conditions, such as schizophrenia, Alzheimer's disease, and depression [50,51].

A total of six studies reported the theta band power changes after the application of tPBM [37–40,42,44]. Among these three studies mentioned that there is no significant change in theta band [37,42,44]. However, two studies reported a decrease [39,40] and one study mentioned the increase in theta power followed by tPBM application [38]. In the theta band, right hemisphere centrality was considerably reduced following tPBM compared to sham, although left hemisphere centrality was unchanged. In addition, no significant differences in single electrodes and other network properties were found between the two groups [40]. Theta wave amplitude decreased significantly in the experimental groups ($p < 0.02$), and the magnitude of the decrease was greater with higher stimulation frequency compared to the control group [39]. Suppression in the increase in the theta power was observed in the active tPBM group compared to the sham group. Overall, a significant decrease in theta band was found between the active and sham group ($t = -3.736$; $p < 0.01$) [38].

3.6.3. Alpha

Alpha waves have a frequency of 8–13 Hz. It is found to be associated with alertness, awareness, and brain processes associated with cognition such as attention, memory encoding, and synchronization of the brain network [52–56]. These waves are substantially altered during cognitive functions and play a crucial part in communication between various brain rhythms [57–59].

Nine studies considered alpha frequency in reporting of EEG [36–44]. Out of these, eight studies have reported the effect of tPBM on alpha waves [37–44]. Six studies have noted an increase in the alpha EEG activity post tPBM [37–39,42–44]. tPBM of 1064 nm on the right forehead significantly increased the alpha power, whereas thermal stimulation caused contrasting effects on the EEG topographic patterns [42]. Frontal tPBM caused improvement in EEG power which was noted over the frontoparietal regions of the alpha band [43]. tPBM of 1064 nm wavelength induced alpha power enhancement happened at default and executive control modes, and lateral visual and fronto-parietal networks [44]. Alpha relative energy is one of the important EEG signal parameters. Post near-infrared light (NIR) LED light stimulation, alpha relative energy amplitudes increased ($p < 0.02$). The increase in alpha waves' relative energy was dependent on the stimulation frequency [39]. Following a single session of tPBM there was an increase noted in higher frequency bands and substantial changes in centro-frontal areas for alpha power. (t value > 3; $p < 0.05$) [38]. Post tPBM, the laser-induced increase of EEG activity was frequency dependent as the strength of alpha bands electrophysiological oscillations was increased. Also, as the strongest increase in the alpha oscillation power was during the first 8–11 min of laser, it shows the time- dependency [37]. When compared to the sham control, tPBM had a very large effect on alpha power ($|d| > 1.2$) [37].

One study did not conclude a clinically significant boost in EEG alpha spectral density in eyes open and eyes closed conditions at rest post continuous tPBM [41]. Another study concluded that post-tPBM, there were no significant changes in the relative alpha network between the sham and experimental groups [40].

3.6.4. Beta

The frequency of Beta waves ranges between 12 and 30 Hz and is most typically seen in the frontal and central brain areas. They can also be found in other areas of the brain, such as the parietal and temporal lobes [60]. Beta waves may be involved in various cognitive abilities, such as working memory, attention, and executive function, as well as the suppression of undesirable emotions, implying that they may be involved in motor control [61–65].

Eight studies reported the impact of tPBM on beta wave power [37–44]. Six studies documented that there was an increase in the beta power among the tPBM group when compared to the sham or no

Table 3
JBI Critical Appraisal for Randomized Controlled Trials.

Sl. No.	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Total Score	% of yes	Interpretation
Jahan, 2019[36]	No	No	Yes	Unclear	Unclear	Yes	Unclear	Yes	Yes	NA	Yes	Yes	Unclear	6	50 %	Moderate risk of bias
Zomorrodi,2019 [38]	No	No	Unclear	Yes	Unclear	Unclear	Yes	Yes	Yes	NA	Yes	Unclear	Yes	6	50 %	Moderate risk of bias
Ghaderi, 2021 [40]	No	No	Yes	Unclear	Unclear	Yes	Unclear	Yes	Yes	NA	Yes	Yes	Unclear	6	50 %	Moderate risk of bias
Zhao, 2022 [4]	No	No	Unclear	Yes	Yes	Yes	Unclear	Yes	Yes	NA	Yes	Unclear	Unclear	6	50 %	Moderate risk of bias

Q1. Was true randomization used for assignment of participants to treatment groups? **Q2.** Was allocation to treatment groups concealed? **Q3.** Were treatment groups similar at the baseline? **Q4.**Were participants blind to treatment assignment? **Q5.**Were those delivering the treatment blind to treatment assignment? **Q6.** Were treatment groups treated identically other than the intervention of interest? **Q7.** Were outcome assessors blind to treatment assignment? **Q8.** Were outcomes measured in the same way for treatment groups? **Q9.** Were outcomes measured in a reliable way **Q10.** Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed? **Q11.** Were participants analysed in the groups to which they were randomized? **Q12.** Was appropriate statistical analysis used? **Q13.** Was the trial design appropriate and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial? **NA** not applicable.

treatment group [37,38,40–43]. However, one study implied that there was no significant modification in beta power followed by tPBM [44]. There was no obvious change seen in the beta waves in another study [39].

During the last 4 min of tPBM, the change in power topographic values in beta frequencies following sham subtraction was dramatically improved. Namely, the sham-free beta enhancement power changes were most noticeable in the central area of the brain. tPBM-induced power increases were substantially greater than thermostimulation induced power changes in the beta waves during and post 2-min laser irradiation [42]. Continuous tPBM (c-tPBM) significantly increased beta EEG spectral powers in recordings while eyes were open ($t = 2.91$, $df = 7$, $p < 0.03$), with a broad rise across frontal-central scalp areas [41]. Frontal tPBM raised EEG beta powers in frontal, parietal, and central regions, increased the complexity of the global beta-wave brain network, and improved local information flow and beta oscillation integration across prefrontal cortical regions. During the recuperation period, the large rise in beta power change stopped [43]. In one study tPBM significantly decreased the centrality of the right hemisphere beta band compared to the sham group. tPBM also reduced the synchronizability of the brain network and enhanced the complexity of the resting state network in the beta band [40]. A single tPBM session greatly enhanced the higher beta frequencies in the resting state. Almost all of the electrodes showed substantial increases in the beta (*t*-value > 7, $p < 0.05$). Higher oscillatory beta frequency bands significantly increased in the centro-frontal areas (*t*-value > 3, $p < 0.05$) [38]. The recovery period showed statistical differences in beta bands in several scalp regions suggesting beta to have large effects ($|d| > 0.8$) [37].

3.6.5. Gamma

Gamma waves have neural oscillations frequency between 30 and 70 Hz. It is the fastest brain wave that contributes to many mental processes, including motor control, perception, focus, memory, awareness, and synaptic plasticity [66].

Five articles have included gamma waves in EEG findings [37,38,41,42,44]. Continuous tPBM with near-infrared considerably increased the power spectral density of gamma power in recordings with eyes open ($t = 3.02$, $df = 7$, $p < 0.02$) and eyes closed ($t = 3.61$, $df = 6$, $p < 0.015$) [41]. One study observed a significant increase in the gamma band between pre and post active tPBM ($t > 7$, $p < 0.05$). It also reported a significant global change in gamma power between post active and sham tPBM ($t > 3$, $p < 0.05$). Overall, a comparison between the active and sham group found a significant increase in the gamma band ($t = 2.658$, $p < 0.01$) [38]. Two studies suggest that there was no statistical difference in the gamma power when compared to the thermostimulation and sham PBM [37,42]. One study showed a significant reduction in gamma power by tPBM [44].

3.6.6. Contralateral delayed activity (CDA)

Only one article studied the effect of tPBM on CDA. This study reported that occipito-parietal CDA increment was stronger with active tPBM when the visual working memory changed from low- to high load [4].

3.7. Critical appraisal of the included studies

The 4 RCTs had a moderate risk of bias scoring 50 % each on the JBI critical appraisal tool [4,36,38,40]. The JBI critical appraisal for 6 non-randomized experimental studies are as follows: 1 article presented "moderate risk of bias" with a percentage of 62.5 % [39], 1 article reported "low risk of bias" with a percentage of 75 % [37], and the other 4 articles reported "low risk of bias" with a percentage of 87.5 % each [41–44]. (see Tables 3 and 4).

Table 4
JBI Critical Appraisal for non-randomized experimental studies.

Sl. No.	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Total	% of yes	Interpretation
Wang, 2019 [37]	Yes	Yes	Unclear	Yes	Yes	NA	Yes	Yes	Unclear	6	75 %	Low risk of bias
Yao, 2020 [39]	Yes	Unclear	Unclear	Yes	Yes	NA	Yes	Yes	Unclear	5	62.5 %	Moderate risk of bias
Spera, 2021 [41]	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes	Unclear	7	87.5 %	Low risk of bias
Wang, 2021 [42]	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes	Unclear	7	87.5 %	Low risk of bias
Shahdadian, 2022 [43]	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes	Unclear	7	87.5 %	Low risk of bias
Wang, 2022 [44]	Yes	Yes	Yes	Yes	Yes	NA	Yes	Yes	Unclear	7	87.5 %	Low risk of bias

Q1. Is it clear in the study what is the 'cause' and what is the 'effect'? **Q2.** Were the participants included in any comparisons similar? **Q3.** Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest? **Q4.** Was there a control group? **Q5.** Were there multiple measurements of the outcome both pre and post the intervention/exposure? **Q6.** Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed? **Q7.** Were the outcomes of participants included in any comparisons measured in the same way? **Q8.** Were outcomes measured in a reliable way? **Q9.** Was appropriate statistical analysis used? **NA** not applicable.

4. Discussion

This review aimed to scope evidence on the tPBM effect on electrophysiological activity in healthy individuals. The current review included ten studies consisting of randomized and non-randomized studies. The effect of tPBM on the electrophysiological activity of the brain was mainly evaluated using EEG in the studies.

Six studies have shown to increase the alpha EEG activity post tPBM [37–39,42–44]. Out of which one RCT had a moderate risk of bias [38] and five non-RCTs had moderate to low risk of bias [37,39,42–44]. The possible enhancement in alpha activity with tPBM could be due to the following reasons. Neuromodulation of the frontoparietal network post tPBM and antero-posterior network stimulation which rapidly assists instantiation of any new tasks by coordinating with various processing networks, could be the cause for improvement in human cognition post tPBM [67]. Hence improving the alpha power may cause potential benefits to human cognitive functions [68,69]. Alpha EEG waves are linked with memory, and it has been found that those with enhanced memory had increased frequencies of alpha [53,70]. Pulsed infrared transcranial and intranasal PBM has shown a positive effect on the higher frequency EEG alpha bands due to its possibility of increasing the organization of the neural function by activating the default mode network [71,72]. However, tPBM given to the medial right frontal pole could not significantly change the default mode network activity as there is a correlation noted between the alpha activity and default mode network activity [73,74]. Future research could be done to further study the influence of tPBM on the default mode network activity.

Overall tPBM showed a promising effect on beta oscillations in the six identified studies [37,38,40–43]. The rise in beta power was mostly noticed in one cluster of electrodes in the central/parietal area. tPBM enhances the intensity of electrophysiological oscillations of beta bands, as well as gives information on the working of tPBM in the brain [37]. tPBM capacity to control or synchronize beta oscillations in the frontoparietal network may be strongly related to the electrophysiological mechanism [75,76]. Frontal tPBM's beneficial effect on human cognition can be connected to its substantial electrophysiological alterations of beta power in the frontoparietal circuitry [41]. A decrease in the beta power in the right hemisphere shows a decrease in centrality followed by PBM. Since the right hemisphere has a role in negative emotions, one can conclude that PBM will improve the positive emotions in participants [77–79]. Frontal tPBM strengthened frontal-central-parietal EEG alpha and beta powers, increased the level of complexity of the global beta-wave network, and improved local communication and beta oscillation integration across prefrontal cortical regions. This study contributes to knowledge about the putative link between electrophysiological alterations and tPBM-induced cognitive improvement [40].

Overall effects of tPBM on gamma waves were mixed and inconclusive. Considering gamma oscillations, there is a link noted between mitochondrial function and the gamma band fast neural oscillations. Gamma activity is thought to be caused by the interaction between the cortical inhibitory interneurons and the excitatory principal neurons. The high metabolic demand due to the high interneuron firing rates which is required to synchronize the function of principal neurons, may be linked to the higher levels of mitochondrial cytochrome *c* oxidase (CCO) in these cells compared to the principal neurons. tPBM is targeted to stimulate the CCO, hence causing an enhancement in the gamma oscillations [80–83]. A study conducted by Wang et al. 2022 concluded that there was a significant decrease in gamma power by tPBM which seems to be contradictory because the application of group singular value decomposition was able to decompose 11 networks from EEG signals which resulted in detecting the reduction in gamma power [44].

Overall results of tPBM on delta waves were mixed and inconclusive. Modulation or decrease in delta power might help in promoting cognitive functions. Only a few studies reported the reduction of delta power with the use of t PBM. This reduction could be due to the heating effect of transcranial PBM as it did not show any difference compared to thermostimulation [42]. Lower slow frequencies are seen in high-vigilance individuals and during an increased state of wakefulness [84,85]. Increase in slow wave generation is also associated with hypoxia of the brain and a decrement of blood flow in conditions like stroke and cerebral infarction [86].

The six studies which reported on theta band had a low to moderate risk of bias [37–40,42,44]. Out of these, three studies did not show any improvement post 1064 nm tPBM [37,42,44]. Power spectrum analysis, event-related potentials, and coherence analysis are all methods for measuring and evaluating theta waves in EEG recordings. These techniques enable researchers to investigate the temporal and spatial features of theta [46]. The activity of theta is highly correlated with the central executive and attentional network [87]. Additionally, visual working memory enables us to actively store, update, and change visual information that surrounds us. CDA is sensitive to the number of objects maintained in visual working memory [88]. Potentially, tPBM with low irradiance may require multiple sessions and a longer follow-up period to have a beneficial impact on cognition.

Eleni Magkouti et al. 2023, concluded that the use of tPBM increases high-frequency neural oscillations and inhibits low-frequency activities through a systematic review. In contrast, this scoping review found the use of tPBM on low-frequency neural oscillations inconclusive. This finding could be attributed to the fact that our scoping review had comparatively a greater number of included studies and had mixed findings. The review by Eleni Magkouti et al. 2023, had certain limitations such as only one database was searched which might have caused the missing out of relevant articles [89]. Another systematic review by Tsz-loklee et al. 2023, concluded that tPBM has a positive effect on the cognitive processes of healthy individuals and adults with cognitive impairment. This review evaluated the effect of tPBM on neurophysiological test outcomes only but not on EEG [10]. The observed effect of tPBM on alpha EEG frequency causing a cognitive enhancement in healthy individuals, can guide the understanding of the underlying mechanisms and potential application of tPBM in those with conditions such as traumatic brain injury, stroke, Parkinson's disease, Alzheimer's disease, anxiety, and depression. This might help identify the

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electrophysiological brain activity in these individuals which can be further investigated for future clinical intervention. tPBM may be a desired method to treat cognitive impairment and may potentially enhance cognitive performance in individuals with dementia and Alzheimer's disease. The change in sample entropy of EEG signals is stimulation frequency dependent, indicating that NIR LED light radiation is effective. These findings may open up new avenues for the advancement of phototherapy technologies. Modulation of gamma activity can be linked to higher-order cognition. tPBM can be used as an intervention for treating Alzheimer's disease. These findings have extensive implications for the field of neuromodulation with tPBM [41].

4.1. Limitations

The included studies had a few limitations. Many studies reported inadequate sample sizes. The results of the pilot study with a small sample size can only be considered preliminary. Hence, we are unable to determine with certainty if low-dose pulsed tPBM would affect brain oscillations. Electrode placement, EEG recording procedure, and a few statistical concerns were mentioned in a few studies. There are a few limitations of this review. The review was more focused on the alpha, beta, gamma, delta, and theta neural oscillations of EEG. No other clinical outcomes were assessed. The heterogeneity of the studies included could produce a bias and influence the conclusion. We could not analyze on the estimation of absorbed light energy by the cortex.

4.2. Recommendations

tPBM was found to modify the electrophysiological activity of the brain in healthy individuals. Therefore, based on this finding we recommend that further trial can be conducted on cognitive dysfunction and other neurological disorders. More robust RCTs are needed to determine the effect of tPBM on slow wave oscillations/low-frequency oscillations as the results were inconclusive. More studies are recommended to find out the effect of different parameters of PBM on the electrophysiological activity of the brain. A systematic review with meta-analysis can be carried out to quantify the effect of PBM on alpha and beta powers in the future.

5. Conclusion

tPBM has a promising effect in elevating the higher frequency oscillations such as alpha and beta waves which might help in improving cognitive functions, memory, attention, neural function, and emotions. This might be beneficial in treating many neurological conditions, anxiety, and depression. tPBM can be implemented in young and middle-aged healthy adults to prevent age-related cognitive decline in the future. Future studies are required to prove the effects of tPBM on lower-frequency electrophysiological oscillations.

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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Author contributions

AGM conceptualized and planned the scoping review. SSJ, SS, VP, and DS developed a search strategy and performed the searches on databases. SS, DS, SSJ, and VP screened articles to include in the review and extracted. AGM resolved discrepancies related to article inclusion and data extraction. SSJ, SS, VP, and DS prepared a preliminary draft. AGM critically reviewed the manuscript for its scientific content and analysis. The final manuscript was agreed upon by all the authors.

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