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RESEARCH ARTICLE

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Teaching and learning in biophotonics: Crossing the bridge between educators and students

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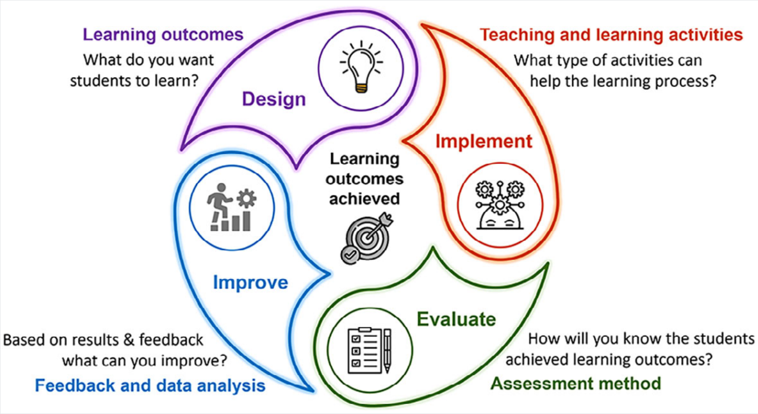
Abstract



As a rapidly growing field, biophotonics demonstrates an increasingly higher demand for interdisciplinary professionals and requires the implementation of a structured approach to educational and outreach activities focused on appropriate curriculum, and teaching and learning for audiences with diverse technical backgrounds and learning styles. Our study shows the main findings upon applying this approach to biophotonics workshops delivered 2 consecutive years while updating and improving learning outcomes, teaching strategies, workshop content based on student and teacher feedback. We provided resources for a variety of lecture-based, experimental, computer simulation activities. Quality of subject matter, teaching, and overall learning was rated as “Very good” or “Good” by 88%, 76%, and 82% of students in average, respectively. Application of our teaching strategies and materials during short- and long-term workshops/courses could potentially increase the interest in pursuing careers in the biophotonics field and related areas, leading to standardized approaches in designing education and outreach events across centers.

KEYWORDS
biomedical optics, biophotonics education, multidisciplinary, teaching and learning, tissue optics

1 | INTRODUCTION

Biophotonics, the science of interaction of the light with biological matter, has provided the opportunity for interdisciplinary collaborations across a wide range of expertise [1], which has led to the development of applications ranging from sensing for medical technologies to therapies including photodynamic therapy or drug delivery. Advances in light-based technologies over the past decades, together with increasing demand for early diagnosis and improvements in the patient care, are the major drivers for the global biophotonics market, which is estimated to reach $91.3 billion by 2024 [2, 3]. The constantly evolving challenges in the health-care system have created a demand for professionals with multidisciplinary expertise. Successful development and deployment of novel biophotonics tools requires not only a solid background in physics, engineering, and optics, but also a working knowledge of laser–tissue interactions and general knowledge of biology and physiology [4]. In response to this need for interdisciplinary scientists and engineers, biophotonics programs have been developed across the world to prepare experts for research-oriented and industry-led professional activities in the field of medical optics and biophotonics [5–7].

At the university level, biophotonics modules are incorporated into biomedical engineering, physics, and medical imaging courses in addition to biophotonics research master's programs. Student engagement with these programs has been steadily increasing [8]. Ideal curricula should bridge scientific and engineering tools with expertise in photonics and life sciences to perform biomedical research on molecular, cellular, and tissue level using bio-inspired photonic devices [9–11]. In addition, a number of textbooks have been published in the field [12, 13]. Moving away from the traditional university teaching setting, two major bi-annual summer schools (International Graduate Summer School in Biophotonics in Sweden since 2003 [14] and Biophotonics and Imaging Graduate Summer School in Ireland since 2008 [15]) provide education for students at post-graduate level. The schools are delivered by internationally renowned lecturers who facilitate an exchange of scientific ideas and discussion on technological advances. Finally, scientific conferences (e.g., SPIE Photonics West, Optica Biomedical Optics) provide the opportunity for technical courses and hands-on workshops on specific topics in the biophotonics field (e.g., tissue optics, Monte Carlo simulations). The biophotonics field also benefits from self-study resources, for example, tutorials written by world leading experts available in specialized journals [16, 17], online research and industry news platforms [18] and a few educational websites providing lectures and materials in microscopy and imaging [19–21], modeling [22, 23], and tissue optics [22, 23]. However, knowledge-based economies are dependent not only on quality but also quantity of STEM graduates. Therefore, the shortage of skilled professionals with suitable expertise might slow down the advances of these novel, non-invasive biophotonics systems and addressing the pressing societal needs. For example, Ireland, with 14 out of 15 top Medtech companies located in the country [24–26], is the second largest Medtech hub in Europe. The Irish pharmaceutical, biotech and medical device industries have a strong demand for top class talent with sector-specific experience in areas such as Quality Control and Quality Assurance (QC & QA), Research and development (R&D), Regulatory Affairs and Manufacturing Technology Transfer. At the same time, students are introduced to biophotonics field late in their educational journey, typically after having separate exposure to all biophotonics subfields. This can be a source of confusion due to the non-standardized tools, methodologies and vocabulary used across different fields (e.g., cellular studies use different optical tools and methodologies compared with tissue research). In order to overcome the shortfall of biophotonics professionals, it is vital to encourage and inspire young people to enter the biophotonics research and manufacturing fields. The exposure to the advances and opportunities that biophotonics creates are needed at all educational levels, from children to under- and post-graduate students. Therefore, a structured approach to educational and outreach activities, focusing not only on appropriate curriculum, but also on effectiveness of teaching and learning should be developed.

There are several techniques available for multidisciplinary teaching. For example, three strategies have been identified by Nikitina [27]: contextualizing (embedding the facts and ideas in the cultural, historical, theoretical, or ideological context), conceptualizing (taking scientific and mathematical thinking beyond the facts and singular theories), and problem-centering (using real-world problems to connect multiple disciplines). An effective

TABLE 1 Main findings on problems and solutions for multi- and interdisciplinary education in biophotonics-related topics.

Problem		Solution	
Aspect observed	**Why does it need to be changed? (reason for changing upon students' and teachers suggestions)**	**What needs to be changed? (action to be taken)**	**How does it need to be changed? (how to implement actions)**
Perception of students with diverse academic backgrounds	Part of experiments and computer exercises were too basic for some students and very challenging for others	More personalized explanations and material taking into consideration the diversity of academic backgrounds in the specific audience taught at each iteration of the workshop/course/module	Adding flipped classroom [61, 62] components, and pre-lecture assignments with online material containing basic concepts to contextualize the lecture content as well as an online platform where students could send questions to the teachers
Workshop structure: duration and types of activities	The lecture was the most challenging part of the workshop. According to one teacher, there was lack of student participation in making or answering questions during computer exercises. According to one participant, there was an unclear overview on how topics would be covered in the second day. According to another student, students could potentially easier focus on the lecture and associate its contents with those of lab experiments and computer simulations if activities are shorter and given in the same day	The workshop schedule and content should provide mini-sessions covering fewer topics	Making hybrid and standalone modules comprising lecture, computer exercises and lab experiments covering fewer topics at shorter durations
Subject-specific interest	Students were more interested in subjects that they could associate with applications in the medical environment. Reducing the number of topics covered in the lecture from 10 (1st workshop) to the 5 (2nd workshop) rated as most interesting by students led to an increase from 29% to 83% of "Very good" responses in the teachers' feedback regarding students' interest, engagement and participation in discussions	Spend more time on applied concepts and give additional examples of applications while still meeting the workshop goals	Inclusion of additional applied topics in future workshops and linking this information with opportunities in the area of careers in biophotonics. Introduce students to more tangible topics first. Invite a professional who is working on the taught subject (peer-learning setting + discussion with expert). Schedule a guided visit to the institutions where the subject is a common practice
Verbalization of questions and answers	Students raised issues with the computer exercises which were not verbalized in the classroom	Introduce a different format of presenting the information and engaging students in discussions with active learning tasks which enable teachers to provide real-time constructive feedback	Adopting a flipped classroom setting clarifying the objectives of computer exercises while providing handouts and a user-friendly graphical user interface (GUI) accessible by students online (via webpage) or offline (via installation)

(Continues)

TABLE 1 (Continued)

Problem		Solution	
Aspect observed	**Why does it need to be changed? (reason for changing upon students' and teachers suggestions)**	**What needs to be changed? (action to be taken)**	**How does it need to be changed? (how to implement actions)**
Professional relevance of technical content	Students were interested in learning how the skills they possessed could be useful to their own careers (partly covered in the workshop)	Short-term overview modules/workshops: emphasize learning outcomes relevant to careers so that students would have the opportunity to choose topics related to the career in which they were interested. Long-term courses: assess students by their creativity and ability to solve problems in their areas of interest in addition to their overall performance	Short-term overview modules/workshops: provide sufficient background for students to discuss about the field with a biophotonics professional or someone that could give relevant insights to their future careers. Long-term courses: simultaneously collect more information about students' interest for subsequent evaluation of customized problem-solving skills via peer teaching and learning (formative assessment), and subsequent exams (summative assessment)

teaching method should incorporate aspects of all three strategies for mutual benefit. Another popular teaching technique, based on discussion among students, is the peer-assisted learning or peer-instruction strategy [28], This strategy works on the assumption that individuals at similar cognitive levels can explain the content in a more understandable manner. Students taught with this strategy have demonstrated better conceptual learning and problem-solving abilities than traditionally taught students [28–31]. Additionally, students with a lower-level background knowledge and understanding gain from this approach as much as students with the higher one. This is a particularly important factor for an interdisciplinary topic such as biophotonics [29].

As a result of the harmonization of various systems of European higher education (Bologna Process) in Europe in recent years, learning outcomes have become the international language for describing programs in primary, secondary, and tertiary education [32]. Learning outcomes are statements describing what a student should know, understand, and be able to demonstrate at the end of a learning activity, including lectures, modules (short courses) or entire programs. Bloom's taxonomy [33] is a useful tool to help to write learning outcomes and is composed of three domains: cognitive (includes knowledge, comprehension, application, analysis, synthesis, and evaluation), affective (ranges from basic willingness to receive information to the integration of beliefs, ideas, values, and attitudes) and psychomotor (co-ordinates brain and muscular activities).

Another important aspect of any teaching strategy is the level of student engagement as it can be directly correlated to their success [34] and achievement of learning outcomes [35]. An effective teaching strategy must also adapt to the different learning styles of the students in the class. Rose et al. [36] categorized them into three areas: visual, auditory, and kinesthetic. A different categorization, provided by Honey et al. [37], separates the styles into theoretical (involves reading and listening to experts), pragmatic (understanding of practical application of the theory), reflective (understanding through imagination and emotional aspect), and activist (learning by hands-on activities). Similarly, the theory of multiple intelligences by Gardner et al. [38] defines the learning styles as visual/spatial, verbal/linguistic, logical/mathematical, bodily/kinesthetic, interpersonal, and intrapersonal.

Due to the unique combination of learning styles exhibited by each individual, sufficient variety of teaching in multiple formats have to be provided. The traditional lecture-based approach, commonly applied in biophotonics, provides students with knowledge of each of the multidisciplinary fields. However, this method does not engage all types of learners and it does not promote the real-world problem-solving skills, critical thinking or team work which are crucial in professional practice [39]. On the other hand, an active learning approach based on discovery and problem-solving challenges stimulates a different group of learners while also promoting motivation and enthusiasm of all the students in addition to the development of skills outlined above. In the area of biophotonics, these active learning methodologies should include activities such as interactive laboratory experiences, discussions, and the development and use of practical biophotonics devices [40–44]. With the above in mind, we designed and tested our education approach involving a variety of activities to meet the needs of students of every learning style, and to enable knowledge exchange during group discussions and activities (due to the potential focus on particular activities and technical topics). It is worth noting that the effectiveness of our approach is valid in any point of view involving learning styles, since their existence and influence in the learning process has been strongly debated [45].

While the curriculum of biophotonics modules, courses and activities has been developed over the years, structured approach for the design of biophotonics programs incorporating different stimuli and teaching methods, student assessment, qualitative and quantitative feedback, and subsequent update of the course design is still missing. Furthermore, challenges to increase the engagement of audiences with diverse technical backgrounds have not been addressed for a range of inter- and multidisciplinary topics including biophotonics. These challenges are even more evident for short modules/events of <10 h, as providing the audience with information cross-cutting multiple disciplines is time-consuming. Our study aims to provide resources for a variety of lecture, experimental, and computer simulation activities compatible with short events and/or modules within long-term courses in biophotonics and related areas. Our study also illustrates the implementation of a state-of-the-art approach for interdisciplinary education which focuses on the continuous update and improvement of learning outcomes, teaching strategies, and workshop content based on student and teacher feedback. In order to achieve this, we have designed a workshop based on different learning styles, multidisciplinary teaching, and learning techniques to foster student interaction and engagement. We have implemented contextualizing, conceptualizing, and problem-centering strategies in addition to brainstorming [46] and recapitulation as integral parts of the workshop. The learning outcomes were drawn from the cognitive and affective domains of Bloom's Taxonomy and designed in accordance with best practice in the literature [32]. Quantitative and qualitative information were provided to us through feedback questionnaires and 12 recorded semi-structured interviews with students, as well as teacher and teacher assistant feedback about student participation and discussions in class. The collected data were analyzed to identify the strengths and weaknesses of our approach and subsequently used to improve the workshop content. The design and implementation of this biophotonics workshop can be considered as a case study in educational research [47] and our findings (Table 1 at the Results and Discussion section) may be applied to multi- and interdisciplinary settings at short and long-term workshops/courses to increase the number of next-generation biophotonics professionals. Our research includes training both future technology developers and clinical practitioners within a course where they learn and work together, not only promoting knowledge of the latest tools for disease diagnostics and therapy but also encouraging future clinical pull of the technology development process based on unmet clinical needs (instead of a technology push toward general needs).

2 | METHODS

2.1 | Workshop description

Our workshop was delivered in two consecutive years (years 1 and 2) to a group of 34 students ranging from first-year undergraduate courses to first-year Master's courses in Ireland. All students participated in the annual undergraduate and postgraduate summer student bursary program of the Irish Photonic Integration Centre (IPIC) at Tyndall National Institute. This program offers an immersive research experience to students from physics and engineering majors, ranging from astrophysics, instrument engineering to biomedical sciences, who are seeking to gain insight into the photonics research environment. During their internship students are assigned a research mentor and spend 10 weeks undertaking a research project. In addition, students are invited to a series of workshops and talks covering a range of technical and non-technical skills, as well as the opportunity to network with current PhD students and scientists. The overall aim of the biophotonics workshop focused on delivering a wide overview of the biophotonics field and sparking interest in pursuing a career within the field or in a related area among the participants. Given the short duration of our workshop (about 7 h), we designed the workshop primarily for outreach instead of education (with a goal of learning the content). Our outreach goals included inspiring students to continue studying biophotonics by teaching them basic concepts and illustrating promising application areas.

The workshop objectives were developed and divided into non-technical and technical areas [48, 49]. The non-technical objectives involved giving students

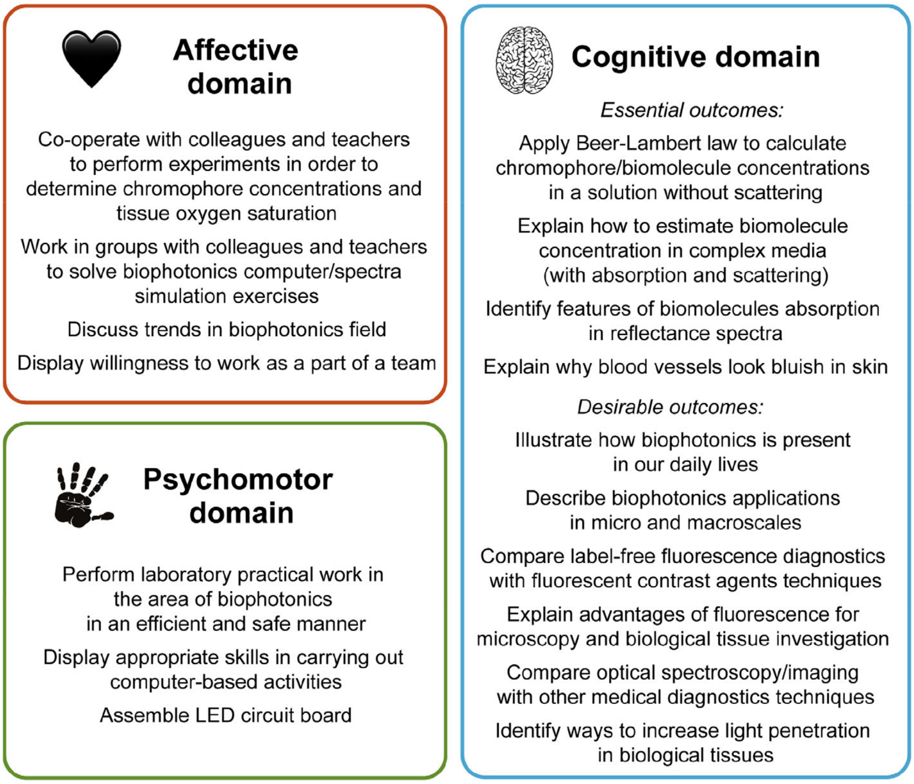


FIGURE 1 Biophotonics workshop learning outcomes in the cognitive (blue, right), affective (red, top left), and psychomotor domain (green, bottom left).

an overview of basic research applications, the potential for future industrial growth, as well as providing the opportunity to enhance their communication skills, critical thinking skills, and ability to work as part of a team. Technical objectives included the understanding of basic concepts in the area of tissue optics, the advantages and disadvantages of different optical imaging techniques when compared to other medical imaging modalities, simulation of reflectance spectrum under different conditions and subsequent comparison with experimental results, and becoming acquainted with relevant laboratory equipment when performing experiments. The workshop content and activities were planned assuming students did not have a background in optics or biology.

2.2 | Learning outcomes

Having developed the overall aim and specific objectives of the workshop, the next step in the process of designing workshops and modules, as recommended in the education literature [50], is the crafting of the learning outcomes. A list of learning outcomes from the cognitive, affective and psychomotor domains of Bloom's taxonomy was developed as shown in Figure 1. Since this was our first attempt to carry out a workshop targeting future technology developers and clinical practitioners, the learning outcomes were designed to suit the general audience (especially undergraduate students) interested in getting deeper insight into the research and industrial environment in the field of biophotonics. In order to challenge the students and stimulate their interest, learning outcomes from higher categories of Bloom's taxonomy were also included [32]. The learning outcomes from cognitive domain were sub-divided into two categories: essential (necessary to achieve by all students) and desirable (achievable for most students). After successful completion of the workshop, all students should be able to understand general ideas and future potential of the biophotonics field.

2.3 | Teaching strategy

Our teaching strategy was designed to be inclusive in order to give students an opportunity to review and discuss biophotonics concepts, show clear, and logical transition from one topic to another and stress the connection between theory and practical work. Figure 2A presents seven main teaching strategies implemented in the workshop design in order to achieve this goal. Students' activities were balanced by taking into account the different learning styles [36, 38] shown in Figure 2B. In addition, students were encouraged to participate in brainstorming activities and answer open-ended questions evaluating their understanding of underlying concepts (e.g., "How is biophotonics present in our daily lives?," "Why do blood vessels look

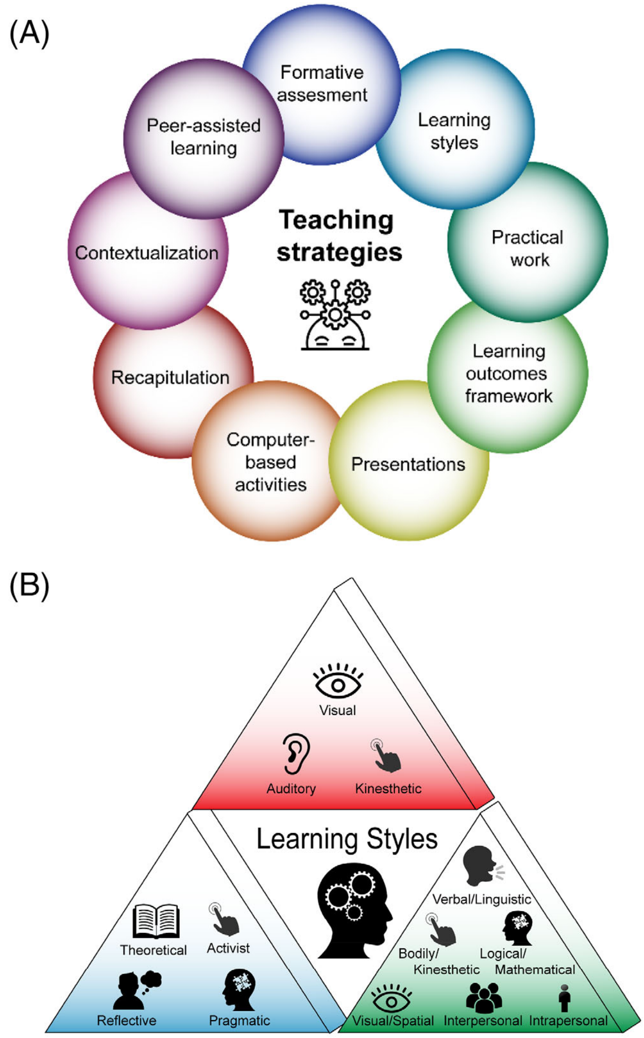


FIGURE 2 (A) Summary of teaching strategies used in the workshop to help students achieve the learning outcomes. (B) Learning styles described by Rose (top red triangle) [36], Honey and Mumford (left blue triangle) [37], and Gardner (right green triangle) [38].

bluish in skin?"). After each brainstorming session the correct answers were revealed in a discussion format between the instructor and the group of students. Recapitulation of the concepts was used to help contextualize activities of the practical session. Furthermore, the practical sessions were centered on the same essential key points as the computer exercises to strengthen the knowledge and understanding of the participating students. Finally, students had the opportunity to assemble their own circuit board with light-emitting diodes (LEDs) to test concepts they had learned in the workshop (fluorescence and light penetration in tissues and everyday objects). Participants were allowed to keep the LED boards after the workshop as a tangible reminder of the learning outcomes they achieved.

2.4 | Workshop structure and resources

Our workshop was carried out across two non-consecutive days. Each day consisted of 4 h (maximum) of various activities. Day 1 of the workshop comprised a lecture and a laboratory tour, while day 2 focused on computer-based activities and laboratory practical work. The students were separated into two smaller groups during day 2 and rotated between the computer-based activities and laboratory practical work. The workshop material provided to the students is included in Data S1. Finally, we aligned the content between theoretical and practical activities to facilitate the communication and teamwork between students pursuing different future specialties. For example, we fostered discussion on various technical domains of biophotonics by showing:

1. How wavelengths are selected in a computer simulation (computer-based activities),
2. What is the effect of wavelengths in a prototype device (laboratory-based activities),
3. Practical considerations of device design (lecture, laboratory tour, round-table discussion, and quiz session),

while enabling focused discussions among students with diverse technical backgrounds, interests, and learning styles. We aimed to build up students' connections starting from their early careers while fostering participation in the workshop activities.

2.4.1 | Lecture

The first day of the workshop began with a lecture given in a conventional setting, including a presentation using Powerpoint slides. During the lecture, students were introduced to biophotonics for macro and microscale applications, learned about different aspects of research environments, as well as industrial and clinical applications. For all lectures, we used a similar workshop material shown during our workshop webinars during COVID-19, which can be found in the Biophotonics YouTube channel [51].

2.4.2 | Laboratory tour

The first day of the workshop concluded with a visit to the biophotonics lab to showcase advanced optical instrumentation. Demonstrations including fluorescent materials and LEDs of different colors were used in order to illustrate biophotonics concepts emphasized during the lecture.

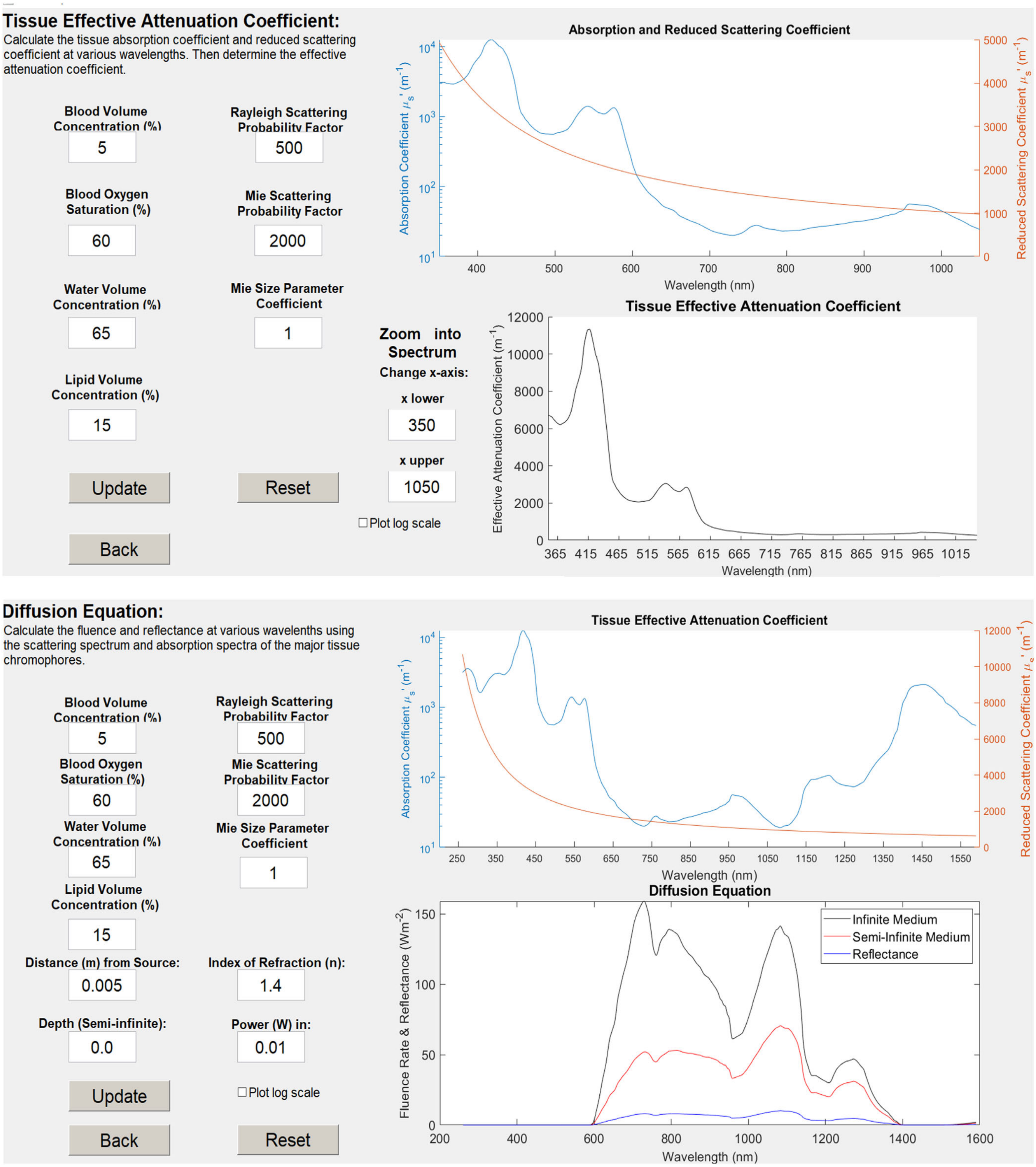


FIGURE 3 Example of two different exercises of the biophotonics app.

2.4.3 | Computer-based activities

The computer-based activities took place on day two and were focused on the application of the theoretical concepts covered in the teaching session. A short introduction and discussion were carried out using Powerpoint slides and whiteboard. Each student received handouts containing instructions and questions to be answered in class. The complete list of computer exercises and simulation guidelines can be found at [52]. A computer with appropriate software installed was assigned to every attendee.

To address the need of different learning styles, students were given the option of group discussion or doing the exercises by themselves. The simulations were performed using a custom-made app (code to generate the app can be found at [53]), which was created as a series of MATLAB graphical user interfaces (GUIs) and allowed students to model optical properties of biological tissues and fluence rates without requiring any prior MATLAB experience [54–56] (Figure 3). Within the app students could vary different parameters such as chromophore concentrations and observe the influence on the spectra. In addition to examining the absorption and scattering spectra, the effective attenuation and reflectance spectra were calculated using the 1D diffusion approximation. By matching spectra simulations with experimentally obtained data, students were able to obtain the original chromophore concentrations. The app allowed students to instantly change the parameters with no need of prior programming experience required by most biophotonics courses and modules, the wavelength range, and scale of the graph. Both computer-based exercises and lab practical activities covered the same topics (tissue absorption, scattering, effective attenuation, reflectance spectra, tissue oxygenation) in order to make it easier for students to achieve the learning outcomes related to measurements and simulations. The complete guidelines to install and use our Tissue Optics app can be found at [57, 58].

2.4.4 | Laboratory activities

The laboratory activities were designed to encourage students to perform calculations and explain the results of their experiments using the concepts learned during day one. With the aid of Powerpoint slides, the concepts learnt during the first day were summarized and experimental procedures were introduced to the students. Detailed instructions for experiments were provided in the form of handouts. Students were divided into groups, and provided with sample material shared within the group. The laboratory practical activities were held in a research-active biophotonics laboratory, where students had access to high-end equipment including spectrometers, commercial medical-grade pulse oximeter, etc.

The first topic was related to tissue absorption. The Beer–Lambert law experiment involved measurements of transmission of light through instant coffee solutions prepared by students and calculations of the unknown concentrations of samples. To understand the limitations of Beer–Lambert law, the effective attenuation coefficient was then introduced with the addition of scatterers in the solutions. During the second activity, students measured the reflectance spectrum of their skin in the visible and near-infrared wavelength range and evaluated the biomolecular features. Finally, pulse oximetry was discussed by taking into consideration all of the previous concepts. Students could compare readings from a commercial pulse oximeter with an experimental result from a simple setup to measure oxygen saturation. In addition, students had the opportunity to build their own circuit board containing ultraviolet, red, green, and blue LEDs. The ultraviolet LEDs had 385 nm peak wavelength 30° viewing angle, and very low brightness (80 mcd luminous intensity), making it safe to use. All LEDs were cheap LEDs commonly sold in electronics stores. The low luminosity of the ultraviolet LED intensity makes it safe to shine on skin for short periods of time. To ensure students used the LEDs safely and to ensure no concerns to ultraviolet LEDs being harmful and/or hazardous, we instructed students not to shine LEDs directly into eyes of any person and not have their tissues (skin, ear, etc) exposed to UV for long periods of time (>30 s).

Suggested at-home experiments with the LED circuit board are described at [59], including experiments illustrating similar concepts as the reflectance spectroscopy experiment by describing the penetration of red, green and blue light in skin. The LED circuit tutorial [59] also described light scattering and propagation experiments that could be performed with experiments with phantoms in our second experimental manual [60], which could allow students to reproduce the Beer–Lambert law coffee experiments and the effective attenuation experiments at home. In addition, the phantom matrix tutorial [60] covered more sophisticated experiments that could continue to foster students learning on light propagation in biological tissues. These experiments were suggested as optional because making them during the workshop would take longer than our 7-h allowance by the internship program students were taking part on.

2.4.5 | Recapitulation and round table discussion

After covering each activity during the second day, a set of questions was prepared to test the students' knowledge and understanding and enhance their learning by allowing them to discuss the questions and answers with fellow students and teachers. At this stage, hands-on activities involved the same topics while showing a different practical perspective with computer exercises and experimental activities. The computer exercises detailed concepts by showing all the underlying theory involved

TABLE 2 Lecture topics for the workshop delivered in years 1 and 2. Topics were chosen to meet all learning outcomes.

Year 1	Year 2
Fluorescence and microscopy	Fluorescence and multiphoton processes
History of Nobel prizes in Biophotonics	Diffuse optics
Fluorescence diagnostics and optical treatments	Optical spectroscopy and imaging—medical applications
How to see deep into tissue	Optics and ultrasound
Scattering and absorption and applications	Future trends
Diffusion theory	
Optical medical imaging applications	
Photoacoustics	
Acousto-optics	
Future trends	

in simulating tissue optics. On the other hand, the experimental activities were focused on how to take reliable and reproducible measurements, while identifying potential sources of error in a real-life setting.

After the hands-on activities, students were grouped together and encouraged to discuss a challenging question involving the concepts presented throughout the workshop. After a short round-table discussion on potential solutions, the full explanation was presented to the group.

2.4.6 | Quiz session (summative assessment)

The quiz session comprised of a set of two open-ended listing questions and 10 multiple-choice questions (see Data S1). During the quiz session, students were grouped in pairs for the listing questions and given 3 min to solve both of them. The same pairs were kept for the first five quiz questions, which were asked one by one. Students were given 1 min to answer each question. Then, students switched pairs to respond to the five remaining questions. Due to the length limit of the workshop, the quiz session was only introduced in the year 2 workshop after briefing activities of day 2 after the day-1 lecture and reducing the lecture content (discussed in Section 3.4 and Table 2).

Despite the nature of the quiz session to provide summative assessment for learning outcomes in the cognitive domain, it is important to note that we did not expect as high scores as in the context of long-term university courses. We planned the quiz session to provide opportunities for peer-assisted learning, while emphasizing concepts that students can potentially use the most if pursuing a career in Biophotonics, and giving students an idea of how much more there is to learn (not only how much learning outcomes were met, but also putting the small fraction of workshop content into a broader perspective).

2.5 | Teacher's assessment (formative assessment)

Our assessment method comprised of the evaluation of the whole group of students in terms of engagement, participation, and interest in the three parts of the workshop (presentation, laboratory practical activities, and computer-based activities) and sub-activities. The teachers also assessed students' ability to use the biophotonics app and laboratory equipment to solve computer and laboratory exercises. Finally, the achievement of learning outcomes was assessed by the teachers based on their impressions regarding the participation and performance of each student. This information was considered together with student feedback to help in reviewing the learning outcomes and the overall structure of the workshop to assist in planning future workshops.

As part of the assessment, feedback questionnaires were circulated to the teachers and teacher assistants. Teachers rated various statements on a Likert scale varying from 5 for "Very high"/"Very good", to 1 for "Very low"/"Very poor." The method of assessment carried out by the teachers was of a formative nature (i.e., in the beginning and during the workshop) rather than the traditional summative assessment approach commonly used at the university level for long-term courses involving assessment at the end of the program [32].

2.6 | Student's feedback

As mentioned above, all students were asked to complete an anonymous feedback questionnaire at the end of the workshop to rate their interest in the topics and workshop sessions. In addition, students provided feedback about the quality of the subject material, teaching, explanations given to them, as well as what influenced their learning process throughout the workshop. Students rated the statements on a Likert scale varying from 5 for "Very interesting"/"Very good," to 1 for "No interest"/"Very poor." The feedback questionnaire focused on quantitative information regarding specific aspects of the workshop and was analyzed by the distribution of the answers for each question. Students were also invited to participate in a 20-min semi-structured interview to be held 2 weeks after the workshop, which data was only used to suggest general improvements for future workshops. Qualitative analysis was not the focus of this paper and will be featured in future work.

3 | RESULTS AND DISCUSSION

In this section, we introduce the results achieved in our workshop and improvements to be implemented based on the components of constructive alignment (see Section 3.4). We discuss several aspects of student's and teacher's feedback focusing on the best educational practices listed in the literature. Then, we explain how to improve the workshop by giving suggestions associated with each issue raised by students and teachers (see Supporting Information for the feedback questionnaires and interviews).

3.1 | Improvements based on student's feedback

Overall, the data analysis has shown that the biophotonics lecture was successful in the areas of quality of the subject matter and teaching (94% and 94% "Very good" or "Good" scores for the year 1 workshop, respectively, and 88%, 100% for the year 2 workshop). High rates of "Very good" or "Good" scores were also observed for computer exercises in quality of teaching (94% for the year 1 workshop and 100% for the year 2 workshop) and subject matter (77% for the year 1 workshop and 94% for the year 2 workshop). Similar scores were observed for the laboratory activities (100% for quality of teaching and 93% for quality of subject matter), as per evaluated in the year 2 workshop. Scores of laboratory activities were not evaluated for the year 1 workshop. The overall learning was >72% for each and every part of the workshop (on average for each workshop, 88% $\pm$ 7% for the lecture, 76% $\pm$ 4% for computer exercises, and 82% $\pm$ 2% for laboratory experiments) and laboratory activities were considered the most interesting part (46% votes out of 5 activities in the year 1 workshop and 71% of "Very interested" and "Interested" responses in the year 2 workshop). In addition, students found the connection between laboratory experiments and computer exercises clear and useful.

Even though we received positive feedback in most aspects, the clarity and relevance of our instructions were perceived differently among students with different background and learning styles. For instance, participants from physics and chemical physics backgrounds were already familiar with some of the experiments and found the laboratory experiments the least challenging part of the workshop. Also, a small number of participants mentioned the computer exercises were too basic, while students in biomedical science were not familiar with the software. Therefore, the design of future workshops will need to take into consideration to a greater extent the diverse academic backgrounds from which the students originate. Recommendations include adding flipped classroom components and pre-lecture assignments with online material. This material should contain basic concepts to contextualize the lecture content. Another suggestion involves an online platform where students could send questions to the teachers. Then, teachers could either respond to the questions online or prepare materials to discuss answers and solution in the class.

In the second workshop, students correctly responded 58% $\pm$ 12% of the quiz questions, from which 43% $\pm$ 11% were correct among the questions referring to the content of the first day of the workshop (conducted in the previous week) and 67% $\pm$ 19% referred to those of the second day. Overall, questions on topics covered only in the first day (1 week before the quiz) were perceived as challenging. In terms of the listing questions, students suggested (7 $\pm$ 2) correct entries for "biophotonic applications in your daily lives" and "technologies that are future trends in the biophotonics field". The interview feedback showed students enjoyed the quiz session experience and would be willing to answer more questions. Also the length and amount of concentration during the lecture differed from interactive exercises at the computer and research labs.

Regarding the duration and types of activities, improvements can be made by restructuring the workshop schedule and content in order to provide mini-sessions covering fewer topics in a shorter hybrid lecture (Table 1). Each session would have a lecture assisted by computer modeling that would lead into experimental activities. By placing these three parts together in the same day, students can readily associate concepts covered by means of three different types of activities.

Students were more interested in subjects that they could associate with applications in the medical environment. One of the main suggestions for improvements in future workshops was to spend more time on applied concepts and give additional examples of applications. Since applied concepts and laboratory activities were effective in generating interest and improving student learning, the inclusion of additional applied topics in future workshops and linking this information with opportunities in the area of careers in biophotonics may attract more students to the field. The same strategy applies to outreach activities or the first lectures of biophotonics modules whose objective is providing an overview of the topic and attracting students' interest to increase their participation throughout the module. Therefore, even when the instructor is teaching theoretical concepts, we recommend the teacher to introduce students to more tangible topics first. In addition, inviting a professional who is working on the taught subject or scheduling a guided visit to the institutions where the subject is a common practice (e.g., industry, research center, hospital, etc) can stimulate students' engagement. In this case, more benefits can be achieved in a peer-learning setting, that is, when students monitor their learning by comparing answers to a set of questions before and after discussing among themselves and with an expert.

In both feedback questionnaires and interviews, students felt working in groups was beneficial. This indicates that the students achieved the essential learning outcomes in the affective domain. One of the interviewees mentioned this approach helped them to successfully complete group activities. This suggests that using additional teaching strategies to encourage discussion among students and provide constructive feedback, e.g. making more use of peer-assisted learning [28, 29], may be effective in a future workshop and in interdisciplinary modules. Regarding the implementation of peer-assisted learning strategies, discussion time and topics should be limited to key points shown to be unsuccessfully understood by students in their summative assessment.

3.2 | Improvements based on teachers' assessment

The teachers were asked to quantify the extent to which they thought the students understood various concepts. The teachers agreed that all students grasped the main concepts introduced in the second day of the workshop. Also, most of the essential learning outcomes were well rated, but several desirable ones did not achieve high scores.

Teaching and learning approaches scored well with the teachers choosing either "Good" or "Very good" responses. Student engagement and interest scored well for all activities throughout the workshop. The use of the biophotonics app for the computer exercises was rated very well.

Teacher's feedback was in agreement with student feedback, which suggests teachers understood the students' point of view sufficiently to improve the next workshop. The success of the teaching and learning approach "matching topics between laboratory and computer exercises" can be corroborated by the student's feedback where 100% students said that they felt there was good coordination between what was learned in the laboratory and the computer activities. The success of experimental activities in terms of student interest, participation, and engagement agrees with the positive student feedback. In the lecture presentation, students were less likely to ask questions, but once in the lab they were willing to participate to a greater extent. This behavior agrees with interviewed students' comments about the most challenging part of the workshop (the lecture) and suggests the strategy discussed in the Section 3.1 (i.e., placing lecture, computer exercises, and experimental activities in each day of the event) would help students to learn about the introduced concepts. This strategy can also help to solve the lack of student participation in making or answering questions commented by one of teachers, as well as to solve the unclear overview on how topics would be covered in the second day, as mentioned by one of the interviewees. Since, in the student questionnaires, the students raised issues with the computer exercises which were not verbalized in the classroom, a different format of presenting the information and engaging students in discussions could enable student participation while maintaining the quality of teaching and subject matter. This format should not depend only on computer exercise questions provided both as a worksheet (in the handouts) and on the presentation, but also include active learning tasks in order to give a chance for teachers to understand student needs and provide constructive feedback. One example is adopting a flipped classroom setting clarifying the objectives of computer exercises while providing handouts and a user-friendly GUI accessible by students online (via webpage) or offline (via installation).

3.3 | Practical constraints of this study

This study took place over 7 h in total, split over 2 days. Ideally, an introduction to a multidisciplinary field such as biophotonics could be longer in duration, taking place over multiple weeks. Nevertheless, despite the workshop's relatively short duration, students were exposed to a broad range of concepts in biophotonics, via numerous methods (presentation, practical experiments, and computer exercises), and experienced the multidisciplinary nature of this field. A longer workshop, although aspirational, requires greater time-commitment from the studied cohort, and may be impractical, considering such students are engaged in full-time undergraduate or postgraduate education.

Also, it is important to note that measuring long-term outcomes can be challenging in a workshop of short duration. While we have implemented a system to request permission to follow up on student career development, this follow-up tends to have less responses compared to longer courses associated with a university ecosystem of partner companies and research/medical institutions offering employment to alumni through events such as career fairs. In short-term courses, we believe that create a similar ecosystem can help to track student career development and potentially measure long-term outcomes. Also, measuring the influence of a 7-h workshop in long-term career prospects would be effective upon asking short questions on information that can be fully associated with the workshop (e.g., career development associated to pursuing career in Biophotonics-related areas and/or the use of the workshop in other career paths).

Finally, measuring long-term outcomes would require decoupling workshop activities from any other associated activity and information from student background. Currently, the long-term follow up on student career development will be collected for all activities in the IPIC/Tyndall bursary program (not specific to the Biophotonics workshop only), and will not separate what students learned in the workshop as opposed to in their undergraduate and Master's courses. If there is institutional interest in tracking the learning outcomes of a specific course, questions to be asked in feedback evaluation must not be associated with all courses the institution offers, and should minimize acquiring information from potentially related courses (which may be difficult in several cases, since students may have subsequent specialization courses and/or Master's/PhD in areas associated with their undergraduate courses).

3.4 | Future recommendations

The workshop was modified using the three components of constructive alignment [32, 63, 64], which involved the interaction among the learning outcomes, teaching and learning activities, and assessment (Figure 4). These three components were considered and revised according to the feedback received.

It is clear from the education literature [50] that the development of a module or workshop should be carried out in an iterative fashion involving the steps shown in Figure 5.

In the first workshop, the students and teachers' feedback (Data S1) clearly showed that success has been achieved in assessing the learning outcomes in the affective and psychomotor domains. Analysis of this feedback indicated that students were interested in learning how the skills they possessed could be useful to their own careers. This learning could involve pursuing a career in

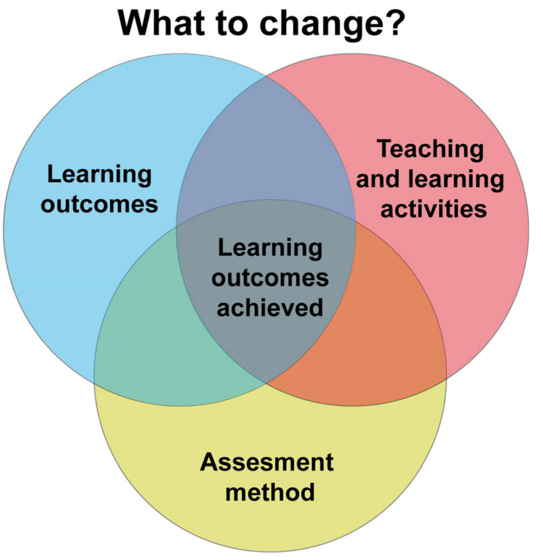


FIGURE 4 The three components of constructive alignment.

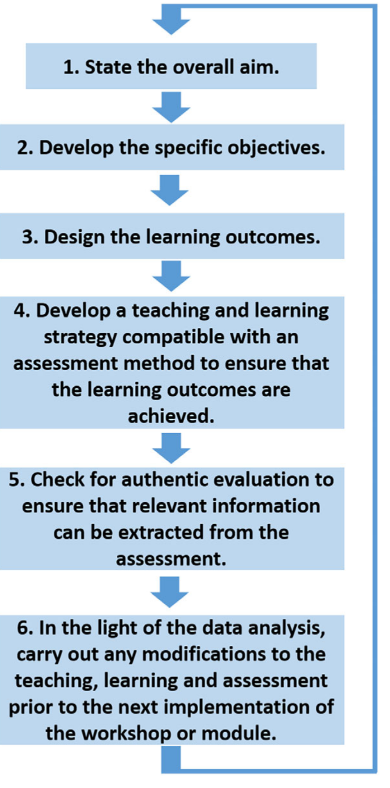


FIGURE 5 Iterative steps for the development of a module or workshop.

biophotonics (or related area) or having sufficient background to discuss about the field with a biophotonics professional or someone that could give relevant insights to their future careers. We decided to emphasize learning outcomes relevant to careers so that students would have the opportunity to choose topics related to the career in which they were interested. In long-term courses, teachers need to assess students by their creativity and ability to solve problems in their areas of interest instead of taking into consideration only their overall performance. This assessment requires simultaneously collecting more information about students' interest for subsequent evaluation of customized problem-solving skills. For example, a formative assessment method based on peer teaching and learning should be implemented in the workshop.

Implementing active learning strategies such as peer-instruction would be ideal for multi/interdisciplinary teaching and learning settings, as this strategy allows individuals to discuss solutions to open-ended interdisciplinary questions in groups including participants with different backgrounds. With this in mind, prior knowledge of student interest would facilitate the selection of topics for interdisciplinary questions based on evidence about student interest in real-life biophotonics applications. This selection can shorten the time allocated to discussion, as peer learning is dependent on student interaction and teachers have less control in guiding this type of learning [30, 31]. In the first delivery of our workshop, we opted to cover as many topics as possible in our lectures, and gather student feedback on the most and the least interesting lecture topics. In the second workshop, we reduced the number of topics from 10 to 5 (Table 2) based on students' interest and used the extra time on demonstrations that reinforced the main biophotonics concepts. It is worth noting that the reduction in the number topics did not affect any other workshop activity and association between concepts of lecture, computer simulations, and lab experiments. As a result, "Very good" responses on the teachers' feedback regarding students' interest, engagement and participation in discussions went from 29% to 83%. Also, we observed improvements in student ratings for quality of teaching (from 94% in year 1 to 100% in year 2), a decrease in quality of subject matter (from 94% in year 1 to 88% in year 2), importance of lectures for student learning (from 94% in year 1 to 81% in year 2), and in overall learning associated with the lectures (from 100% in year 1 to 93% in year 2). However, we emphasize that the decrease in some student ratings was partially due to the awareness of the importance of lecture content in the context of the overall obtained knowledge when tested in the quiz session. This is because the time reduction of the year-1-workshop content allowed us to implement the quiz session only in year 2 for better evaluation of learning outcomes in the cognitive domain. As prior knowledge about the audience is relevant to understand how the group of students will interact, teachers must be aware of the additional time demand peer-instruction requires in the beginning of its implementation.

Teachers must also be trained to carefully carry out instructional roles when students at different academic levels are present in the same class [30]. Instead of emphasizing the original peer-instruction approach (asking the same question before and after student discussion), we adapted its approach by giving students the opportunity to think about sets of questions, discuss, and suggest answers before the teacher discussed the full explanation. This adaptation was necessary to fit the discussions in the short time limit of the workshop schedule. However, if all peer-instruction requirements are addressed and it can be applied systematically, its advantages far outweigh its drawbacks when compared to teacher-led educational approaches. Peer-instruction can lead to higher academic achievement and have other classroom benefits even for teachers [30]. Therefore, when organizing future workshops, greater emphasis should be placed on peer-assisted learning.

4 | CONCLUSIONS

With the present rapid growth of the field of biophotonics, strategies for the development and harmonization of education programs worldwide are becoming increasingly relevant. The challenges in biophotonics education are particularly difficult due to the inter- and multi-disciplinary needs leading to time-consuming activities and relatively low cognitive engagement [65]. In the presented workshop, designed for sparking the interest in biophotonics field among a cohort of undergraduate students, the essential learning outcomes were achieved and students responded positively to the teaching methods used in this study. We believe that the success of this workshop illustrates the importance of implementing state-of-the-art educational approaches in biophotonics education and outreach. We hope that the work described in this paper will contribute to addressing the challenges faced by other researchers involved in the education of the new generation of professionals working in biophotonics and related areas.

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CONFLICT OF INTEREST STATEMENT

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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