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INFERTILITY: REVIEW

A Comprehensive Systematic Review of the Effects of Photobiomodulation Therapy in Different Light Wavelength Ranges (Blue, Green, Red, and Near-Infrared) on Sperm Cell Characteristics in Vitro and in Vivo

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Abstract

Around 7% of the male population in the world are entangle with considerable situation which is known as male infertility. Photobiomodulation therapy (PBMT) is the application of low-level laser radiation, that recently used to increase or promote the various cell functions including, proliferation, differentiation, ATP production, gene expressions, regulation of reactive oxygen spices (ROS), and also boost the tissue healing and reduction of inflammation. This systematic review's main idea is a comprehensive appraisal of the literatures on subjects of PBMT consequences in four light ranges wavelength (blue, green, red, near-infrared (NIR)) on sperm cell characteristics, in vitro and in vivo. In this study, PubMed, Google Scholar, and Scopus databases were used for abstracts and full-text scientific papers published from 2003–2023 that reported the application of PBM on sperm cells. Criteria's for inclusion and exclusion to review were applied. Finally, the studies that matched with our goals were included, classified, and reported in detail. Also, searched studies were subdivided into the effects of four ranges of light irradiation, including the blue light range (400–500 nm), green light range (500–600 nm), red light range (600–780 nm), and NIR light range (780–3000 nm) of laser irradiation on human or animal sperm cells, in situations of in vitro or in vivo. Searches with our keywords results in 137 papers. After primary analysis, some articles were excluded because they were review articles or incomplete and unrelated studies. Finally, we use the 63 articles for this systematic review. Our category tables were based on the light range of irradiation, source of sperm cells (human or animal cells) and being in vitro or in vivo. Six% of publications reported the effects of blue, 10% green, 53% red and 31% NIR, light on sperm cell. In general, most of these studies showed that PBMT exerted a positive effect on the sperm cell motility. The various effects of PBMT in different wavelength ranges, as mentioned in this review, provide more insights for its potential applications in improving sperm characteristics. PBMT as a treatment method has significant effectiveness for treatment of different medical problems. Due to the lack of reporting data in this field, there is a need for future studies to assessment the biochemical and molecular effects of PBMT on sperm cells for the possible application of this treatment to the human sperm cells before the ART process.

Keywords Photobiomodulation therapy · Low-level laser therapy · Green light · Blue light · Red light · NIR light · Male infertility · Sperm cells · Semen

Abbreviations

AIPIHP	Acrosome and plasma membranes integrity and high mitochondrial membrane potential
AlGaInP	Aluminum gallium indium phosphide
ATP	Adenosine triphosphate
CCO	Cytochrome c oxidase
DFI	DNA fragmentation index
GaAlAs	Gallium aluminum arsenide
GSH/ GSSG	Glutathione
He–Ne	Helium–neon
IR	Infrared radiation
LEDs	Light Emitting Diode
LLLT	Low-level light therapy
MDA	Malondialdehyde
MIR	Mid-Infrared
miRNAs	MicroRNA
MMP ($\Delta\Psi m$)	Mitochondrial membrane potential

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mtNOS	Mitochondrial nitric oxide
NIR	Near infra-red
NO	Nitric oxide
PBMT	Photobiomodulation therapy
PKA	Protein kinase A
PKC	Protein kinase C
PSM	Progressive sperm motility
ROS	Reactive oxygen species
SCD	Sperm chromatin dispersion
SDH	Succinate dehydrogenase
Src	Proto-oncogene tyrosine-protein kinase
STZ	Streptozotocin
T1DM	Type 1 diabetes mellitus

Introduction

Male infertility is a multifactorial and pathological situation and nearly 7% of the male population in the world are entangled with it [1]. It was estimated that 70 million in the world and 9% of couples are struggling with infertility treatment and male factors contribute approximately 50% of it [2]. Ejaculatory ducts and epididymis obstruction, cryptorchidism, torsion and trauma of the testicles, varicocele, autoimmunity, and hormonal imbalance can be causes of male infertility [3]. In addition, chronic and untreated infections in the urogenital tract like urethritis, prostatitis, epididymitis, and orchitis could damage the spermatogenesis process and produce poor sperm quality situations that cause decreased viability, motility, and concentration of sperm cells. The presence of leukocytes in semen fluid can induce agglutination and reactive oxygen species (ROS) in inflammation situations and cause huge damage to sperm cells [4–6]. On the other hand, cancers, especially reproductive organ cancers, strongly affect male fertility. Moreover, treatments for it, including surgeries, radiotherapies, and chemotherapies, can cause destructive effects that are temporary or even permanent on fertility structures. To prevent these, routinely in cancers treatment, sperm cryopreservation is applied to maintain male fertility after cancer survival [7].

Furthermore, sperm cryopreservation has massively destructive biological effects, including severely decreased sperm motility and viability, acrosome and mitochondrial membrane destruction, an increase in ROS production, and even nuclear and DNA damages that rises in the cryopreservation process. Also, changes in miRNA regulation can happen during the freeze–thaw process [8], so as a suggestion irradiation of laser to reduce all those effects could be used. Dysfunction in mitochondrial performance is related to infertility, especially asthenozoospermia disorder. In other words, motility, capacitation ability and acrosome reactions of sperm are adjusted by mitochondrial actions like the production and regulation of ATP, Ca^{2+} and nitrogen oxide (NO) [9–11]. Oxidative stresses have severely harmful effects on the quality of sperm. A high ROS concentration is the main cause of oxidative stress. Rises in ROS in this condition can induce DNA damages, lipids peroxidation, and disorder in the infrastructure and function of sperm. However, normal or physiological amounts of ROS can regulate the intracellular cascades and mediate physiological actions like sperm maturation and sperm hyperactivation, acrosome reaction, sperm capacitation, and fertilization ability [11–15].

Low-level light therapy (LLLT) or its updated term photobiomodulation therapy (PBMT) mostly known as the irradiation of light at red or near-infrared (NIR) wavelengths (600–1000 nm). Applications of this therapy have grown rapidly in the last decade. Many factors, situations, and parameters, including fluency power, irradiance type, time of irradiation and repetition, pulsed or continuous model, and wavelength, are involved in PBMT effects [16]. Many studies suggest a comprehensive definition of PBMT as a kind of light therapy that can utilize the non-ionizing shape of light sources, including all laser types and Light Emitting Diode (LED)s, in the visible and infrared (IR) ranges [17]. The IR radiation subdivision, named NIR under the alternative classification provided in ISO 20473, refers to wavelength ranges between 780 and 3000 nm. That is between the red (600–780 nm) wavelength edge of visible lights and the mid-infrared (MIR, 3000–5000 nm) [16, 18]. In recent decades' various cellular repercussions to visible and NIR radiation have been studied for investigate the mechanisms of PBMT. Also, studies have state that, the reconciliation of mitochondrial signaling components like mitochondrial membrane potential (MMP or $\Delta\Psi m$), mitochondrial ROS and Ca^{2+} in under-irradiation cells, and the responses to irradiation in the nucleus (rise in DNA and RNA synthesis, expression of genes) are well documented [19]. Several studies have announced the effects related to enhanced mitochondrial activity, including rising ATP levels, ROS levels, and MMP ensuing the light irradiation [20, 21].

Cytochrome c oxidase (CCO) is an important photoreceptor and can be used to liberate the free nitric oxide (NO) [22]. It has been propounded that, PBMT operates on an electron transport chain in the mitochondrial membrane, especially on CCO, and could increase the efficiency of CCO proton pumping and catalyze it as well [23–25]. Cellular respiration is decreased by the fabrication of NO by mitochondrial NO synthase (mtNOS), which can attach to CCO and impede it. In the following, NO can displace oxygen from CCO, have an inhibiting effect on cellular respiration, and decrease the production of ATP. Some studies suggest that PBMT can causes the photo-dissociation of NO from CCO, which lead to reduce the mitochondrial inhibitory effects of NO. So it can be concluded that PBMT could increase the ATP production. These

effects are reportedly stronger with red light compared with some other wavelengths [26–29].

After PBMT in oxidative stressed cells, the level of ROS in this situation can decrease. PBM can up-regulate antioxidant defenses. At the same time, PBM causes the separation of NO from binding sites and leads to oxygen influx and respiration complete, which then generate ROS products, mostly in normal cells [30]. Studies suggest that small amounts of ROS are important mediators of cell activity [31, 32]. Production of ROS in PBMT has been observed in fibroblasts, sperm, and lymphocytes [33–35]. PBM can cause a rise in the Ca^{2+} elevation in cells. Increases in Ca^{2+} can initiate cellular signaling pathways. Thus, changes in Ca^{2+} after PBMT are an important part of the photobiostimulation effects [36–39]. In general, in many studies, PBMT was used to promote spermatozoa's metabolism, viability, and progressive and non-progressive motility, owing to its effective action on mitochondria by activating the mitochondrial respiratory chain for ATP production. PBMT can also enhance the spermatozoa survival rate and increase their movement, especially progressive motility after thawing frozen sperms or in immobile sperm samples. In addition, in patients who struggle with vesiculitis and prostatitis, PBMT can diminish infiltrative-exudative changes and enhance reproductive functions, that could causes promotion in sperms motility [40–42]. PBMT not only improves sperm motility, but can also act as a stimulator for antioxidant defenses and increase the fertility power of sperm in male infertility disorders. Results from expansive studies in this field suggested that temperate levels of red and NIR irradiation cause stimulator results with non-significant DNA damage, and a decrease in ROS production also positive effects on the population of germ cells [43, 44].

In the absence of review studies comprehensively assessing all ranges of Photobiomodulation (PBM) and LED collectively, our systematic review aimed to present the findings of studies examining the effects of PBMT on actions and characteristics in both human and animal sperm samples, both in vitro and in vivo. In this study, we meticulously collected, categorized, and summarized relevant research conducted between 2003 and 2023 in six tables. These tables were organized based on light wavelength range (blue, green, red, NIR), sample source type (human or animal), and application type (in vitro or in vivo), providing detailed insights into various radiation and sample parameters. The outcomes of this study have the potential to offer novel perspectives for enhancing current PBMT methods on sperm cells.

Materials and Methods

The databases used in this study were PubMed, Google Scholar, and Scopus. In search, we use the following keywords in combination: photobiomodulation, low laser therapy, green light, blue light, red light, NIR light, male infertility, sperm cells and semen. The relevant articles were studies that in vitro or in vivo examined the impact of PBMT on sperm cells. The inclusion criteria were relevancy of topics, subjects and methods, availability of achieve to full-text articles, English language, and publication from 2003 to 2023. Initially, we selected articles based on a review of titles and abstracts, and those that had nonrelated titles or abstracts to our aims were excluded. Also, the papers whose abstracts were unmatched with the theme or didn't deliver proper data for a complete assessment were excluded. The quality of provided data was analyzed for randomization, conflict of interest, blinding, and ethical approve and each of these items in the article, 25% was added to the quality of the study option. For prevent the bias and increase the quality of investigation, two reviewers were reviewed and assessment the quality of the selected articles according to our exclusion and inclusion criteria. Also, data extraction process was achieved by one reviewer and double-checked by the second one. Finally, the studies that match our goal were included, classified and reported in detail. In addition, to enrich our searches, the references in related articles were checked. All the searched studies were subdivided into the effects of four ranges of light irradiation, including the blue light range (400–500 nm), green light range (500–600 nm), red light range (600–780 nm), and NIR light range (780–3000 nm) of laser irradiation on human or animal sperm cells, in situations of in vitro or in vivo.

Results

Our searches in online databases with the keywords "photobiomodulation, low laser therapy, green light, blue light, red light, NIR light, male infertility, sperm cells, and semen" resulted in 137 papers. After primary analysis, 91 articles were selected for this study. 23 of these articles were excluded because they were review articles or incomplete and unrelated studies. Finally, we use the 68 articles for this systematic review. Our category was based on the light ranges of irradiation (blue, green, red, NIR), provided source of sperm cells (human or animal cells) and situation of in vitro or in vivo. In this regard, four articles used the blue range (400–500 nm) type of laser irradiation (Table 1), seven articles used the green range (500–600 nm) (Table 2), 34 articles used the red range (600–800 nm) (Table 3), and 12 articles used the NIR range (up to 800 nm) type of laser (Table 4) on human and animal sperms in vitro. On the other hand, two articles used red lasers (Table 5) and nine articles used NIR range lasers (Table 6) on human and animal sperm in vivo. (Seven of these studies used more than one laser with different types of irradiation light range).

Table 1 Blue range wavelength (400–500 nm) laser irradiation on sperm cell, in vitro

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/frozen, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
Human	*H.B.Frangez* et al. *2015*	LED 470 nm	Continuous 10 cm	——5.06 mW/cm^2	—— 3 min	Fresh Astheno	Increased Increased	—— ——	PBM can promote the motility in astheno-zoospermic patients regardless of the wavelength [45]
	S.Mohammed et al. *2021*	LED 410 nm	Continuous 30 cm	100 mW 0.67 mW/cm^2	—— 60 s	Fresh Astheno	Increased ——	—— ——	Low level laser of 410 nm wavelength cause increase in sperm motility for a short period of time [46]
Animal	*R.Ankri et all. 2010*	LED 400–500 nm	Continuous ——	—— 78 mW/cm^2	—— 300 s	Fresh Bovine	—— ——	—— Increased	Blue light illumination was found to increases NO concentration in sperm cells and also can be more effective than red lights [47]
	D.J.Miranda et al. *2017*	Solid-state 405 nm	Continuous ——	70 mW ——	4, 6 J/ cm^2 60 s, 90 s	Frozen Rabbit	Improve ——	—— ——	Low laser irradiation is a suitable technique to use in spermatic photobiostimulation and it was enough to foment sperm motility [48]

LED: light emitting diode, *Astheno*: asthenozoospermia, *NO*: nitric oxide

Table 2 Green range wavelength (500–600 nm) laser irradiation on sperm cell, in vitro

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/ cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
Human	*Q.A.Jasim* et al. *2022*	—— 532 nm	Continuous ——	54 mW 1.719 mW/cm^2	—— 10,20,30 min	Fresh Oligo/Astheno	Increased ——	—— ——	Laser increase energy for sperm motility more than other technique and it can activate ATP secretion by mitochondria and enhance the sperm motility [49]
Animal	*V.Plavskii* et al. *2020*	Nd:YAG 532 nm	Continuous 5.5 cm	5–300 mW 0.5–30 mW/cm^2	—— 5s-10 min	Fresh Sturgeon	Increased ——	—— Green is higher than red	Depending on the used dose, the radiation can have both a stimulatory and an inhibitory effect on motility. Laser have an effect on motility and increase the fertilizing rate [50]
	V.Plavskii et al. *2021*	Nd:YAG 532 nm	Quasi continuous, & Pulsed	30 mW 3 mW/cm^2	—— 10s-10 min	Fresh Sturgeon	Increased ——	—— ——	The laser effects depend on the dose of radiation. and the parameters characterizing the spermatozoa motion after their activation can be changed [51]
	SEIOUDY.A et al. *2021*	—— 532 nm	Continuous ——	3 mW 3 mW/cm^2	—— 2,4,6,8,10, min	Fresh Camel	Increased ——	—— ——	Green laser can improve of the camel spermatozoa quality and motility [52]

Table 2 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/ cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
Seioudy.A et al. *2021*	LSR-PS-II 532 nm	Continuous ——	3 mW 3 mW/cm^2	0.38 J/cm^2 2,4,6,8,10, min	Fresh Camel	Increased Increased	—— ——	PBMT raised the motile spermatozoa, livability, acrosome integrity and improve mitochondrial functions [53]
Z.A.Salam et al. *2011*	—— 532 nm	Continuous ——	1 mW 1.719 mW/cm^2	0.076, 0.15, 0.23, 0.31, 0.38 J/cm^2 1,2,3,4,5 min	Fresh Buffalo	Increased ——	—— ——	laser irradiation increases semen quality parameters. Maximum improvement has been reached after 4 min of exposure [54]
M.R.Ramírez et al. *2022*	LED-P1G70 490–540 nm	Continuous 1.5 cm	—— ——	33.44 J/cm^2 10,20,30 min	Fresh Mice	Increased/ Decreased ——	—— Favorable/ harmful	At 37 °C the overall sperm motility increased. green light at 10 °C can diminish sperm motility. generation of ROS at 37 °C is favorable, while at 10 °C it is harmful [55]

LED: light emitting diode, *Astheno*: asthenozoospermia, *Oligo*: oligozoospermia, *Oligo/Astheno*: oligoasthenozoospermia, *ROS*: reactive oxygen spices

Table 3 Red range wavelength (600–780 nm) laser irradiation on sperm cell, in vitro

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
Human	*K.L.Harrison* et al. *2008*	LED 660 nm	Continuous ——	200 mW ——	100–400 J/cm^2 ——	Fresh Astheno	Increased ——	—— ——	Human sperm motility is improved by LLLT with an effect that is both dose and sample dependent [56]
	S.Shahar et al. *2011*	LED 600 nm	Continuous ——	—— 40 mW/cm^2	—— 3 min	Fresh Normo	Increased ——	—— Enhances	Light irradiation increase the ROS production, activation of PKA, Src and also Ca^{2+} influx [57]
	G.T.Saeed et al. *2014*	He–Ne 632.5 nm	Continuous ——	—— ——	12 J/ cm^2 30 min	Fresh Normo/Astheno	Increased ——	—— ——	Irradiation on human sperms can increase motility depends on both laser density and post-exposure time [58]
	E.Fekrazad et al. *2014*	—— 635 nm	Continuous ——	200 mW ——	4 J/cm^2 8 s	Fresh Normo/Astheno	Increased ——	—— ——	Red lights can be used as an optimal therapeutic technique for treatment of male infertility result by disordered motility[59]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
H.B.Frangez et al. *2015*	LED 625,660 nm	Continuous 10 cm	—— 3.92,8.23 mW/ cm^2	—— 3 min	Fresh Astheno	Increased ——	—— ——	PBM promote the motility in asthenozoospermia patients regardless of wavelength area [45]
N.Salama et al. *2015*	LED 636.6 nm	Continuous ——	1.3 W ——	0.49,1.2,2.4 J/cm^2 2,5,10 min	Fresh Normo/Astheno	Increased ——	—— ——	Treating sperm with red lights could safely enhance its motility[60]
AL-Ahmed et al. *2017*	He–Ne 630–645 nm	Continuous 1 cm	< 1 mW ——	—— 25 min	frozen/thawed Normo	Increased ——	Decreased ——	Laser could have a useful effects in the preservation and improve sperm motility and DNA integrity [61]
G.T.Saeed et al. *2017*	He–Ne 623.8 nm	Continuous 1cm	2 mW ——	—— 10 min	Fresh Normo/Astheno	Increased Improve	—— ——	Laser increase the motility, decrease the immotile sperms and stimulates viable but immotile sperm to move [62]
D.Preece et al. *2017*	—— 633 nm	Continuous 4.65 cm	—— 5.57,31 mW/cm^2	—— 35,30 min	frozen/thawed Normo	Increased ——	Little or no DNA damage ——	Red light exposure can increased motility but producing a little DNA damage in sperm cells [63]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
C.P.Gabel et al. *2018*	LED 660 nm	Continuous 5 cm	10 mW 39.5 mW/cm^2	––25,50,75,100,200, 400 s	Fresh and frozen/ thawed Astheno	Increased ––	No Increase ––	A higher stimulatory dose causes a rapid increase in motility, while a lower stimulatory dose causes a slower increase in motility also inhibitory does causes reduced motility [64]
F.Safian et al. *2020*	GaAlAs 630 nm	Continuous 18 cm	50 mW 26.1 mW/cm^2	0.6,1.2,2.4 J/cm^2 23,46,92 s	Fresh Normo	Improve Decreased	Increased ––	The red light at 2.4 J/cm^2 increased PSM and DFI. but 0.6 J/cm^2 light decreased viability [65]
Q.A. Jasim et al. *2022*	–– 650 nm	Continuous ––	128 mW 1.024 mW/cm^2	–– 10,20,30 min	Fresh Astheno	Increased ––	–– ––	Sperm motility and motility quality improved in the treated samples with low level laser [66]
A.Saylan et al. *2023*	–– 650 nm	Continuous 10 cm	200 mW 5.5 mW/cm^2	—- 30,60 min	Fresh Astheno	Increased ––	–– ––	PBMT can increase the sperm motility of astenozoospermic sampeles independent of the duration of exposure [67]

Table 3 (continued)

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
	B.T. Espey et al. *2021*	—— 655 nm	Pulsed-wave ——	—— 25–50 mW/cm^2	4,6,10 J/cm^2 30,60,90, 120 min	Fresh Normo/ Astheno	improved ——	No significant increase ——	PBM promote the motility and also, maintain the DNA and acrosome integrity [68]
Animal	*V.Plavskii* et al. *2020*	He–Ne 632.8 nm	Continuous ——	5–30 mW 0.5–3 mW/cm^2	—— 5s-10 min	Fresh Sturgeon	Increased ——	—— Green is higher than red	The radiation of laser Depending on the energy dose can have both a stimulatory and a inhibitory effect on sperm motility. Also Laser lights can have a increase the fertilizing rate [50]
	TR. Dreyer et al. *2011*	—— 633 nm	Continuous ——	5,7.5,10 mW ——	30,45,150, 230,300, 450,600J/cm^2 1,5,10 min	Frozen/thawed Bull	Increased and Decreased ——	—— Increase	Irradiation causes more acrosome/ plasma membrane damage. a conclusion is not unique, due to the powers of irradiation suggest positive effects of low power laser irradiation [69]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
M.I.C.Baque´s et al. *2005*	— 655 nm	Continuous —	21.7 mW —	4,6,10 J/cm^2 103,154, 258s	Fresh Dog	Increase —	— —	Laser increase the speed and linear coefficient of the sperm. Changes in the motility pattern could be related to an increase in the energetic efficiency [70]
AFP.Siqueira et al. *2016*	He–Ne 633 nm	Continuous —	5,7.5,10 mW 0.510,0.765, 1.02 mW/cm^2	0.156,0.312,0.234,0.468, 0.624 J/cm^2 5,10 min	Frozen/thawed Bovine	Improve —	— —	PBMT can modulate sperm functions. Effects is dependent of the output power and duration of exposure [71]
N. Iaffaldano et al. *2016*	He–Ne 632.8 nm	Continuous —	6 mW —	3.96,6.12,9 J/cm^2 11,17, 25 min	Frozen/thawed ram	Improve Improve	Depend on dose increased —	Sperm quality improved by mitochondria-laser light interactions. also DNA integrity was damaged by the 9 J/cm^2 [72]
TR. Dreyer et al. *2014*	He–Ne 633nm	Continuous —	5,7.5,10 mW —	0.15,0.23,0.3,0.45,0.6 J/cm^2 5,10 min	Frozen/thawed bovine	Improve —	Modify DNA methylation —	laser irradiation can improve the fertilizing capacity of sperm cells and induce metabolic and structural changes in sperms [73]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
SM. Dessouki et al. *2022*	— 625 nm	Continuous —	500 mW —	— 5 min	Frozen/thawed Buffalo	Improve —	— —	Red laser light can have a positive effects on post thawing semen, mostly on motility parameter [74]
M.I.C.Baque´s et al. *2009*	— 655 nm	Continuous —	6.8,15.4,33.1, 49.7 mW —	5.97 J/cm^2 15 min	Fresh Dog	Improve —	— —	Different output powers used may causes significant alteration in sperm structure [75]
GH.Fernandes et al. *2015*	AlGaInP 660 nm	Continuous 1 cm	30 mW 1.2 mW/cm^2	4,6 J/cm^2 133,200 s	Frozen/thawed Bovine	Increased Increased	— —	LLLT have a beneficial effect in the preservation of sperm. It was more effective especially before cryopreservation [76]
J. Catalan et al. *2020*	LED 620–630 nm	Pulsed —	— —	— (1–1-1:2–2-2: 3–3-3 min) (Light- darkness-light)	Frozen/thawed Stallion	Improve —	— No significant differences	Red-light could increase the resiliency of frozen thawed sperm to tolerate post-thaw incubation [77]
J. Catalan et al. *2020*	LED 620–630 nm	Pulsed —	— —	—- (1,2,3,4,5,10,15 min) (Light- darkness-light)	Fresh Donkey	Increased —	— No clear impact	Irradiation increase sperm motility and activity of mitochondria with changes in MMP [78]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
N. Iaffaldano et al. *2005*	He–Ne 632.8 nm	Continuous ——	6 mW ——	—— ——	Fresh Turkey	Increased ——	—— ——	Laser irradiation promote the longevity of stored spermatozoa, and maintain the semen quality in long-term storage [79]
F.Pezo et al. *2019*	LED 620–630 nm	Continuous ——	—— ——	—— 30 min (Light- darkness-light)	Fresh Boar	Increased ——	—— Not affected	Photostimulation of sperms has a positive effect on motility of spermatozoa subjected to a short-term moderate thermal stress [80]
O.B.Prieto et al. *2020*	LED 620–630 nm	Continuous ——	—— 0.035 mW/cm^2	—— 1,5,10 min	Fresh Pig	Decreased ——	Depended ——	Irradiation of sperms would increase their resilience to withstand thermal stress [81]
S.M.Dessouki et al. *2022*	LED 625 nm	Continuous ——	5 W ——	—— 5 min	Fresh Buffalo	Increased ——	—— ——	red light irradiation is a suitable tool for increasing sperm motility [82]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
O.B.Prieto et al. *2022*	LED 620–630 nm	Continuous ——	—— ——	—— 1,5,10 min	Fresh Boars	Modulate ——	—— No significant differences	red light has an effect on mitochondrial electron chain. Additionally, light-activated PKC pathways can modulate sperm motility and CCO activity [83]
D.Nicolae et al. *2015*	He–Ne 632.8 nm	Continuous ——	6 mW ——	3.96–6.12 J/cm^2 ——	Frozen/thawed Ram	Increased ——	—— ——	laser action on thawed semen caused an improvement of motility, viability, mitochondrial function [84]
J Catalán et al. *2021*	LED 620–630nm	Pulsed ——	—— ——	—— light–dark–light 3–3-3 min	Fresh Stallion	Increased ——	—— Increased	irradiation increased motion variables, MMP, and ROS, but not affecting the integrities of the plasma membrane and acrosome [85]
N. Iaffaldano et al. *2013*	He–Ne 632.8 nm	Continuous ——	6 mW ——	3.96 J/cm^2 ——	Frozen/thawed Chicken, Pheasant Turkey	Increased ——	—— ——	PBMT by He–Ne has a different effects on bio-stimulation of turkey, chicken and pheasant spermatozoa [86]

Table 3 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
Z.M.Hussein et al. *2008*	LED 660,680 nm	Continuous 0.25 cm	10,100 mW 51,510 mW/cm^2	—- 2,4,8,12, 16,20 min	—- Bull	Improve —-	—- —-	Light red irradiation at certain exposure times can make a reduction of bacterial count and improving of semen motility [87]

LED: light emitting diode, *He–Ne*: helium–neon, *GaAlAs*: gallium aluminum arsenide, *AlGaInP*: aluminum gallium indium phosphide, *CCO*: cytochrome C oxidase, *Astheno*: asthenozoospermia, *Oligo*: oligozoospermia, *Normo/Astheno*: normal + oasthenozoospermia, *MMP*: mitochondrial membrane potential, *ROS*: reactive oxygen spices, *PKC*: protein kinase C, *PSM*: progressive sperm motility, *DFI*: DNA fragmentation index, *Src*: proto-oncogene tyrosine-protein kinase

PBM on Sperm Cells with Blue Range Wavelength (400–500 nm) in Vitro

In general, according to studies carried out in the field of infertility treatment, four studies have been conducted on the effects of laser irradiation with light in the blue range wavelength (400–500 nm) on spermatozoa, of which half of them were conducted on human sperm cells and the rest on animal sperm cells (Table 1). All these studies used the wavelength range of blue light, and the radiation was done continuously. They used different ranges of radiation powers and radiation times. In addition, in only 25% of these studies, frozen and thawed samples were assessed, and in rest of them, samples were fresh. In two human studies in this category, samples with asthenozoospermia were used, and in animal studies, samples were obtained from rabbits and bovines. 75% of these studies have stated that laser light radiation in the blue wavelength range can increase sperm motility and improve the quality of sperm movements. Also, only one study had conducted investigation on production of ROS in sperm cells, and their results indicated that, this type of light can increase this substance in the sperm cells. None of these studies has assessments related to DNA damages or fertility rate.

PBM on Sperm Cells with Green Range Wavelength (500–600 nm) in Vitro

According to the studies carried out based on our research in this review, three studies have been conducted on the effects of laser irradiation with green light (500–600 nm wavelength) on sperm cells; one of them was conducted on human cells, and the rest of them were on animal cells (Table 2). In six studies, radiation was done continuously, and rest was quasi-continuous. They had a different range of radiation powers and radiation times. All these studies were done on fresh samples except one, that used human samples with normozoospermia, asthenozoospermia and oligozoospermia characteristics. Also, in animal studies samples were obtained from sturgeon, camels, buffalo and mice. These studies have stated that laser light radiation in the green wavelength range can increase sperm motility. Only two studies had conducted investigation on production of ROS, and their results indicated that green light might increase this substance. None of these studies have assessments related to DNA damages, though only one study assessed fertility rates.

PBMT on Sperm Cells with Red Range Wavelength (600–780 nm) in Vitro

In the studies carried out in appraisal of the effects of laser irradiation with red range wavelength (600–780 nm) on

Table 4 NIR range wavelength (780–3000 nm) laser irradiation on sperm cell, in vitro

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
Human	*C.P.Gabel* et al. *2018*	GaAlAs 810 nm	Continuous 5 cm	200 mW 90 mW/cm^2	—— 10,15,30, 40 s	Fresh, Frozen/ thawed Normoz/ astheno	Increased ——	—— ——	LLLT modified sperm motility and its dependent on beam irradiance and time as well as the condition of the sample [64]
	F.Safian et al. *2022*	GaAlAs 810 nm	Continuous 18 cm	50 mW 26.1 mW/cm^2	0.6, J/ cm^2 23 s	Frozen/thawed Normo	Improve Improve	decreased ——	PBM have a protective role against cryo-damage by preserving the functions of spermatozoa [88]
	H.Highland et al. *2018*	LED 750–1100 nm	Pulsed 50 Hz 100 cm	150 W ——	87 J/ cm^2 15 min	Fresh Normo	Not assessed decreased	increased ——	NIR can have a detrimental effect on sperm function when exposed in vitro [89]
	R.S.Yazdi et al. *2014*	GaAlAs 830 nm	Continuous 3 cm	100 mW ——	4,6,10 J/ cm^2 30,45,60 min	Fresh Astheno	Increased ——	not significant increased ——	Low-level laser can improve progressive motility depending on laser density and post-exposure time [90]
	E.Fekrazad et al. *2014*	—- 830 nm	Continuous ——	200 mW ——	4 J/ cm^2 8 s	Fresh Normo	Increased ——	—— ——	Lasers can be used for treatment of male infertility owed to disordered motility [59]

Table 4 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
F.Safian et al. *2021*	GaAlAs 810 nm	Continuous 18 cm	50 mW 26.1 mW/cm^2	0.6 J/ cm^2 23 s	Frozen/thawed Normo	Increased Increased	—— decreased	PBM-preconditioning of semen with a NIR laser before the cryopreservation, increased the progressive motility, viability and MMP. It also decreased ROS and lipid peroxidation [91]
F.Safian et al. *2020*	GaAlAs 810 nm	Continuous 18 cm	50 mW 26.1 mW/cm^2	0.6,1.2,2.4 J/ cm^2 23,46,92 s	Fresh Normo	Increased Not negative affect	Not negative affect ——	NIR laser at 2.4 J/ cm^2 increased PSM. The red + NIR lasers can decreased viability. Unlike the NIR laser, the red and red + NIR lasers at 2.4 J/ cm2 significantly increased DFI [65]
H.B.Frangez et al. *2015*	LED 850 nm	Continuous 10 cm	—— 2.16 mW/cm^2	—— 3 min	Fresh Astheno	Increased ——	—— ——	PBM enhancing the sperm motility in infertile men with asthenozoospermia [45]
KL.Harrison et al. *2008*	GaAlAs 810,850 nm	Continuous ——	200 mW ——	2,4 J/ cm^2 ——	Fresh Astheno	Increased ——	—— ——	sperm motility is imoroved by LLLT with an effect that is both dose and sample dependent [56]

Table 4 (continued)

	1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
	L.Zupin et al. *2020*	—— 800 nm	Continuous ——	—— 100 mW/cm^2	5,15 J/ cm^2 ——	Fresh Normoz/astheno	Improve ——	—— ——	after PBMT increase in the Na content happened, this change could improve sperm movement and function [42]
	R.Fireston et al. *2012*	—— 905 nm	Pulsed ——	—— 50 mW/cm^2	1.5 J/ cm^2 30 s	Fresh Normoz/astheno /oligo	Increased ——	No significant increase ——	PBMT have a positive short-term effects on spermatozoa motility and didn't DNA damage [92]
Animal	*A.Amaroli* et al. *2017*	—— 808 nm	Continuous ——	1,3 W ——	64,192 J/ cm^2 ——	Fresh Sea Urchin	Increased ——	—— ——	The overstimulation of some sperm leading to an accelerated cleavage [93]

LED: light emitting diode, *GaAlAs*: gallium aluminum arsenide, *Astheno*: asthenozoospermia, *Oligo*: oligozoospermia, *Normo/Astheno*: normal + oasthenozoospermia, *MMP*: mitochondrial membrane potential, *ROS*: reactive oxygen spices, *PSM*: progressive sperm motility, *DFI*: DNA fragmentation index,

Table 5 Red range wavelength (600–780 nm) laser irradiation on sperm cell, in vivo

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/ cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
Human *P.Hasan* et al. *2004*	He–Ne 632.8 nm	Continuous ––	6 mW ––	–– 4 min for 10 time twice per week	––Azoo/oligo	Improve ––	–– ––	No improvement in sperm count following LLLT showed in azoospermic subjects. But in oligospermic subjects improvement was observed [94]
Animal *S.Banerjee* et al. *2021*	He–Ne 632.8 nm	Continuous ––	5 mW ––	–– 5,10,15 min for 7,14 & 21 day	–– Mice	–– ––	–– ––	Morphological changes of sperm heads occurred and increased. Also, normal sperm count was decreased [95]

LED: light emitting diode, *He–Ne*: helium–neon, *Azoo/oligo*: azoospermia + oligozoospermia

Table 6 NIR range wavelength (780–3000 nm) laser irradiation on sperm cell, in vivo

1st Author & Year		Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/ cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
							Motility & viability	DNA fragmentation & ROS production	
Human	*P.Hasan* et al. *2004*	GaAlAs 904 nm	Pulsed 80 Hz ——	0.5 mW ——	1.3 J/ cm^2 4 min twice per week for 10 time	Fresh Azoo/oligo	Improve ——	—— ——	Following LLLT on the azoospermic and oligospermic subject's improvement in sperm count was observed [94]
	S.Behtaj et al. *2019*	—— 810,904 nm	Pulsed ——	400 mW, 300 W ——	1–6,10 J/cm^2 twice a week in 15 sessions	Fresh low quality sperm (idiopathic)	Improve ——	—— ——	Changes in sperm count and volume were seen and Sperms mobility, quality and morphology were improved [96]
Animal	*S.Ziaeipour* et al. *2023*	GaAlAs 890 nm	Pulsed 80 Hz ——	1.08 mW 1.08 mW/cm^2	0.03, 0.2 J/ cm^2 30,200 s for 21 days	Azoospermic mice	Increased ——	—— decrease	PBMT reduced ROS, MMP and lipid peroxidation levels in the azoospermia models. Also, improved the testicular cells number, volume and length of seminiferous tubules [97]
	T.D.Almeida et al. *2019*	GaAlAs 808 nm	Continuous ——	30 mW ——	28 J/ cm^2 Every 48h for 15 day	—— Rams	Improve ——	—— ——	LLLT increased the percentage of AIPIHP cells after cryopreservation, MMP and integrity acrosome membrane [98]
	MB.R.Alves et al. *2016*	GaAlAs 808 nm	Continuous ——	1 mW ——	28,56 J/ cm^2 Every 48h for 15 day	—— Rams	Did not affect negatively ——	—— Improve	LLLT can induce sperm damages and increase the seminiferous tubule cells. [99]

Table 6 (continued)

1st Author & Year	Laser type & Wavelength	Irradiation type & Distance	Power (mW) & Power density (mW/ cm^2)	Energy Density (J/ cm^2) & Time	Sample condition (fresh/freeze, Pathology or Source type)	Results		Conclusions
						Motility & viability	DNA fragmentation & ROS production	
S.Dadras et al. *2018*	GaAlAs 890 nm	Pulsed 80 Hz ——	1.08 mW 1.08 mW/cm^2	0.03, 0.2 J/ cm^2 30,200 s Every 54h for 21 day	—— Diabetic mice	Improve ——	—— ——	PBMT improved stereological parameters and sperm characteristics. Irradiation of 0.2 J/cm^2 of energy density was more effective than 0.03J/ cm^2 [100]
A.Hasani, et al. *2020*	GaAlAs 890 nm	Pulsed 80 Hz ——	1.08 mW 1.08 mW/cm^2	0.03 J/ cm^2 30 s daily for 35 days	—— Azoospermic mice	Improve Increased	decrease ——	Laser irradiation improved spermatogenesis. after laser irradiation, diminishment of the apoptotic cells observed [101]
F.Rezaei et al. *2021*	GaAlAs 890 nm	Pulsed 80 Hz ——	1.08 mW 1.08 mW/cm^2	0.03,0.2 J/ cm^2 30,200 s 21 day,3 times a week	—— Azoospermic mice	Improve Improve	—— ——	PBMT improved stereological parameters of testicles and sperm analysis. PBM is able to improve the damages related to busulfan injection [102]
H.Tajalli et al. *2022*	—— 808 nm	Continuous ——	—— ——	2,4,8 J/ cm^2 Daily for 21 day	—— Azoospermic mice	—— ——	—— ——	Low energy laser irradiation had a positive effects on sperm production and can improve germ cells production [103]

LED: light emitting diode, *GaAlAs*: gallium aluminum arsenide, *Azoo/oligo*: azoospermia + oligozoospermia, *AIPIHP*: acrosome and plasma membranes integrity and high mitochondrial membrane potential, *MMP*: mitochondrial membrane potential, *ROS*: reactive oxygen spices

spermatozoa, 41% were assessed on human sperm cells and 59% on animal sperm cells (Table 3). These studies used the wavelength range of red light, and the radiation was done continuously, in 91%; but rest of them used pulsed radiation. They had different ranges of radiation powers and radiation times. Also, in 30% of these studies, frozen and thawed samples were used, and 70% samples were fresh. In most of the human studies in this category, samples with asthenozoospermia were used, although normozoospermia samples have been used. In other side, animal studies samples were obtained from sturgeon, bulls, dogs, donkeys, turkeys, boars, rams, buffalo, stallion and mostly bovines. More than 90% of these studies have stated that red laser light radiation can increase sperm motility and improve the quality of sperm movement, but one of them stated that it can increase or decrease sperm motility. Also, nearly 24% of studies had conducted investigation on the ROS production levels in sperm cells, and the results in most of them indicated that red light can increase this substance. Around the 24% of these studies were done assessments related to DNA damages, and none of them, had assessments related to fertility rate.

PBM on Sperm Cells with NIR Range Wavelength (780–3000 nm) in Vitro

In the studies accomplish in evaluation on the effects of laser irradiation with NIR light rang (780–3,000 nm wavelength) on spermatozoa, almost 92% were assessment on human sperm cells and only one of them was used the animal sperm cells (Table 4). These studies utilized the wavelength range of NIR light and radiations type were continuously in 84% and others were used pulsed type. They used different ranges of radiation powers and times. In addition, 25% of these studies, frozen and thawed samples were employed, and rest of them were done on fresh samples. The majority of human studies of this category, used samples with asthenozoospermia characteristics, although samples with normozoospermia and oligozoospermia were used to. In other hand in single animal study in this category, samples obtained from Sea Urchin. 92% of these studies observed that NIR light radiation can increase sperm motility but one of them sperm motility parameters was not evaluated. Also, only one study had conducted assessment for production of ROS in the sperm cell, and the results indicated that NIR light can decrease this substance in sperm. 41% of these researches had done assessments related to DNA integrity and none of them, had done assessments related to fertility rate.

PBM on Sperm Cells with Red Range Wavelength (600–780 nm) in Vivo

In the studies performed for evaluation of the in vivo effects of laser irradiation with a red light range (600–780 nm wavelength) on sperm cells, one study assessed human subjects and also one study used the animal subjects (Table 5). These studies utilized the wavelength range of red light, and the radiation type was continuous in all of them. They used different ranges of radiation powers and times. In the human study of this category, subjects were azoospermic and oligospermic and in animal study, samples were mice. Only one of these studies observed that red light radiation can improve sperm motility, in one of them, sperm motility parameters were not assessed. Also, none of these studies had done assessments related to the production of ROS, DNA integrity, or fertility rate.

PBM on Sperm Cells with NIR Range Wavelength (780–3000 nm) in Vivo

In the studies with aim to evaluate the in vivo effects of laser irradiation with NIR light (780–3,000 nm wavelength) on sperm cells, two studies used human models and seven used the animal models (Table 6). These studies utilized the wavelength range of NIR light, and the radiation type was continuous in three of them, while others used pulsed-type radiation. They used different ranges of radiation powers and times. In addition, in human studies of this category, subjects were azoospermic, normozoospermic and idiopathic. In animal studies, samples were mostly mice's, although rams were used as well. Nearly all of these studies observed that NIR light radiation can improve sperm motility, but one of them states that sperm motility parameters were not affected negatively, and in one study, sperm motility was not assessed. Also, only one study had assessed the production of ROS in the sperm cell, and the results indicated that NIR light can decrease this substance. On the other side, one of these researchers had done assessments related to DNA integrity, and in none of them, assessments related to fertility rate had done.

Discussion

PBM with Blue Range

In the last decade, new types of lasers with LED radiation in a wide wavelength range, including the blue zone (400–500 nm), have been developed. These types of light sources are a novel low-light-based therapy that is used for the treatment of several pathological conditions like skin, brain and spinal cord injuries. Also, it can improve the healing process, especially in wounds. Blue LED light can be useful to regulate metabolism and proliferation of human cells and enhance differentiation of stem cells [104–109]. In this regard, the use of therapeutic lasers with wavelengths in the range of blue light to stimulate and improve the quality and speed of

sperm cell movement has been researched over the last few years, as mentioned in Table 1.

One of the good examples of this category that must be report was the Helena Ban Frangez et al. study. They observed that the sperm motility of asthenozoospermia patients improved after exposure by PBM. They used two protocols for blue-range laser irradiation, including, 470 nm with 5.06 mW/cm^2 and 470 nm with 8.23 mW/cm^2 [45]. In addition, S.E. Mohammed et al. were used fresh human semen samples that were result revealed the progressive and non-progressive sperm were significantly increased, and immobile sperm were significantly decreased compared to the control samples [46]. Also, D.E. Jesus.miranda et al. observed that a 405 nm blue laser beam on rabbit sperm cells inside a chamber at 37 °C can raise the sperms' motility [48].

PBM with Green Range

In general, green light lasers irradiation is available in range between 500–600 nm wavelength. Published studies have revealed that PBMT in the green light range can; improve cellulite appearance, reduce tissue swelling, and promote wound healing by improving the integrity of the skin. At cellular levels, green light can significantly increase the proliferation and migration of endothelial cells, stimulating cell differentiation, alter in cellular gene expressions, rise in mediator's release, intracellular calcium and ROS. Also, reduce the MMP and intracellular pH [107, 110–113]. The application of green light lasers to stimulate and improve the sperm characteristics' parameters, like sperm motility, has been studied in some research that we mentioned in Table 2. In this category, QA Jasim et al. study results suggests that activation by green laser light is more effective at increasing ATP production, and could increase sperm motility [49]. V.Plavskii et al. studied continuous wave, quasi-continuous wave, nano and picosecond laser radiation model with a 532 nm wavelength and a 3 mW/cm^2 power output. Results showed that, both stimulatory and inhibitory effects, depending on the energy dose and type of laser, on sperm motility may occur [51]. M. Ríos-Ramírez et al. research, the effects of green lights on the mice's sperm cells motility investigated and their results suggested that the motility drastically diminishes and generation of ROS at 37 °C is favorable to the sperm cells, while at 10 °C it can harmful for them [55].

PBM with Red Range

Red light refers to visible light with a wavelength of 600–780 nm. In the last two decades, the action of radiation in red regions on tissues and cells has been studied by scientists, and red-light irradiation has been developed as a new utilization and has been widely consumed for the therapy of various diseases, including dermatological, orthopedic, obstetrical, and gynecological diseases. Red light therapy is an inexpensive, safe and noninvasive treatment. This type of irradiation can modulate cellular processes and also mitochondrial functions, including increased intra-mitochondrial calcium, alterations in MMP, modification in the absorption of photons by chromospheres, reaction with respiratory oxygen, and stimulation of the copper/heme–iron centers on CCO, an intra-mitochondrial component of the electron transport chain; therefore, it's widely used for therapeutic interventions [114–119]. The utilization of red-light lasers to motivate and improve the spermatozoa parameters, including sperm motility and viability, has been done in some studies that we aforesaid in Tables 3 and 5.

In this regard, we must mention some of the best studies, including Safian et al. study. In this research, they randomly divided normal human semen samples for the three different PBM protocols. Results show that the NIR and red + NIR lasers at 2.4 J/cm^2 energy density remarkably increased progressive motility after 60 min. Their data confirmed the superiority of the NIR laser at 0.6 J/cm^2 in sperm motility, viability, and DFI compared with the other protocols [65]. G.T.Saeed et al. evaluated the helium–neon laser irradiation on seminal samples. They mentioned that laser irradiation can increase the sperm's activity and decrease the immobile sperm, which means, it can stimulate viable immotile sperm to move [62]. S.M.Dessouki et al. used the red laser (625 nm) with 5 watts of output power on buffalo bull samples and their results reveal that the motility increased insignificantly after laser exposure [82]. Another study was accomplished by Q.A. Jasim et al. evaluation of the role of laser activity in solving infertility problems was aimed. This team observed that red laser irradiation on asthenozoospermic samples for 10, 20, and 30 min caused a remarkable increase in progressive sperm motility. [66]. T. R. Dreyer et al. tried to characterize the topological and biochemical alterations that were induced by laser irradiation at 633nm on post-thawing bull sperm cells. In these study, sperm motility had no difference, but, ROS generation was increased with 5 mW compared to 7.5 and 10 mW, as well as with 10 min of irradiation. They conclude that LLLT can be an effective technique to induce changes in sperm cell metabolism [69].

In general, lasers are a widely used device in the medical treatment field. Also, the invivo effects of singular and repeated radiation from a laser beam on mammalian models were studied to determine every possible effect on their germ cells. Accordingly, those effects are considered mutagenic for sperm cells, so studies should be done with an applicable screening for laser effects on germ cells. Perhaps it is not far from the mind that significant morphological changes in sperm heads and scrotal sac lesions could occur and even be increased by repetitive exposure to the laser beam. Also, the normal sperm count could decrease. So, it is strongly suggested that laser irradiation may have an adverse effect

on male germ cells; therefore, in vivo studies should be done to reveal these issues [95]. One of the invivo studies in this field that must be mentioned is P. Hasan et al. research. In this study, the patients were azoospermic and oligozoospermic and treated with a HeNe laser with 6 mW power and a pulsed GaAs diode laser. Although they did not observe an improvement in the azoospermic subject's situation, but the sperm count increased in the oligospermic patients. Also, the decrease in abnormal spermatozoa in several subjects was recorded, and the patient's libido also increased. [94]. Z.M.Hussein et al. by using diode lasers and commercial LEDs, tried to inhibit the bacterial growth in semen. They observed that laser exposure could be suitable for artificial insemination, reduce bacterial growth, and also have a significant effect on sperm motility and viability [87].

PBM with NIR Range

NIR spectral-range laser irradiation is the process by which nonionizing optical radiation is absorbed by endogenous chromophores to induce photophysical and photochemical events at various biological levels without causing thermal damage. Lasers, using this broadband light source (NIR), are an effective treatment for target tissues and cause clinical effects and therapeutic benefits. The interaction of photons and cell mitochondria is a primary effect of photoreception and could also be used to modulate cellular activity. Protein synthesis, growth factor secretion, degranulation, neurotransmitter modification, depending on the cell type, are a secondary effect of this process. Irradiation with NIR causes stimulation of neuronal growth, rises DNA and RNA synthesis, promotes cell adhesion, neurological function post-traumatic injuries and strokes, and has retino-protective effects, post-ischemia protective effects in cardiomyocytes, wound healing acceleration, raised proliferation of the proliferation cellular and extracellular matrix, collagen production and formation of granulation tissue, and inflammatory response reduction in wounds. Intracellular and tissue ATP levels could increase in irradiated cells with NIR lasers [19, 120–125]. The employment of NIR lasers to induce and improve sperm motility and livability has been studied in many research studies in the last two decades, as we mentioned in Tables 4 and 6.

In this matter, the study of F. Safian et al. could be a good example. They use an 810-nm diode laser with a 0.6 J/cm^2 energy density on a human semen sample. They irradiated the samples before and after cryopreservation. They observed that the pre-freezing PBM group, due to the beneficial effect of PBM, exhibited the highest motility levels compared to other groups. Also, lipid peroxidation and DNA fragmentation were significantly reduced in this group. In addition, parameters of apoptosis, dead and necrotic cells were decreased as well. No significant differences in expression of PRM1, PRM2, or ADD1 were observed among the study groups.

Based on their results, it could be concluded that PBMT prior to cryopreservation could play as a protective technique against the cryo-damaging process [88]. R.S. Firestone et al. determine the effects of low-level laser light exposure on sperm motility and DNA integrity. Results show a significant increase in motility, mostly in oligozoospermic and asthenozoospermic samples, after 30 min. No significant increase in DNA damage after irradiation was observed [92]. R.S.Yazdi et al. evaluated how laser irradiation affects sperm motility. They reveal that the doses of 4 and 6 J/cm^2 have resulted in significant increases in their motility. No significant difference was observed in the SCD test results. [90]. Fatereh, Rezai, et al. showed that PBMT with 0.03 J/cm^2 could have a significant increase in the testosterone hormone level. Also, in spermatogenic cells, GSH, ATP, and SDH levels increased, and with the reduction of apoptotic cells, levels of MDA and ROS production were observed. [102]. Habib Tajalli et al. investigate the effect of laser irradiation on the spermatogenesis process in the testis tissue of azoospermia mice, a model in vitro. Their results show that the employment of a laser with an 8 J/cm^2 energy density could be beneficial in boosting germ cell and sperm cell production [103]. Sara Dadrasa et al. found that the PBM with 0.2 and 0.03 J/cm^2 energy densities can improve the stereological parameters and sperm characteristics in STZ-induced T1DM in the mice. Moreover, PBMT at an energy density of 0.2 J/cm^2 was so effective compared to 0.03 J/cm^2 [100].

Conclusion

In conclusion, the diverse effects of PBM in different wavelength ranges, as discussed in this review, provide valuable insights into its potential applications in improving sperm characteristics. The positive outcomes observed in various studies underscore the need for continued research to optimize PBM protocols for enhancing male reproductive health. Moreover, the varying results across studies emphasize the importance of tailoring PBM interventions to specific conditions and warrant further investigations to establish standardized approaches in this promising field of research.

Future Prospective

The future of PBM in the context of male reproductive health holds great promise. Advancements in precision, mechanistic insights, clinical translation, integration with existing technologies, safety evaluations, and comprehensive population studies will collectively contribute to establishing PBM as a viable and impactful therapeutic modality

for addressing male infertility and improving reproductive outcomes.

Data availability Available upon request.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflicts of Interest There were no conflicts of interest.

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