Heliyon 9 (2023) e23011

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Biophotonics as a new application in optical technology: A bibliometric analysis

Weng Siew Lam [a,*], Weng Hoe Lam [a], Pei Fun Lee [a], Saiful Hafizah Jaaman [b,**]

[a] Department of Physical and Mathematical Science, Faculty of Science, Universiti Tunku Abdul Rahman, Kampar Campus, Jalan Universiti, Bandar Barat, 31900, Kampar, Perak, Malaysia
[b] Department of Mathematical Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), Bangi, 43600, Selangor, Malaysia

ARTICLE INFO

Keywords:
Biophotonics
Optics
Bibliometric analysis
Subject area
VOSviewer

ABSTRACT

Biophotonics procures wide practicability in life sciences and medicines. The contribution of biophotonics is well recognized in various Nobel Prizes. Therefore, this paper aims to conduct a bibliometric analysis of biophotonics publications. The scientific database used is the Web of Science database. Harzing's Publish or Perish and VOSviewer are the bibliometric tools used in this analysis. This study found an increasing trend in the number of publications in recent years as the number of publications peaked at 347 publications in 2020. Most of the documents are articles (3361 publications) and proceeding papers (1632 publications). The top three subject areas are Optics (3206 publications), Engineering (1706 publications) and Radiology, Nuclear Medicine, and Medical Imaging (1346 publications). The United States has the highest number of publications (2041 publications) and citation impact (38.07 citations per publication; *h*-index: 125). The top three publication titles are *Proceedings of SPIE* (920 publications), *Journal of Biomedical Optics* (599 publications), and *Proceedings of the Society of Photo Optical Instrumentation Engineers SPIE* (245 publications). The potential areas for future research include to overcome the optical penetration depth issue and to develop publicly available biosensors for the detection of common diseases.

1. Introduction

Biophotonics is the scientific application of optics in life sciences. It is a breakthrough in biological, pharmaceutical, environmental and agricultural science, and in the medical area [1]. This field can be traced back to the 1600s when Antonie van Leeuwenhoek created the single-lens microscope to observe bacteria and protozoa [2]. Then, in 1903, Niels Ryberg Finsen won the Nobel Prize for the treatment of lupus vulgaris with concentrated light radiation [3,4]. In 2008, Shimomura, Chalfie and Tsien received the Nobel Prize for the findings of green fluorescent protein which is used as a marker protein to observe cells [5,6]. In 2014, Betzig, Hell and Moerner were also recognized with the Nobel Prize award for their super-resolved fluorescence microscopy [7]. Nakamura, Mukai and Senoh's discovery of gallium nitride blue light emitting diodes, which has also been awarded with the Nobel Prize, has potential applications in phototherapy and photobiomodulation [8–10]. In 2018, a Nobel Prize was partly awarded to Arthur Ashkin for the

* Corresponding author.
** Corresponding author.
E-mail addresses: lamws@utar.edu.my (W.S. Lam), shj@ukm.edu.my (S.H. Jaaman).

https://doi.org/10.1016/j.heliyon.2023.e23011
Received 21 July 2023; Received in revised form 23 November 2023; Accepted 23 November 2023
Available online 29 November 2023

invention of optical tweezers which can be used to study the DNA in bacteriophage capsids [11–13].

The application of biophotonics in diagnostics and therapeutics has helped patients with early detection and targeted treatments for their infections. Electron microscopy and light microscopy can detect nano-scale particles to elucidate virus morphology. Interferometric light microscopy can also differentiate viruses from other nano-scale particles with higher sensitivity to determine virus concentration [14,15]. Atomic force microscopy-infrared spectroscopy and tip-enhanced Raman spectroscopy also enable the retrieval of the structural characteristics of viruses such as the COVID-19 virus [16–18]. Surface plasmon resonance sensing is also useful to characterize biomolecular interactions by immobilizing the receptors on the sensors [19–21]. Methods such as fluorescence microscopy and vibrational spectroscopy can be used to determine the viral load of a patient. Since biophotonics has many practical uses, this paper performs a bibliometric analysis of the application and practicability of biophotonics throughout the years of research in the Web of Science database.

Bibliometric analysis is the precise exploration of scientific data to unravel the evolution of a research area [22,23]. Bibliometric analysis also sheds light on the prominent topics in the research area [24]. However, the bibliometric analysis application in biophotonics is very new and underdeveloped and has not been carried out in the current literature. Bibliometric analysis of biophotonics is timely considering the presence of scientific databases such as Web of Science for data extraction and the ease of analysis with bibliometric tools such as Harzing's Publish or Perish and VOSviewer [25–27]. Bibliometric analysis is powerful for its ability to analyse large volume of data and provide impartial insights on the performances of articles, authors, and journals. There are two parts of bibliometric analysis to study the intellectual structure of a research area, namely performance analysis and thematic analysis. Performance analysis involves three metrics in terms of publication, citation, and both citation and publication [28–30]. Publication metric includes total publications (TP); citation metrics are total citations (TC) and average citations per paper (C/P); citation and publication metrics include citations per cited publication (C/CP), *h*-index (*h*), and *g*-index (*g*). Thematic analyses examine the co-authorship, co-citation, and co-occurrence of the research area [31]. Hence, this paper conducts a bibliometric analysis of biophotonics using the Web of Science database from 1984 to 2023 as of July 5, 2023. This bibliometric analysis of biophotonics publications began with the first indexed publication on the Web of Science database, which was in 1984. The endpoint was chosen based on the date of extraction on July 5, 2023. The research questions of this bibliometric analysis are as follows.

1. What are the publication trend and citation trend of biophotonics publications?
2. What are the document types and subject areas of biophotonics publications?
3. What are the top contributing countries in biophotonics publications?
4. What are the top publication titles and highly cited publications in biophotonics studies?
5. What are the related keywords and areas of research in biophotonics studies?

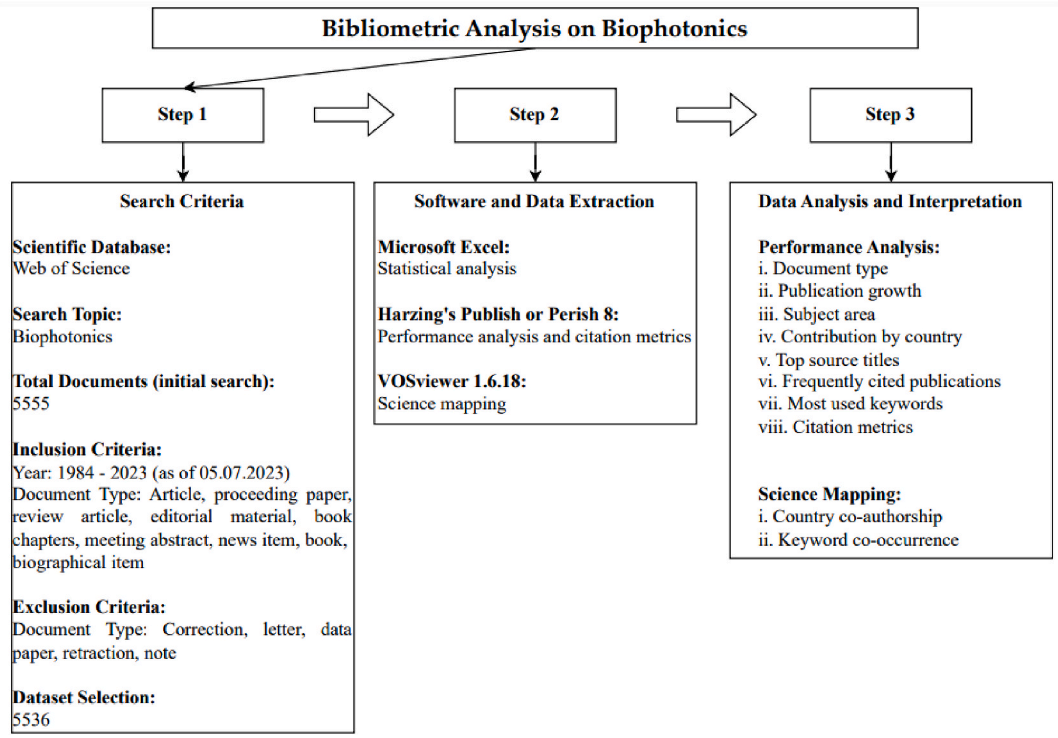

Fig. 1. A three-step approach to conduct bibliometric analysis on biophotonics.

Regarding this, the main aim of this study is to perform a bibliometric analysis of biophotonics publications with the following objectives.

1. To identify the publication trend and citation trend of biophotonics publications.
2. To determine the document types and subject areas of biophotonics publications.
3. To identify the top contributing countries in biophotonics publications.
4. To discover the top publication titles and highly cited publications in biophotonics studies.
5. To uncover the related keywords and areas of research in biophotonics studies.

The next sections present the data and methodology, results and discussion, and conclusion.

2. Data and methodology

This paper conducts a bibliometric analysis of biophotonics using the Web of Science database. The Web of Science database houses more than 21,000 well established articles that have been peer-reviewed [32,33]. This database is also internationally recognized by universities, academicians, scholars, and researchers [34,35]. This bibliometric analysis involves three steps as shown in Fig. 1 [36,37].

In the beginning, research on biophotonics was queried on the Web of Science database on July 5, 2023. The keywords used were ‘biophotonics’, ‘tissue optics’ and ‘biomedical optics’. 5536 publications were found with the document types shown in Table 1 [38–41]. More than half of the documents are articles (3361 documents or 58.63 %), followed by proceeding papers (1632 documents or 28.47 %) and review articles (329 documents or 5.74 %). There are also editorial materials (199 documents or 3.47 %), book chapters (95 documents or 1.66 %), meeting abstracts (62 documents or 1.08 %), news items (38 documents or 0.66 %), books (10 documents or 0.17 %), and biographical items (7 documents or 0.12 %). Then, data were extracted from the Web of Science database for bibliometric analysis. Performance analyses which include publication metrics, citation metrics, and both citation and publication metrics were obtained from Harzing’s Publish or Perish 8. Thematic analyses for country co-authorship and keyword co-occurrence were mapped with VOSviewer 1.6.18 [42,43].

3. Results and discussion

This section is a presentation of the bibliometric analysis results of biophotonics from 1984 to 2023 as of July 5, 2023. The analyses include publication growth, subject area, country contribution, top publication titles, highly cited publications, keyword analysis and citation metrics.

3.1. Publication growth

Table 2 highlights the publication growth of biophotonics publications from 1984 to 2023 as of July 5, 2023. There were only single-digit publications annually from the first indexed paper in 1984 until the beginning of the 1990s. Even though the number of publications experienced slight fluctuations in the 1990s, there was a growing trend as seen in Fig. 2. The number of publications exceeded 3-digit in 2005 and peaked in 2020 with 347 total publications. The first indexed publication on the Web of Science database was titled “Main and Additional Problems of Biophotonics” by Yanbastiev [44], which has received 2 total citations to date. This paper found that there were different spectra of UV-rays emitted from the individual’s body in various pathological and physiological states. The second paper listed on the Web of Science database was “Wavelength selection in macular photocoagulation. Tissue optics, thermal effects, and laser systems” by Mainster [45] which received 141 total citations as found on Web of Science. This paper proposed the application of argon green and krypton red lasers to treat choroidal neovascularization. This paper has contributed to some recent developments in ophthalmology such as treating glaucoma [46], diabetic macular edema [47–52] and chorioretinopathy [53–56].

The paper by Patterson et al. [57] was among the first publications listed on the Web of Science database in 1989 which has a very high impact with 1698 total citations on Web of Science. This paper is also the fourth most cited paper. This paper has captured the

Table 1
Document types of biophotonics publications.

Document Type	Total Publications (TP)	Percentage (%)
Article	3361	58.63
Proceeding paper	1632	28.47
Review Article	329	5.74
Editorial Material	199	3.47
Book Chapters	95	1.66
Meeting Abstract	62	1.08
News Item	38	0.66
Book	10	0.17
Biographical Item	7	0.12

Table 2
Publication growth of biophotonics publications.

Year	TP[a]	Percentage (%)	Cumulative Percentage (%)	NCP[b]	TC[c]	C/P[d]	C/CP[e]	*h*[f]	*g*[g]
1984	1	0.02	0.02	1	2	2.00	2.00	1	1
1986	1	0.02	0.04	1	141	141.00	141.00	1	1
1987	1	0.02	0.05	0	0	0.00	0.00	0	0
1988	1	0.02	0.07	1	19	19.00	19.00	1	1
1989	5	0.09	0.16	3	1727	345.40	575.67	3	5
1990	1	0.02	0.18	1	361	361.00	361.00	1	1
1991	2	0.04	0.22	2	153	76.50	76.50	2	2
1992	31	0.56	0.78	27	1817	58.61	67.30	15	31
1993	38	0.69	1.46	35	2066	54.37	59.03	18	38
1994	21	0.38	1.84	18	2047	97.48	113.72	13	21
1995	46	0.83	2.67	27	4674	101.61	173.11	17	46
1996	52	0.94	3.61	40	3338	64.19	83.45	20	52
1997	70	1.26	4.88	64	6173	237.42	96.45	32	70
1998	58	1.05	5.92	45	2553	102.12	56.73	20	50
1999	65	1.17	7.10	51	2973	45.74	123.88	22	54
2000	82	1.48	8.58	63	4898	59.73	77.75	19	69
2001	81	1.46	10.04	58	2696	33.28	46.48	28	51
2002	79	1.43	11.47	64	4237	53.63	66.20	26	65
2003	93	1.68	13.15	69	4866	52.32	70.52	27	69
2004	88	1.59	14.74	59	3666	41.66	62.14	19	60
2005	155	2.80	17.54	119	5520	35.61	46.39	38	73
2006	148	2.67	20.21	109	3817	25.79	35.02	34	60
2007	159	2.87	23.09	110	3104	19.52	28.22	31	53
2008	200	3.61	26.70	150	4536	22.68	30.24	37	63
2009	213	3.85	30.55	160	5303	24.90	33.14	41	66
2010	268	4.84	35.39	216	6990	26.08	32.36	43	77
2011	248	4.48	39.87	191	5569	22.46	29.16	41	68
2012	252	4.55	44.42	198	7325	29.07	36.99	42	80
2013	229	4.14	48.55	167	6949	30.34	41.61	37	80
2014	265	4.79	53.34	207	6284	23.71	30.36	43	72
2015	298	5.38	58.72	222	6587	22.10	29.67	37	74
2016	289	5.22	63.95	218	4949	17.12	22.70	35	60
2017	292	5.27	69.22	221	4698	16.09	21.26	33	57
2018	288	5.20	74.42	220	4559	15.83	20.72	34	58
2019	334	6.03	80.46	287	6329	18.95	22.05	32	71
2020	347	6.27	86.72	296	3901	11.24	13.18	32	48
2021	308	5.56	92.29	250	2283	7.41	9.13	23	34
2022	326	5.89	98.18	203	692	2.12	3.41	10	12
2023	101	1.82	100.00	21	34	0.34	1.62	3	3
Total	5536	100			137,836				

[a] Total publications.
[b] Number of cited publications.
[c] Total citations.
[d] Citations per paper.
[e] Citations per cited paper.
[f] *h*-index.
[g] *g*-index.

attention of researchers from many fields such as neurology for the detection and treatment of brain injuries [58–64], treatment of pancreatic diseases [65,66], skin evaluation [67,68], microvascular investigations [69–71], orthopedic treatment [72], and diagnosis and treatment of cancer [73–77].

From Table 2, the highest total citation (TC) was 7325 citations in 2012. Out of the 252 publications in 2012, the top 3 cited papers were by Chung et al. [78], Hess et al. [79] and Yuan et al. [80] which contributed 762, 455 and 441 total citations respectively. The highest *h*-index of 43 was recorded in 2010 and 2014. This shows that, from the 268 total publications in 2010 and 265 publications in 2014, 43 documents have received 43 or more citations for both years. The highest *g*-index of 80 was in 2012 and 2013. This implies that 80 documents have received 80^2 (equivalent to 6400) total citations. In terms of the citation impacts, the paper "Optical reflectance and transmittance of tissues: principles and applications" published by Wilson and Jacques [81] in 1990 has received the highest number of citations per paper (C/P). This paper recorded 361 total citations and was the only paper listed in the Web of Science database in 1990. The highest citations per cited paper (C/CP) was in 1989. The papers by Patterson et al. [57], Wilson et al. [82] and Wilson et al. [83] received 1698, 22, and 7 citations respectively. In total, there were 1727 total citations from 3 cited papers, thereby garnering 575.67C/CP. Fig. 2 illustrates the publication and citation growth of the biophotonics publications. A downward trend in the total citations (TC) from 2019 to 2023 was due to the short time elapse since the publication [84–88]. Since Fig. 2 shows an increasing trend in the number of publications, TC is expected to increase over time because of the greater attention in biophotonics.

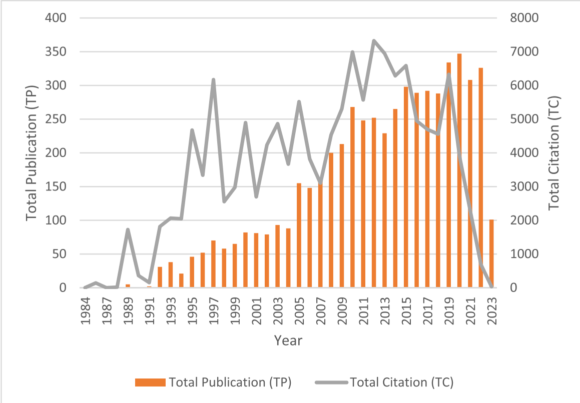

Fig. 2. Publication and citation trends of biophotonics publications.

3.2. Subject areas

The 5736 documents on biophotonics come from various subject areas. Most of the publications are under Optics (3206), Engineering (1706), Radiology Nuclear Medicine Medical Imaging (1346), Physics (1075), Biochemistry Molecular Biology (994), Science Technology Other Topics (425), Materials Science (367), Biophysics (359), Chemistry (339), and Instruments Instrumentation (254). The top 20 subject areas are tabulated in Table 3.

The Web of Science database subject categories are described in Table 4. The top 10 categories are Optics (3206), Radiology Nuclear Medicine Medical Imaging (1346), Engineering Biomedical (940), Physics Applied (936), Biochemical Research Methods (918), Engineering Electrical Electronic (780), Biophysics (359), Materials Science Multidisciplinary (301), Nanoscience Nanotechnology (290), and Instruments Instrumentation (254).

3.3. Country contribution

Researchers from around 90 countries have contributed to the publication in biophotonics from 1984 to 2023. The top 10 countries producing biophotonics publications are the United States (2041), China (743), Germany (392), Canada (327), Russia (319), and England (292), Italy (254), France (194), the Netherlands (182), and Japan (162). There are 137,836 total citations from the 5536 documents. The United States (77,696) has the highest number of total citations, which contributes more than 56 % of the total citations. The United States also has the highest number of cited papers (1607), citations per paper (38.07), citations per cited paper (48.35), h-index (125), and g-index (235). 125 documents published by researchers in the United States have received 125 or more total citations while 235 documents have received 55,225 or more average citations. Table 5 lists the top 10 country contribution in biophotonics publications.

Table 3
Subject areas of biophotonics publications.

Research Areas	Total Publication
Optics	3206
Engineering	1706
Radiology Nuclear Medicine Medical Imaging	1346
Physics	1075
Biochemistry Molecular Biology	994
Science Technology Other Topics	425
Materials Science	367
Biophysics	359
Chemistry	339
Instruments Instrumentation	254
Computer Science	243
Spectroscopy	206
Imaging Science Photographic Technology	198
Surgery	147
Oncology	122
Telecommunications	105
Dermatology	90
Research Experimental Medicine	75
Microscopy	70
Neurosciences Neurology	68

Table 4
Web of Science classification of biophotonics publications.

Research Areas	Total Publication
Optics	3206
Radiology Nuclear Medicine Medical Imaging	1346
Engineering Biomedical	940
Physics Applied	936
Biochemical Research Methods	918
Engineering Electrical Electronic	780
Biophysics	359
Materials Science Multidisciplinary	301
Nanoscience Nanotechnology	290
Instruments Instrumentation	254
Spectroscopy	206
Imaging Science Photographic Technology	198
Chemistry Multidisciplinary	188
Quantum Science Technology	166
Surgery	147
Multidisciplinary Sciences	133
Oncology	122
Chemistry Physical	111
Telecommunications	105
Physics Condensed Matter	103

Researchers may join efforts across various geographical regions and countries to share knowledge, expertise, and resources. These efforts can be visualized using the country co-authorship analysis with VOSviewer [89]. Fig. 3 displays the country co-authorship map in biophotonics publications. The United States has the largest node as the United States has the highest total link strength (75,368). This shows that researchers in the United States have been actively working with researchers in other countries on biophotonics research. China (14,396) has the second highest total link strength, followed by England (9539), Germany (7444) and Russia (4472). Researchers from the United States and China (119) have the strongest collaborative strengths, followed by the United States and Canada (58), the United States and Germany (51), the United States and England (50), and the United States and South Korea (43).

3.4. Source titles

There are about 200 source titles that have been published in biophotonics-related documents. Table 6 explains the top 10 source titles that have published biophotonics documents. *Proceedings of SPIE* (920) has the highest total publications in biophotonics, followed by *Journal of Biomedical Optics* (599), *Proceedings of the Society of Photo Optical Instrumentation Engineers SPIE* (245), *Applied Optics* (131), *Biomedical Optics Express* (129), *Journal of Biophotonics* (123), *IEEE Journal of Selected Topics in Quantum Electronics* (117), *Optics Express* (96), *Optical Engineering* (69), and *Lasers in Surgery and Medicine* (66).

3.5. Highly cited publications

Table 7 lists the top 10 highly cited biophotonics publications. The top highly cited publication with 2735 total citations in Web of

Table 5
Country contribution in biophotonics publications.

Country	TP[a]	NCP[b]	TC[c]	C/P[d]	C/CP[e]	*h*[f]	*g*[g]
United States	2041	1607	77,696	38.07	48.35	125	235
China	743	558	14,498	19.51	25.98	57	103
Germany	392	310	9385	23.94	30.27	51	88
Canada	327	279	11,817	36.14	42.35	48	104
Russia	319	213	4515	14.15	21.20	31	60
England	292	246	10,385	35.57	42.22	47	96
Italy	254	205	5378	21.17	26.23	38	65
France	194	153	3003	15.48	19.63	28	49
Netherlands	182	148	5305	29.15	35.84	35	69
Japan	162	130	2301	14.20	17.70	25	44

[a] Total publications.
[b] Number of cited publications.
[c] Total citations.
[d] Citations per paper.
[e] Citations per cited paper.
[f] *h*-index.
[g] *g*-index.

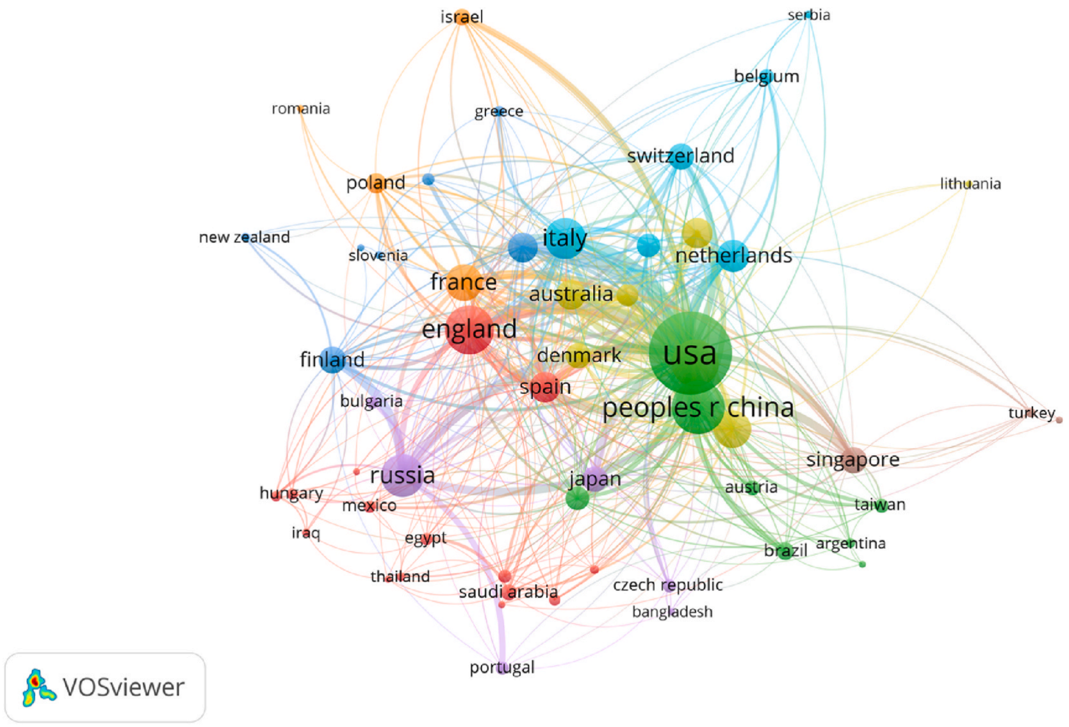

Fig. 3. Country co-authorship of biophotonics publications.

Table 6
Source titles of biophotonics publications.

Publication Title	TP[a]	%[b]	TC[c]	Publisher	JIF[d]	JCI[e]	Cite Score[f]	SJR[g]	SNIP[h]	*h*[i]
Proceedings of SPIE	920	0.17	1566	SPIE-SOC PHOTO-OPTICAL INSTRUMENTATION ENGINEERS	N/A	N/A	0.7	0.166	0.235	187
Journal of Biomedical Optics	599	0.11	19,435	SPIE-SOC PHOTO-OPTICAL INSTRUMENTATION ENGINEERS	3.500	0.90	7.1	0.824	1.37	154
Proceedings of the Society of Photo Optical Instrumentation Engineers SPIE	245	0.04	853	SPIE-SOC PHOTO-OPTICAL INSTRUMENTATION ENGINEERS	N/A	N/A	N/A	N/A	N/A	N/A
Applied Optics	131	0.02	11,413	OPTICA PUBLISHING GROUP	1.900	0.59	3.6	0.515	0.885	211
Biomedical Optics Express	129	0.02	1939	OPTICA PUBLISHING GROUP	3.400	0.98	6.7	0.955	1.164	100
Journal of Biophotonics	123	0.02	1541	WILEY-V C H VERLAG GMBH	2.800	0.73	6.4	0.64	0.895	74
IEEE Journal of Selected Topics in Quantum Electronics	117	0.02	2728	IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC	4.900	1.31	10.2	1.221	1.358	170
Optics Express	96	0.02	4052	OPTICA PUBLISHING GROUP	3.800	1.19	6.9	1.138	1.434	297
Optical Engineering	69	0.01	1249	SPIE-SOC PHOTO-OPTICAL INSTRUMENTATION ENGINEERS	1.300	0.35	2.8	0.353	0.67	114
Lasers in Surgery and Medicine	66	0.01	2524	WILEY	2.400	1.04	5.3	0.665	1.281	123

[a] Total publications.
[b] Percentage.
[c] Total citations.
[d] Journal Impact Factor 2022.
[e] Journal Citation Indicator 2022.
[f] Cite Score 2022.
[g] SCImago Journal Ranking 2022.
[h] Source Normalized Impact per Paper 2022.
[i] *h*-index.

Science is "MCML - Monte-Carlo Modeling of Light Transport in Multilayered Tissue" by Wang et al. [90]. This paper presented a study on light transport in composite turbid media with Monte Carlo simulation. The second highly cited paper "Optical Properties of Biological Tissues: A Review" by Jacques [91] focused on tissue optical properties that summarized the wavelength depending behaviour of scattering and absorption. The third highly cited paper by Weiner [92] was a review on the femtosecond pulse shaping

Table 7
Highly cited publications of biophotonics.

Title	Year	TC	Publication Title
MCML - Monte-Carlo Modeling of Light Transport in Multilayered Tissues [90]	1995	2735	*Computer Methods and Programs in Biomedicine*
Optical properties of biological tissues: a review [91]	2013	2278	*Physics in Medicine and Biology*
Femtosecond pulse shaping using spatial light modulators [92]	2000	1766	*Review of Scientific Instruments*
Time Resolved Reflectance and Transmittance for the Noninvasive Measurement of Tissue Optical-Properties [57]	1989	1698	*Applied Optics*
Mechanisms in photodynamic therapy: part one-photosensitizers, photochemistry, and cellular localization [93]	2004	1434	*Photodiagnosis and Photodynamic Therapy*
Medical hyperspectral imaging: a review [94]	2014	1202	*Journal of Biomedical Optics*
Non-invasive optical spectroscopy and imaging of human brain function [95]	1997	1187	*Trends in Neurosciences*
A Diffusion-Theory Model of Spatially Resolved, Steady-State Diffuse Reflectance for the Noninvasive Determination of Tissue Optical-Properties *in vivo* [96]	1992	1150	*Medical Physics*
Quantitative optical spectroscopy for tissue diagnosis [97]	1996	971	*Annual Review of Physical Chemistry*
Boundary-Conditions for the Diffusion Equation in Radiative-Transfer [98]	1994	957	*Journal of the Optical Society of America A-Optics Image Science and Vision*

and its applications in optical communications, laser-electron beam, biomedical optical imaging, quantum control as well as high power laser amplifiers. Patterson et al. [57] presented a model using the diffusion approximation to radiative transfer theory for the temporal and spatial dependence of diffusely transmitted and reflected light. The next highly cited document by Castano et al. [93] discussed the mechanisms that operate in the field of photodynamic therapy.

The sixth highly cited paper by Lu and Fei [94] conducted a review on medical hyperspectral imaging technology and its applications. The seventh highly cited paper by Villringer and Chance [95] investigated functional optical imaging by focusing on the interactions of photons with brain tissue based on optical parameters, the physiological events related to brain activity based on physiological parameters as well as the relationship between optical and physiological parameters. The next highly cited paper by Farrell et al. [96] presented a model to study the radial dependence of diffuse reflectance of light from tissues based on steady-state diffusion theory. Richards-Kortum and Sevick-Muraca [97] investigated the optical interactions for biomedical applications and presented a framework for light interaction based on tissue absorption as well as scattering properties. Haskell et al. [98] studied the three boundary conditions commonly applied to the surface of a semi-infinite turbid medium with the method of images.

3.6. Keyword analysis

The keyword analyses are made up of the keyword co-occurrence map and the keyword overlay visualization map. The keyword co-occurrence map illustrates the fields of a research area and the connection among the fields to develop a hotspot [99]. Table 8 presents the top 20 keywords with the total link strengths. "Scattering" appeared 496 times in the 5536 documents with a total link strength of 2487, followed by "spectroscopy" with 481 appearances and 2409 total link strength and "*in vivo*" with 445 occurrences and 2129 total link strength. Other keywords with high total link strengths are "biomedical optical imaging (2059), "turbid media" (1731), "absorption" (1715), "tissue optical properties" (1689), "biomedical optics" (1680), "tissue optics" (1675) and "tissue" (1625). Fig. 4 demonstrates the keyword co-occurrence map of biophotonics publications.

Table 8
Keywords with high total link strengths in biophotonics.

Keywords	Occurrences	Total Link Strength
Scattering	496	2487
Spectroscopy	481	2409
In vivo	445	2129
Biomedical optical imaging	571	2059
Turbid media	305	1731
Absorption	319	1715
Tissue optical properties	338	1689
Biomedical optics	515	1680
Tissue optics	420	1675
Tissue	342	1625
Model	315	1614
Biophotonics	692	1607
Light	339	1504
Fluorescence	312	1401
Optical properties	289	1346
Cancer	242	1128
Tomography	252	1085
Reflectance	209	1039
Optical coherence tomography	290	1030
Microscopy	267	995

From Fig. 4, scattering has the largest node because of its high total link strength (2487). The link connecting scattering and absorption is the thickest because it has the highest link strength of 133. The second highest link strength connects scattering and spectroscopy (99). The third highest link strength is between scattering and tissue optical properties (79).

There are five clusters in the keyword co-occurrence map. The first cluster, which is red, is made up of ablation, biophotonics, biosensor, cells, cellular biophysics, DNA, drug delivery, emission, excitation, fibre, films, fluorescence, fluorescence microscopy, imaging, *in vivo*, laser, luminescence, microfluidics, microscopy, multiphoton microscopy, nanocrystals, nanoparticles, nonlinear optics, optical fibres, optical microscopy, optical sensors, optical tweezers, optics, photonics, probe, protein, quantum dots, radiation, Raman spectroscopy, refractive index, sensitivity, sensor, temperature, therapy, water, and wavelength. The first cluster highlights the application of biophotonics in molecular biology such as molecular imaging and delivery. The second cluster (green) consists of absorption, absorption coefficient, approximation, calibration, diffuse reflectance, diffuse reflectance spectroscopy, haemoglobin, hyperspectral imaging, inverse model, light, light propagation, Monte Carlo simulation, multispectral imaging, near-infrared spectroscopy, non-invasive determination, optical properties, oxygenation, photon migration, reduced scattering coefficient, reflectance spectroscopy, scattering coefficient, spatial frequency domain imaging, spectra, spectroscopy, state diffuse-reflectance, steady state, time-resolved reflectance, tissue optical properties, tissue optics, turbid media, and wave-length range. This second cluster is related to the biomedical applications of biophotonics. The second cluster contains a collection of *in vivo*, non-invasive monitoring and imaging of tissues.

The third cluster revolves around the medical applications of optical imaging for disease detection and targeted treatment. This cluster presents keywords that related to the high resolution images for medical applications. The third cluster, in blue, has adaptive optics, biological tissues, biomedical optical imaging, biomedical optics, biopsy, brain, breast, deep learning, diffuse optical tomography, diseases, eye, feature extraction, image processing, image reconstruction, image segmentation, lesions, machine learning, mammography, medical image processing, medical imaging, optical coherence tomography, oxygen saturation, photoacoustic imaging, photoacoustic tomography, resolution, surgery, tumors, ultrasound, and visualization. The fourth cluster revolves around the studies in optical properties of biological tissues and optical clearing methods in blood vessels and skin. The fourth cluster is in yellow and has backscattering, blood, blood flow, collagen, confocal microscopy, contrast, depth, interferometry, multiple scattering, optical clearing, polarization, skin, speckle, and tissue optical clearing. Cluster 5 (purple) consists of 5-aminolevulinic acid, autofluorescence, contrast agents, diagnosis, dosimetry, endoscopy, laser-induced fluorescence, molecular imaging, optical spectroscopy, and photodynamic therapy. This fifth cluster focuses on the use of contrast agents for precise imaging in biophotonics.

The keyword overlay visualization map shows the trend of publication over time. The node color in the keyword overlay visualization map shows the publication period. Lighter color highlights the recent focus in a research area [100]. Fig. 5 describes the keyword overlay visualization map of biophotonics publications. From Fig. 5, biomedical optical imaging, optical imaging, adaptive optics, deep learning, image segmentation, medical image processing, machine learning, surgery, photoacoustic imaging, optical tweezers, optical sensors, sensors, optical fibers, photonics, biosensors, tissue optical clearing, hyperspectral imaging, spatial frequency domain imaging, and multispectral imaging are some of the recent focused keywords of researchers.

Based on the recent focused keywords, an important area in biophotonics is optical imaging [101]. However, some challenges in optical imaging could serve as the research gaps to be explored in future studies. Deep optical penetration has its limitations in spatial resolution. As the penetration depth increases, the resolution becomes lower, thus limiting the application of optical imaging and phototherapeutics [1,102,103]. There is also an issue in *in-vivo* optical imaging as there is scattering in the tissues because of the difference in the refractive index while light can also be absorbed by the hemoglobin and endogenous fluorophores [104]. Large wavelengths also weaken light penetration [105]. The development of non-invasive optical imaging to detect tumors or act as biomarkers at the early stages of a disease is also an important contribution area [106].

Moreover, there is also a gap in biosensors that can be made commercialized and publicly available for rapid detection of diseases, such as during the COVID-19 pandemic [107,108]. The innovation and development of biosensors for emergency healthcare are still limited [109,110]. The detection of multiple diseases with a single biosensor device could speed up the diagnosis and treatment processes [111]. There is also a need to improve the stability of biosensors so that the results are not affected by the ambient conditions [112]. Biosensors for tissue regeneration and tissue engineering are also crucial in the current biomedical field [113,114]. Fluorescence resonance energy transfer (FRET), which is applied in biomedical and pharmaceutical fields, is highly dependent on the distance of energy transfer from donors to acceptors [115]. Some FRET microscopy methods produce out of focus signals while some are confined to standard lasers with fixed wavelengths. Many FRET images also have bleedthrough parts that can only be removed using external software [116,117]. Near-field spectroscopy, which is non-invasive and economical, has multiple applications in biomedical fields [118,119]. However, at times, the results of the near-field spectroscopy may be inconsistent with the functional magnetic resonance imaging (fMRI) [120]. Therefore, future studies can also investigate on improving the reliability of near-field spectroscopy. Moreover, given that nuclear medicine is highly contributing to the biomedical field, Noltes et al. [121] noted that there is huge potential for greater precision and collaborative efforts between nuclear medicine and optical imaging for further advancements in the area. Ozsahin et al. [122] applied the multi-criteria decision making (MCDM) method to determine the probable nuclear medical imaging technique including positron emission tomography which could potentially contribute to optical imaging [123]. This also opens another potentially interesting area which is the application of machine learning and MCDM in biophotonics for more advanced diagnostics [124–127].

3.7. Citation metrics

Table 9 shows the citation metrics of biophotonics publications. 5536 documents were analysed in this bibliometric analysis from

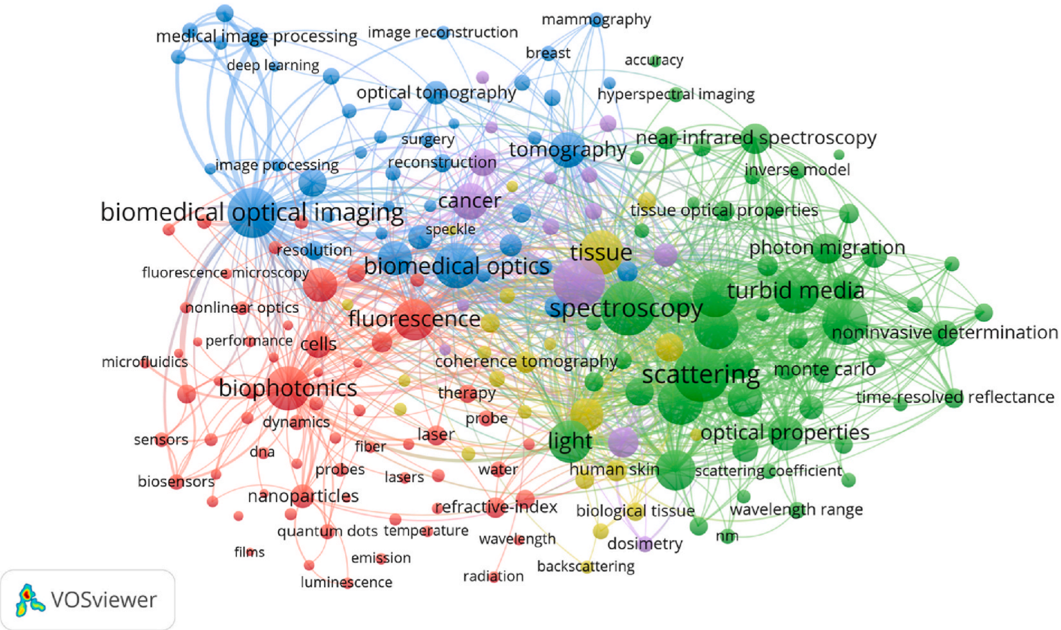

Fig. 4. Keyword co-occurrence map of biophotonics publications.

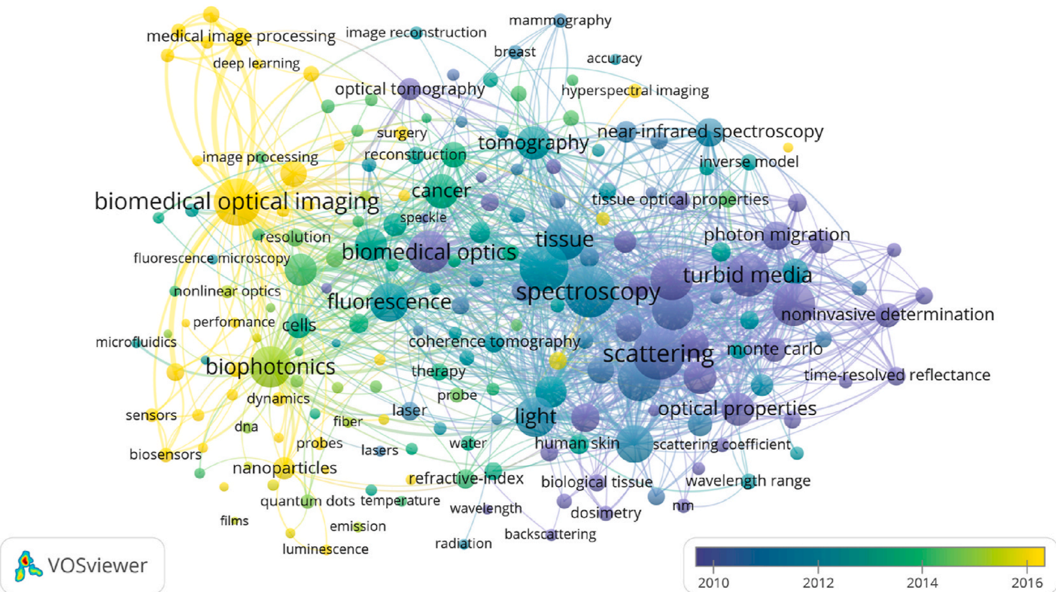

Fig. 5. Keyword overlay visualization map of biophotonics publications.

1984 to 2023 as of July 5, 2023. The total number of citations from these documents is 137,836, the average citation per paper is 24.90, the h-index is 156, and the g-index is 271.

Overall, this paper has analysed biophotonics publications using bibliometric analysis on the Web of Science database as of July 5, 2023. This bibliometric analysis highlighted the positive trend in the number of publications in biophotonics. Research in biophotonics mostly contributed to the areas of optics, engineering, radiology, nuclear medicine, and medical imaging. The United States has the highest number of publications and citation impact. The publication titles with the three most documents in biophotonics are *Proceedings of SPIE*, *Journal of Biomedical Optics*, and *Proceedings of the Society of Photo Optical Instrumentation Engineers SPIE*. Another highlight of this study is the identification of research gaps in biophotonics field. The limitation of clarity and resolution in optical imaging is currently a challenge in medical treatment and diagnosis. Research in enhancing the contribution of optical imaging for non-invasive detection of diseases is ongoing and expected to continue in the future. The development of an all-in-one biosensor to

Table 9
Citation metrics of biophotonics publications.

Items	Descriptions
Date	5-Jul-23
Total Publications	5536
Citations	137,836
Years	39
Citation per Year	3534.26
Citation per Paper	24.9
Citation per Author	43337.27
Papers per Author	1701.38
Authors per Paper	4.73
h-index	156
g-index	271

detect multiple diseases, tissue regeneration, and tissue engineering is also currently being researched for applications in the biomedical field. Cross-disciplinary research involving nuclear medicine, machine learning, MCDM, and optical imaging is also a potential future research area. This study has some limitations. Firstly, this study only queried the Web of Science database. Future studies can consider other prominent databases for analysis. Secondly, the Web of Science database is continuously updating the new publications from time to time. Therefore, a bibliometric analysis of biophotonics may be revisited in the future.

4. Conclusion

The aim of this paper is to perform a bibliometric analysis of biophotonics publications. The Web of Science database was queried on July 5, 2023. Data from the 5536 documents were extracted and analysed. Most of the documents are articles and proceeding papers. There has been an increasing trend in the number of publications in biophotonics in recent years. The first indexed publication was titled “Main and Additional Problems of Biophotonics” by Yanbastiev [44]. The top three subject areas are Optics, Engineering, and Radiology Nuclear Medicine Medical Imaging. The United States has the highest number of publications, followed by China and Germany. The United States has received the highest publication impact as the United States has the highest number of citations, citations per paper, citations per cited paper, *h*-index, and *g*-index. The top three publication titles are *Proceedings of SPIE*, *Journal of Biomedical Optics*, and *Proceedings of the Society of Photo Optical Instrumentation Engineers SPIE*. The most cited paper is “MCML – Monte-Carlo Modeling of Light Transport in Multilayered Tissues” by Wang et al. [90], with 930 total citations to date.

Biomedical optical imaging, optical imaging, adaptive optics, deep learning, image segmentation, medical image processing, machine learning, surgery, photoacoustic imaging, optical tweezers, optical sensors, sensors, optical fibres, photonics, biosensors, tissue optical clearing, hyperspectral imaging, spatial frequency domain imaging, and multispectral imaging are some of the recent focused keywords of researchers. Based on the keyword analysis, the potential topics for future research are to tackle the issues of optical penetration depth and the development of commercialized and publicly available biosensors for common diseases. The issues of out of focus signals and bleed-through parts in FRET can also be researched to maximize the potential of FRET imaging. The reliability of the results of near-field spectroscopy can also be studied in future research. The limitation of this study is that it mainly queries the publications listed in the Web of Science database. Therefore, future studies may consider other databases for bibliometric analysis of biophotonics. Besides, the Web of Science database is continuously updating the new publications from time to time. Thus, a bibliometric analysis of biophotonics publications may be revisited in the future.

Funding

This research was funded by research grants provided by Universiti Kebangsaan Malaysia (GUP-2019-038 and GP-2021-K006416).

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Weng Siew Lam: Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Weng Hoe Lam:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pei Fun Lee:** Writing - review & editing, Writing - original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Saiful Hafizah Jaaman:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Data curation.

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.

Acknowledgments

This research was supported by the Universiti Kebangsaan Malaysia and Universiti Tunku Abdul Rahman, Malaysia.

References

[1] B. Anvari, Grand challenges and opportunities in biophotonics, Front. Photon. 2 (2021). https://www.frontiersin.org/articles/10.3389/fphot.2021.719131 (accessed March 16, 2023).
[2] D.P. Flores, T.C. Marzullo, The construction of high-magnification homemade lenses for a simple microscope: an easy "DIY" tool for biological and interdisciplinary education, Adv. Physiol. Educ. 45 (2021) 134–144, https://doi.org/10.1152/advan.00127.2020.
[3] K.I. Møller, B. Kongshoj, P.A. Philipsen, V.O. Thomsen, H.C. Wulf, How Finsen's light cured lupus vulgaris, Photodermatol. Photoimmunol. Photomed. 21 (2005) 118–124, https://doi.org/10.1111/j.1600-0781.2005.00159.x.
[4] A. Grzybowski, K. Pietrzak, From patient to discoverer—Niels Ryberg Finsen (1860–1904)—the founder of phototherapy in dermatology, Clin. Dermatol. 30 (2012) 451–455, https://doi.org/10.1016/j.clindermatol.2011.11.019.
[5] M. Zimmer, GFP: from jellyfish to the Nobel prize and beyond, Chem. Soc. Rev. 38 (2009) 2823–2832, https://doi.org/10.1039/b904023d.
[6] O. Shimomura, Discovery of green fluorescent protein (GFP) (Nobel lecture), Angew. Chem. Int. Ed. 48 (2009) 5590–5602, https://doi.org/10.1002/anie.200902240.
[7] L. Möckl, D.C. Lamb, C. Bräuchle, Super-resolved fluorescence microscopy: Nobel prize in Chemistry 2014 for eric Betzig, stefan Hell, and william E. Moerner, Angew Chem. Int. Ed. Engl. 53 (2014), 13972, https://doi.org/10.1002/anie.201410265. –13977.
[8] S. Nakamura, T. Mukai, M. Senoh, Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes, Appl. Phys. Lett. 64 (1994) 1687–1689, https://doi.org/10.1063/1.111832.
[9] T.M. Veloso, A. de Souza da Fonseca, G. Costa dos Santos, Effects of light-emitting diodes on cell biology, Frontiers in Photonics 3 (2022). https://www.frontiersin.org/articles/10.3389/fphot.2022.1018773 (accessed March 16, 2023).
[10] G. Magni, F. Tatini, G.D. Siena, F.S. Pavone, D. Alfieri, R. Cicchi, M. Rossi, N. Murciano, G. Paroli, C. Vannucci, G. Sistri, R. Pini, S. Bacci, F. Rossi, Blue-LED-light photobiomodulation of inflammatory responses and new tissue formation in mouse-skin wounds, Life 12 (2022) 1564, https://doi.org/10.3390/life12101564.
[11] A. Ashkin, Optical trapping and manipulation of neutral particles using lasers, Proc. Natl. Acad. Sci. USA 94 (1997) 4853–4860, https://doi.org/10.1073/pnas.94.10.4853.
[12] M. Ordyan, I. Alam, M. Mahalingam, V.B. Rao, D.E. Smith, Nucleotide-dependent DNA gripping and an end-clamp mechanism regulate the bacteriophage T4 viral packaging motor, Nat. Commun. 9 (2018) 5434, https://doi.org/10.1038/s41467-018-07834-2.
[13] G. Pesce, P.H. Jones, O.M. Maragò, G. Volpe, Optical tweezers: theory and practice, Eur. Phys. J. Plus. 135 (2020) 949, https://doi.org/10.1140/epjp/s13360-020-00843-5.
[14] V. Turkki, E. Alppila, S. Ylä-Herttuala, H.P. Lesch, Experimental evaluation of an interferometric light microscopy particle counter for titering and characterization of virus preparations, Viruses 13 (2021) 939, https://doi.org/10.3390/v13050939.
[15] C. Roose-Amsaleg, Y. Fedala, C. Vénien-Bryan, J. Garnier, A.-C. Boccara, M. Boccara, Utilization of interferometric light microscopy for the rapid analysis of virus abundance in a river, Res. Microbiol. 168 (2017) 413–418, https://doi.org/10.1016/j.resmic.2017.02.004.
[16] T. Dou, Z. Li, J. Zhang, A. Evilevitch, D. Kurouski, Nanoscale structural characterization of individual viral particles using atomic force microscopy infrared spectroscopy (AFM-IR) and tip-enhanced Raman spectroscopy (TERS), Anal. Chem. 92 (2020) 11297–11304, https://doi.org/10.1021/acs.analchem.0c01971.
[17] Z. Zhang, S. Sheng, R. Wang, M. Sun, Tip-enhanced Raman spectroscopy, Anal. Chem. 88 (2016) 9328–9346, https://doi.org/10.1021/acs.analchem.6b02093.
[18] L. Zhang, M. Xiao, Y. Wang, S. Peng, Y. Chen, D. Zhang, D. Zhang, Y. Guo, X. Wang, H. Luo, Q. Zhou, Y. Xu, Fast screening and primary diagnosis of COVID-19 by ATR–FT-IR, Anal. Chem. 93 (2021) 2191–2199, https://doi.org/10.1021/acs.analchem.0c04049.
[19] F.B. Kamal Eddin, Y.W. Fen, The principle of nanomaterials based surface plasmon resonance biosensors and its potential for dopamine detection, Molecules 25 (2020) 2769, https://doi.org/10.3390/molecules25122769.
[20] P. Damborský, J. Švitel, J. Katrlík, Optical biosensors, Essays in Biochemistry 60 (2016) 91–100, https://doi.org/10.1042/EBC20150010.
[21] M.M. Hassan, F.S. Sium, F. Islam, S.M. Choudhury, A review on plasmonic and metamaterial based biosensing platforms for virus detection, Sensing and Bio-Sensing Research 33 (2021), 100429, https://doi.org/10.1016/j.sbsr.2021.100429.
[22] F.N. Aziz, A. Roziqin, M.J. Loilatu, T. Sulistyaningsih, Y.S. Hijri, Kismartini, research trends of creative industries in Indonesia: a bibliometric analysis, J Knowl Econ (2023), https://doi.org/10.1007/s13132-023-01299-5.
[23] T. Sulistyaningsih, M.J. Loilatu, A. Roziqin, Research trends on smart urban governance in Asia: a bibliometric analysis, Journal of Science and Technology Policy Management (2023), https://doi.org/10.1108/JSTPM-03-2022-0045 ahead-of-print.
[24] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, W.M. Lim, How to conduct a bibliometric analysis: an overview and guidelines, J. Bus. Res. 133 (2021) 285–296, https://doi.org/10.1016/j.jbusres.2021.04.070.
[25] S. Kordana-Obuch, M. Starzec, M. Wojtoń, D. Słyś, Greywater as a future sustainable energy and water source: bibliometric mapping of current knowledge and strategies, Energies 16 (2023) 934, https://doi.org/10.3390/en16020934.
[26] W.H. Lam, W.S. Lam, S.H. Jaaman, P.F. Lee, Bibliometric analysis of information theoretic studies, Entropy 24 (2022) 1359, https://doi.org/10.3390/e24101359.
[27] W.S. Lam, P.F. Lee, W.H. Lam, Cellulose nanofiber for sustainable production: a bibliometric analysis, Mater. Today Proc. 62 (2022) 6460–6467, https://doi.org/10.1016/j.matpr.2022.04.198.
[28] V. Tiberius, M. Rietz, R.B. Bouncken, Performance analysis and science mapping of institutional entrepreneurship research, Adm. Sci. 10 (2020) 69, https://doi.org/10.3390/admsci10030069.
[29] M. Gaviria-Marin, J.M. Merigo, S. Popa, Twenty years of the journal of knowledge management: a bibliometric analysis, J. Knowl. Manag. 22 (2018) 1655–1687, https://doi.org/10.1108/JKM-10-2017-0497.
[30] W.S. Lam, W.H. Lam, S.H. Jaaman, P.F. Lee, Bibliometric analysis of granger causality studies, Entropy 25 (2023) 632, https://doi.org/10.3390/e25040632.
[31] Y.-S. Ho, P. Ranasinghe, A bibliometric analysis of highly cited insulin resistance publications in Science Citation Index Expanded, Obes. Med. 31 (2022), 100399, https://doi.org/10.1016/j.obmed.2022.100399.
[32] W.H. Lam, W.S. Lam, P.F. Lee, The studies on gallium nitride-based materials: a bibliometric analysis, Materials 16 (2023) 401, https://doi.org/10.3390/ma16010401.
[33] E.Ç. Bilge, H. Yaman, Research trends analysis using text mining in construction management: 2000–2020, Eng. Construct. Architect. Manag. 29 (2021) 3210–3233, https://doi.org/10.1108/ECAM-02-2021-0107.
[34] B. Tijjani, M. Ashiq, N. Siddique, M.A. Khan, A. Rasul, A bibliometric analysis of quality research papers in Islamic finance: evidence from Web of Science, ISRA Int. J. Islam. Financ. 13 (2020) 84–101, https://doi.org/10.1108/IJIF-03-2020-0056.

[35] S. Hossain, M.S. Batcha, I. Atoum, N. Ahmad, A. Al-Shehri, Bibliometric analysis of the scientific research on sustainability in the impact of social media on higher education during the COVID-19 pandemic, Sustainability 14 (2022), 16388, https://doi.org/10.3390/su142416388.
[36] G. Herrera-Franco, N. Montalván-Burbano, P. Carrión-Mero, M. Jaya-Montalvo, M. Gurumendi-Noriega, Worldwide research on geoparks through bibliometric analysis, Sustainability 13 (2021) 1175, https://doi.org/10.3390/su13031175.
[37] C. Mejia, M. Wu, Y. Zhang, Y. Kajikawa, Exploring topics in bibliometric research through citation networks and semantic analysis, Front. Res. Metr. Anal. 6 (2021). https://www.frontiersin.org/articles/10.3389/frma.2021.742311 (accessed March 29, 2023).
[38] Y. Cheng, C. Zhao, P. Neupane, B. Benjamin, J. Wang, T. Zhang, Applicability and trend of the artificial intelligence (AI) on bioenergy research between 1991–2021: a bibliometric analysis, Energies 16 (2023) 1235, https://doi.org/10.3390/en16031235.
[39] W. Yu, X. Zhang, M. Du, Y. Dong, L. Liu, H. Rong, J. Liu, Bibliometric analysis and key messages of monkeypox research, Sustainability 15 (2023) 1005, https://doi.org/10.3390/su15021005.
[40] A.-N. Soh, C.-H. Puah, M.A. Arip, A bibliometric analysis on tourism sustainable competitiveness research, Sustainability 15 (2023) 1035, https://doi.org/10.3390/su15021035.
[41] G. Mentel, A. Lewandowska, J. Berniak-Woźny, W. Tarczyński, Green and renewable energy innovations: a comprehensive bibliometric analysis, Energies 16 (2023) 1428, https://doi.org/10.3390/en16031428.
[42] F. Ghorbel, W. Hachicha, Y. Boujelbene, A.M. Aljuaid, Linking entrepreneurial innovation to effectual logic, Sustainability 13 (2021) 2626, https://doi.org/10.3390/su13052626.
[43] T. Karakose, S. Papadakis, T. Tülübaş, H. Polat, Understanding the intellectual structure and evolution of distributed leadership in schools: a science mapping-based bibliometric analysis, Sustainability 14 (2022), 16779, https://doi.org/10.3390/su142416779.
[44] M.I. Yanbastiev, Main and additional problems of biophotonics, J. Mol. Struct. 115 (1984) 299–302, https://doi.org/10.1016/0022-2860(84)80073-3.
[45] M.A. Mainster, Wavelength selection in macular photocoagulation. Tissue optics, thermal effects, and laser systems, Ophthalmology 93 (1986) 952–958, https://doi.org/10.1016/s0161-6420(86)33637-6.
[46] R.L. Pimentel, R.R. Alves Júnior, W.M.M.L. Lima, L.O.R. Dantas, V.P. Costa, Selective laser trabeculoplasty versus micropulse laser trabeculoplasty for intraocular pressure control in patients with primary open angle glaucoma: a 12-month retrospective comparative study, Laser Med. Sci. 38 (2023) 102, https://doi.org/10.1007/s10103-023-03771-9.
[47] J. Zhang, J. Zhang, C. Zhang, J. Zhang, L. Gu, D. Luo, Q. Qiu, Diabetic macular edema: current understanding, molecular mechanisms and therapeutic implications, Cells 11 (2022) 3362, https://doi.org/10.3390/cells11213362.
[48] X. Mi, X. Gu, X. Yu, The efficacy of micropulse laser combined with ranibizumab in diabetic macular edema treatment: study protocol for a randomized controlled trial, Trials 23 (2022) 736, https://doi.org/10.1186/s13063-022-06593-2.
[49] W. Kikushima, T. Shijo, Y. Furuhata, Y. Sakurada, K. Kashiwagi, Comparison of the 1-year visual and anatomical outcomes between subthreshold red (670 nm) and yellow (577 nm) micro-pulse laser treatment for diabetic macular edema, Pharmaceuticals 14 (2021) 1100, https://doi.org/10.3390/ph14111100.
[50] M.G. Altınel, B. Acikalin, M.G. Alis, G. Demir, K.M. Mutibayraktaroglu, O.M.G. Totuk, A. Ardagil, Comparison of the efficacy and safety of anti-VEGF monotherapy versus anti-VEGF therapy combined with subthreshold micropulse laser therapy for diabetic macular edema, Laser Med. Sci. 36 (2021) 1545–1553, https://doi.org/10.1007/s10103-021-03306-0.
[51] R.M. Passos, F.K. Malerbi, M. Rocha, M. Maia, M.E. Farah, Real-life outcomes of subthreshold laser therapy for diabetic macular edema, Int J Retina Vitreous 7 (2021) 4, https://doi.org/10.1186/s40942-020-00268-3.
[52] K. Inagaki, K. Ohkoshi, S. Ohde, G.A. Deshpande, N. Ebihara, A. Murakami, Comparative efficacy of pure yellow (577-nm) and 810-nm subthreshold micropulse laser photocoagulation combined with yellow (561-577-nm) direct photocoagulation for diabetic macular edema, Jpn. J. Ophthalmol. 59 (2015) 21–28, https://doi.org/10.1007/s10384-014-0361-1.
[53] T. Zhao, J. Li, Y. Wang, X. Guo, Y. Sun, Intravitreal injections with anti-VEGF agent aflibercept versus subthreshold micropulse laser for chronic central serous chorioretinopathy: the alternative treatment regimens for verteporfin-shortage in China, Ann. Med. 55 (2023), 2227424, https://doi.org/10.1080/07853890.2023.2227424.
[54] M.A. Mainster, T. Desmettre, G. Querques, P.L. Turner, G. Ledesma-Gil, Scanning laser ophthalmoscopy retroillumination: applications and illusions, Int. J. Retina Vitr. 8 (2022) 71, https://doi.org/10.1186/s40942-022-00421-0.
[55] H. Long, M. Liu, Q. Hu, X. Li, 577 nm subthreshold micropulse laser treatment for acute central serous chorioretinopathy: a comparative study, BMC Ophthalmol. 22 (2022) 105, https://doi.org/10.1186/s12886-022-02330-0.
[56] M.G. Altınel, B. Acikalin, H. Gunes, G. Demir, Optical coherence tomography parameters as predictors of treatment response to a 577-nm subthreshold micropulse laser in chronic central serous chorioretinopathy, Laser Med. Sci. 36 (2021) 1505–1514, https://doi.org/10.1007/s10103-020-03225-6.
[57] M.S. Patterson, B. Chance, B.C. Wilson, Time resolved reflectance and transmittance for the noninvasive measurement of tissue optical properties, Appl. Opt. 28 (1989) 2331–2336, https://doi.org/10.1364/AO.28.002331.
[58] S. Iwata, R. Katayama, K. Tsuda, Y.-C. Lin, T. Kurata, M. Kinoshita, K. Kawase, T. Kato, S. Kato, T. Hisano, M. Oda, E. Ohmae, S. Takashima, Y. Araki, S. Saitoh, O. Iwata, Near-infrared light scattering and water diffusion in newborn brains, Ann Clin Transl Neurol 9 (2022) 1417–1427, https://doi.org/10.1002/acn3.51641.
[59] J.P. Fanning, S.F. Huth, C. Robba, S.M. Grieve, D. Highton, Advances in neuroimaging and monitoring to defend cerebral perfusion in noncardiac surgery, Anesthesiology 136 (2022) 1015–1038, https://doi.org/10.1097/ALN.0000000000004205.
[60] D.A. Vera, H.A. García, M. Victoria Waks Serra, G.R. Baez, D.I. Iriarte, J.A. Pomarico, A Monte Carlo study of near infrared light propagation in the human head with lesions-a time-resolved approach, Biomed Phys Eng Express 8 (2022), https://doi.org/10.1088/2057-1976/ac59f3.
[61] M. Hashem, J.F. Dunn, Brain oximetry and the quest for quantified metabolic rate: applications using MRI and near-infrared spectroscopy, Appl. Magn. Reson. 52 (2021) 1343–1377, https://doi.org/10.1007/s00723-021-01345-y.
[62] A. Sudakou, L. Yang, H. Wabnitz, S. Wojtkiewicz, A. Liebert, Performance of measurands in time-domain optical brain imaging: depth selectivity versus contrast-to-noise ratio, Biomed. Opt Express 11 (2020) 4348–4365, https://doi.org/10.1364/BOE.397483.
[63] B.Z. Bentz, S.M. Mahalingam, D. Ysselstein, P.C. Montenegro Larrea, J.R. Cannon, J.-C. Rochet, P.S. Low, K. Webb, Localization of fluorescent targets in deep tissue with expanded beam illumination for studies of cancer and the brain, IEEE Trans. Med. Imag. 39 (2020) 2472–2481, https://doi.org/10.1109/TMI.2020.2972200.
[64] P. Karthikeyan, S. Moradi, H. Ferdinando, Z. Zhao, T. Myllylä, Optics based label-free techniques and applications in brain monitoring, Appl. Sci. 10 (2020) 2196, https://doi.org/10.3390/app10062196.
[65] F. Akhter, S. Manrique-Bedoya, C. Moreau, A.L. Smith, Y. Feng, K.M. Mayer, R.L. Hood, Characterization of thermal and optical properties in porcine pancreas tissue, Laser Surg. Med. 54 (2022) 702–715, https://doi.org/10.1002/lsm.23523.
[66] P. Lanka, L. Bianchi, A. Farina, M. De Landro, A. Pifferi, P. Saccomandi, Estimation of porcine pancreas optical properties in the 600–1100 nm wavelength range for light-based therapies, Sci. Rep. 12 (2022), 14300, https://doi.org/10.1038/s41598-022-18277-7.
[67] C. Kern, U. Speck, R. Riesenberg, C. Reble, G. Khazaka, M. Zieger, M. Kaatz, M. De Gregorio, F. Fischer, Mobile snapshot hyperspectral imaging device for skin evaluation using diffractive optical elements, Skin Res. Technol. 27 (2021) 589–598, https://doi.org/10.1111/srt.12991.
[68] R. Abdlaty, J. Hayward, T. Farrell, Q. Fang, Skin erythema and pigmentation: a review of optical assessment techniques, Photodiagnosis Photodyn. Ther. 33 (2021), 102127, https://doi.org/10.1016/j.pdpdt.2020.102127.
[69] M. Horiuchi, K. Okita, Microvascular responses during reactive hyperemia assessed by near-infrared spectroscopy and arterial stiffness in young, middle-aged, and older women, Microvasc. Res. 129 (2020), 103972, https://doi.org/10.1016/j.mvr.2019.103972.
[70] M. Horiuchi, L. Stoner, J. Poles, The effect of four weeks blood flow restricted resistance training on macro- and micro-vascular function in healthy, young men, Eur. J. Appl. Physiol. (2023), https://doi.org/10.1007/s00421-023-05230-3.
[71] M. van Hooff, J. Arnold, E. Meijer, P. Schreuder, M. Regis, L. Xu, M. Scheltinga, H. Savelberg, G. Schep, Diagnosing sport-related flow limitations in the iliac arteries using near-infrared spectroscopy, J. Clin. Med. 11 (2022) 7462, https://doi.org/10.3390/jcm11247462.

[72] C. Fisher, J. Harty, A. Yee, C.L. Li, K. Komolibus, K. Grygoryev, H. Lu, R. Burke, B.C. Wilson, S. Andersson-Engels, Perspective on the integration of optical sensing into orthopedic surgical devices, J. Biomed. Opt. 27 (2022), 010601, https://doi.org/10.1117/1.JBO.27.1.010601.

[73] S. Ueda, T. Saeki, A. Osaki, T. Yamane, I. Kuji, Bevacizumab induces acute hypoxia and cancer progression in patients with refractory breast cancer: multimodal functional imaging and multiplex cytokine analysis, Clin. Cancer Res. 23 (2017) 5769–5778, https://doi.org/10.1158/1078-0432.CCR-17-0874.

[74] R.S. Reddy, K.N. Sai Praveen, Optical coherence tomography in oral cancer: a transpiring domain, J. Cancer Res. Therapeut. 13 (2017) 883–888, https://doi.org/10.4103/0973-1482.180684.

[75] P. Taroni, A.M. Paganoni, F. Ieva, A. Pifferi, G. Quarto, F. Abbate, E. Cassano, R. Cubeddu, Non-invasive optical estimate of tissue composition to differentiate malignant from benign breast lesions: a pilot study, Sci. Rep. 7 (2017), 40683, https://doi.org/10.1038/srep40683.

[76] H. Wada, N. Yoshizawa, E. Ohmae, Y. Ueda, K. Yoshimoto, T. Mimura, H. Nasu, Y. Asano, H. Ogura, H. Sakahara, S. Goshima, Water and lipid content of breast tissue measured by six-wavelength time-domain diffuse optical spectroscopy, J. Biomed. Opt. 27 (2022), 105002, https://doi.org/10.1117/1.JBO.27.10.105002.

[77] L. Cortese, G.L. Presti, M. Zanoletti, G. Aranda, M. Buttafava, D. Contini, A.D. Mora, H. Dehghani, L.D. Sieno, S. de Fraguier, F.A. Hanzu, M.M. Porta, A. Nguyen-Dinh, M. Renna, B. Rosinski, M. Squarcia, A. Tosi, U.M. Weigel, S. Wojtkiewicz, T. Durduran, The LUCA device: a multi-modal platform combining diffuse optics and ultrasound imaging for thyroid cancer screening, Biomed. Opt. Express, BOE. 12 (2021) 3392–3409, https://doi.org/10.1364/BOE.416561.

[78] H. Chung, T. Dai, S.K. Sharma, Y.-Y. Huang, J.D. Carroll, M.R. Hamblin, The nuts and bolts of low-level laser (light) therapy, Ann. Biomed. Eng. 40 (2012) 516–533, https://doi.org/10.1007/s10439-011-0454-7.

[79] O. Hess, J.B. Pendry, S.A. Maier, R.F. Oulton, J.M. Hamm, K.L. Tsakmakidis, Active nanoplasmonic metamaterials, Nat. Mater. 11 (2012) 573–584, https://doi.org/10.1038/nmat3356.

[80] W.Z. Yuan, Y. Gong, S. Chen, X.Y. Shen, J.W.Y. Lam, P. Lu, Y. Lu, Z. Wang, R. Hu, N. Xie, H.S. Kwok, Y. Zhang, J.Z. Sun, B.Z. Tang, Efficient solid emitters with aggregation-induced emission and intramolecular charge transfer characteristics: molecular design, synthesis, photophysical behaviors, and OLED application, Chem. Mater. 24 (2012) 1518–1528, https://doi.org/10.1021/cm300416y.

[81] B.C. Wilson, S.L. Jacques, Optical reflectance and transmittance of tissues: principles and applications, IEEE J. Quant. Electron. 26 (1990) 2186–2199, https://doi.org/10.1109/3.64355.

[82] B. Wilson, Y. Park, Y. Hefetz, M. Patterson, S. Madsen, S. Jacques, The potential of time-resolved reflectance measurements for the noninvasive determination of tissue optical properties, in: Thermal and Optical Interactions with Biological and Related Composite Materials, SPIE, 1989, pp. 97–106, https://doi.org/10.1117/12.951952.

[83] B.C. Wilson, M.S. Patterson, S.T. Flock, D.R. Wyman, Tissue optical properties in relation to light propagation models and in vivo dosimetry, in: B. Chance (Ed.), Photon Migration in Tissues, Springer US, Boston, MA, 1989, pp. 25–42, https://doi.org/10.1007/978-1-4757-6178-8_3.

[84] A.R. Abdul Ghaffar, A. Melethil, A. Yusuf Adhami, A bibliometric analysis of inverse optimization, J. King Saud Univ. Sci. 35 (2023), 102825, https://doi.org/10.1016/j.jksus.2023.102825.

[85] T. Bagdi, S. Ghosh, A. Sarkar, A.K. Hazra, S. Balachandran, S. Chaudhury, Evaluation of research progress and trends on gender and renewable energy: a bibliometric analysis, J. Clean. Prod. 423 (2023), 138654, https://doi.org/10.1016/j.jclepro.2023.138654.

[86] Q. Cheng, S. Zhang, Research status and evolution trends of emergency information resource management: based on bibliometric analysis from 2003 to 2022, Int. J. Disaster Risk Reduc. 97 (2023), 104053, https://doi.org/10.1016/j.ijdrr.2023.104053.

[87] G. Demir, P. Chatterjee, D. Pamucar, Sensitivity analysis in multi-criteria decision making: a state-of-the-art research perspective using bibliometric analysis, Expert Syst. Appl. 237 (2023), 121660, https://doi.org/10.1016/j.eswa.2023.121660.

[88] Q. Lin, B. Cai, X. Shan, X. Ni, X. Chen, R. Ke, B. Wang, Global research trends of infantile hemangioma: a bibliometric and visualization analysis from 2000 to 2022, Heliyon 9 (2023), e21300, https://doi.org/10.1016/j.heliyon.2023.e21300.

[89] M. Abdullah, Naved Khan, Determining mobile payment adoption: a systematic literature search and bibliometric analysis, Cogent Bus. Manag. 8 (2021), 1893245, https://doi.org/10.1080/23311975.2021.1893245.

[90] L. Wang, S.L. Jacques, L. Zheng, MCML—Monte Carlo modeling of light transport in multi-layered tissues, Comput, Methods Programs Biomed 47 (1995) 131–146, https://doi.org/10.1016/0169-2607(95)01640-F.

[91] S.L. Jacques, Optical properties of biological tissues: a review, Phys. Med. Biol. 58 (2013) R37–R61, https://doi.org/10.1088/0031-9155/58/11/R37.

[92] A.M. Weiner, Femtosecond pulse shaping using spatial light modulators, Rev. Sci. Instrum. 71 (2000) 1929–1960, https://doi.org/10.1063/1.1150614.

[93] A.P. Castano, T.N. Demidova, M.R. Hamblin, Mechanisms in photodynamic therapy: part one—-photosensitizers, photochemistry and cellular localization, Photodiagnosis Photodyn. Ther. 1 (2004) 279–293, https://doi.org/10.1016/S1572-1000(05)00007-4.

[94] G. Lu, B. Fei, Medical hyperspectral imaging: a review, J. Biomed. Opt. 19 (2014), 10901, https://doi.org/10.1117/1.JBO.19.1.010901.

[95] A. Villringer, B. Chance, Non-invasive optical spectroscopy and imaging of human brain function, Trends Neurosci. 20 (1997) 435–442, https://doi.org/10.1016/s0166-2236(97)01132-6.

[96] T.J. Farrell, M.S. Patterson, B. Wilson, A diffusion theory model of spatially resolved, steady-state diffuse reflectance for the noninvasive determination of tissue optical properties in vivo, Med. Phys. 19 (1992) 879–888, https://doi.org/10.1118/1.596777.

[97] R. Richards-Kortum, E. Sevick-Muraca, Quantitative optical spectroscopy for tissue diagnosis, Annu. Rev. Phys. Chem. 47 (1996) 555–606, https://doi.org/10.1146/annurev.physchem.47.1.555.

[98] R.C. Haskell, L.O. Svaasand, T.T. Tsay, T.C. Feng, M.S. McAdams, B.J. Tromberg, Boundary conditions for the diffusion equation in radiative transfer, J. Opt. Soc. Am. Opt Image Sci. Vis. 11 (1994) 2727–2741, https://doi.org/10.1364/josaa.11.002727.

[99] J. Jiang, W. Lyu, N. Chen, A bibliometric analysis of diffuse large B-cell lymphoma research from 2001 to 2020, Comput. Biol. Med. 146 (2022), 105565, https://doi.org/10.1016/j.compbiomed.2022.105565.

[100] Y. Murdayanti, M.N.A.A. Khan, The development of internet financial reporting publications: a concise of bibliometric analysis, Heliyon 7 (2021), e08551, https://doi.org/10.1016/j.heliyon.2021.e08551.

[101] P.L. Mok, S.N. Leow, A.E.-H. Koh, H.H. Mohd Nizam, S.L.S. Ding, C. Luu, R. Ruhaslizan, H.S. Wong, W.H.W.A. Halim, M.H. Ng, R.B.Hj Idrus, S.R. Chowdhury, C.M.-L. Bastion, S.K. Subbiah, A. Higuchi, A.A. Alarfaj, K.Y. Then, Micro-computed tomography detection of gold nanoparticle-labelled mesenchymal stem cells in the rat subretinal layer, Int. J. Mol. Sci. 18 (2017) 345, https://doi.org/10.3390/ijms18020345.

[102] C. Ahn, B. Hwang, K. Nam, H. Jin, T. Woo, J.-H. Park, Overcoming the penetration depth limit in optical microscopy: adaptive optics and wavefront shaping, J. Innov. Opt. Health Sci. 12 (2019), 1930002, https://doi.org/10.1142/S1793545819300027.

[103] I. Carneiro, S. Carvalho, R. Henrique, L.M. Oliveira, V.V. Tuchin, Optical properties of colorectal muscle in visible/NIR range, in: Biophotonics: Photonic Solutions for Better Health Care VI, SPIE, 2018, pp. 491–502, https://doi.org/10.1117/12.2306586.

[104] J. Kim, J. Shin, C. Kong, S.-H. Lee, W.S. Chang, S.H. Han, The synergistic effect of focused ultrasound and biophotonics to overcome the barrier of light transmittance in biological tissue, Photodiagnosis Photodyn. Ther. 33 (2021), 102173, https://doi.org/10.1016/j.pdpdt.2020.102173.

[105] M. Ahmed, R. Narain, 11 - Biochemical assays used for in vitro and in vivo gene expression, in: R. Narain (Ed.), Polymers and Nanomaterials for Gene Therapy, Woodhead Publishing, 2016, pp. 257–270, https://doi.org/10.1016/B978-0-08-100520-0.00011-4.

[106] S. Lee, J. Oh, M. Cho, J.K. Kim, Fluorescence-based microendoscopic sensing system for minimally invasive in vivo bladder cancer diagnosis, Biosensors 12 (2022) 631, https://doi.org/10.3390/bios12080631.

[107] N. Bhalla, Y. Pan, Z. Yang, A.F. Payam, Opportunities and challenges for biosensors and nanoscale analytical tools for pandemics: COVID-19, ACS Nano 14 (2020) 7783–7807, https://doi.org/10.1021/acsnano.0c04421.

[108] G. Kabay, J. DeCastro, A. Altay, K. Smith, H.-W. Lu, A.M. Capossela, M. Moarefian, K. Aran, C. Dincer, Emerging biosensing technologies for the diagnostics of viral infectious diseases, Adv. Mater. 34 (2022), 2201085, https://doi.org/10.1002/adma.202201085.

[109] S. Alsalameh, K. Alnajjar, T. Makhzoum, N. Al Eman, I. Shakir, T.A. Mir, K. Alkattan, R. Chinnappan, A. Yaqinuddin, Advances in biosensing technologies for diagnosis of COVID-19, Biosensors 12 (2022) 898, https://doi.org/10.3390/bios12100898.

[110] A. Parihar, P. Ranjan, S.K. Sanghi, A.K. Srivastava, R. Khan, Point-of-Care biosensor-based diagnosis of COVID-19 holds promise to combat current and future pandemics, ACS Appl. Bio Mater. 3 (2020) 7326–7343, https://doi.org/10.1021/acsabm.0c01083.
[111] C. Lino, S. Barrias, R. Chaves, F. Adega, P. Martins-Lopes, J.R. Fernandes, Biosensors as diagnostic tools in clinical applications, Biochim. Biophys. Acta Rev. Canc 1877 (2022), 188726, https://doi.org/10.1016/j.bbcan.2022.188726.
[112] S.K. Metkar, K. Girigoswami, Diagnostic biosensors in medicine – a review, Biocatal. Agric. Biotechnol. 17 (2019) 271–283, https://doi.org/10.1016/j.bcab.2018.11.029.
[113] A. Hasan, M. Nurunnabi, M. Morshed, A. Paul, A. Polini, T. Kuila, M. Al Hariri, Y. Lee, A.A. Jaffa, Recent advances in application of biosensors in tissue engineering, Biomed Res Int. 2014 (2014), 307519, https://doi.org/10.1155/2014/307519.
[114] E.Y. Xi Loh, M.B. Fauzi, M.H. Ng, P.Y. Ng, S.F. Ng, H. Ariffin, M.C.I. Mohd Amin, Cellular and molecular interaction of human dermal fibroblasts with bacterial nanocellulose composite hydrogel for tissue regeneration, ACS Appl. Mater. Interfaces 10 (2018) 39532–39543, https://doi.org/10.1021/acsami.8b16645.
[115] G.A. Jones, D.S. Bradshaw, Resonance energy transfer: from fundamental theory to recent applications, Front. Physiol. 7 (2019). https://www.frontiersin.org/articles/10.3389/fphy.2019.00100 (accessed March 31, 2023).
[116] S.T. Mahanwar, S.R. Patil, V.M. Naik, S.B. Wakshe, P.V. Anbhule, G.B. Kolekar, An investigation of fluorescence resonance energy transfer between tryptophan and quinine sulphate, Macromol. Symp. 387 (2019), 1800204, https://doi.org/10.1002/masy.201800204.
[117] R.B. Sekar, A. Periasamy, Fluorescence resonance energy transfer (FRET) microscopy imaging of live cell protein localizations, J. Cell Biol. 160 (2003) 629–633, https://doi.org/10.1083/jcb.200210140.
[118] P. Kaynezhad, R. Fosbury, C. Hogg, I. Tachtsidis, S. Sivaprasad, G. Jeffery, Near infrared spectroscopy reveals instability in retinal mitochondrial metabolism and haemodynamics with blue light exposure at environmental levels, J. Biophot. 15 (2022), e202100283, https://doi.org/10.1002/jbio.202100283.
[119] K.B. Beć, J. Grabska, C.W. Huck, Near-infrared spectroscopy in bio-applications, Molecules 25 (2020) 2948, https://doi.org/10.3390/molecules25122948.
[120] H.-C. (Shawn) Yang, Z. Liang, N.L. Vike, T. Lee, J.V. Rispoli, E.A. Nauman, T.M. Talavage, Y. Tong, Characterizing near-infrared spectroscopy signal under hypercapnia, J. Biophot. 13 (2020), e202000173, https://doi.org/10.1002/jbio.202000173.
[121] M.E. Noltes, G.M. van Dam, W.B. Nagengast, P.J. van der Zaag, R.H.J.A. Slart, W. Szymanski, S. Kruijff, R.A.J.O. Dierckx, Let's embrace optical imaging: a growing branch on the clinical molecular imaging tree, Eur. J. Nucl. Med. Mol. Imag. 48 (2021) 4120–4128, https://doi.org/10.1007/s00259-021-05476-z.
[122] I. Ozsahin, B. Uzun, D.U. Ozsahin, Selection of photodetectors in nuclear medical imaging using MCDM methods, J. Inst. Met. 17 (2022), C06003, https://doi.org/10.1088/1748-0221/17/06/C06003.
[123] E. Spyratou, Advanced biophotonics techniques: the role of optical tweezers for cells and molecules manipulation associated with cancer, Frontiers in Physics 10 (2022). https://www.frontiersin.org/articles/10.3389/fphy.2022.812192. (Accessed 21 July 2023).
[124] D.C. Sordillo, L.A. Sordillo, Chapter 16 - the principles of machine learning algorithms: applications to biophotonics and disease, in: L.A. Sordillo, P.P. Sordillo (Eds.), Biophotonics, Tryptophan and Disease, Academic Press, 2022, pp. 185–198, https://doi.org/10.1016/B978-0-12-822790-9.00016-4.
[125] G. Genty, L. Salmela, J.M. Dudley, D. Brunner, A. Kokhanovskiy, S. Kobtsev, S.K. Turitsyn, Machine learning and applications in ultrafast photonics, Nat. Photonics 15 (2021) 91–101, https://doi.org/10.1038/s41566-020-00716-4.
[126] S.C. Ndlovu, P. Mthunzi-Kufa, Machine learning in biophotonics: progress and challenges, in: Quantum Computing, Communication, and Simulation III, SPIE, 2023, pp. 226–233, https://doi.org/10.1117/12.2662811.
[127] P. Pradhan, S. Guo, O. Ryabchykov, J. Popp, T.W. Bocklitz, Deep learning a boon for biophotonics? J. Biophot. 13 (2020), e201960186 https://doi.org/10.1002/jbio.201960186.