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Systematic Review of Teaching Kits in Biomedical Engineering Education

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1. Introduction

1.1. Motivation

Teaching kits have become invaluable tools in biomedical engineering education, providing students with hands-on opportunities to apply theoretical concepts, develop technical skills, and engage in problem-solving activities. Such kits provide interactive learning opportunities that help students link abstract material to physical concepts. However, despite their increasing adoption in laboratories and classrooms, there is significant variability in the technologies and pedagogical strategies used across different teaching kits. Furthermore, their overall effectiveness in achieving specific learning outcomes remains underexplored, highlighting a critical need for further investigation in this area.

This systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to comprehensively analyze the current landscape of teaching kits in biomedical engineering education. The review focuses on evaluating the types of technologies integrated into these kits, the educational methodologies they support, and the outcomes reported in existing studies. This examination takes a human factors approach and describes and compares existing solutions.

The categorization and exploration of teaching materials is not a frequently researched field and while many educators have individual solutions for their class that spread to other institutions via word of mouth, there is very little formal evidence outlining best practices in the field.

The findings of this review will offer valuable insights for educators, researchers, and developers, providing a foundation for designing more effective teaching tools that align with evolving educational needs. By addressing these gaps and building on identified best practices, this research aims to contribute to the advancement of biomedical engineering education, ultimately enhancing the learning experience and better preparing students for professional practice.

1.2. Definition of "Teaching Kit"

This review defines "teaching kit" as a collection of materials, tools or resources that serves the purpose of assisting educators in delivering an instructional experience or that assists students in understanding and participating in an instructional experience.

1.3. Definition of "Bioengineering"

This review defines "bioengineering" a) as any engineering related activity with the goal of improving human health, or b) an activity that would give students in an accredited biomedical engineering program the skills that would be necessary to engage in a).

1.4. Methodology

PRISMA-S (Preferred Reporting Items for Systematic Reviews and Meta-Analyses – Search) is a reporting guideline designed to enhance the transparency, comprehensiveness, and reproducibility of search strategies in systematic reviews and meta-analyses. As an extension to the broader PRISMA Statement, PRISMA-S focuses specifically on the search component, which is crucial for identifying all relevant studies. The guideline includes twelve checklist items, covering essential aspects such as specifying the databases and platforms used, providing full search strategies with detailed syntax, and reporting any limits or restrictions applied. It also emphasizes transparency in documenting supplementary search methods, such as manual searching or citation chasing, and requires reporting the number of records identified from each source. Additionally, PRISMA-S highlights the need to describe software or tools used, updates to the search, and methods for record deduplication. Justifications for including grey literature and for using non-database search methods are also critical components. By addressing these elements, PRISMA-S ensures that systematic review search strategies are fully documented, facilitating verification, replication, and confidence in the evidence synthesis process [1].

2. Method

2.1. Information Sources and Methods

The databases searched included SCOPUS, Web of Science, ERIC, and Education Source, which represent some of the most widely recognized and comprehensive sources for academic research. To complement these database searches, specific journals were selected for hand searching. The targeted journals were *Biomedical Engineering Education* and *Engineering Studies*, both of which publish research closely aligned with the focus of this study as per their editorial statements. This combined approach ensured coverage of both broad and specialized sources relevant to the topic.

Multi-database searches were initially attempted to cast a wider net; however, the results were not included due to the high proportion of irrelevant results and the overwhelming volume of diverse content that was not feasible to screen effectively. To maintain focus and efficiency, only results from the most reliable and directly applicable sources were retained for further analysis. This approach ensured the data remained manageable and aligned with the study's objectives. It is important to note that education technology is a new and emerging field with a lack of standardized terminology, so most searches need to have a broad scope to identify all useful papers.

Additional strategies, such as searching study registries, citing literature, or contacting authors, were not prioritized for this review. Study registries are not commonly utilized in engineering education research, making their inclusion less impactful. Similarly, citing literature and author contact were deemed less effective, as many papers in this field are authored by researchers whose primary focus lies outside of engineering education or by teaching-focused faculty who do not consistently contribute to research. By concentrating on the most relevant and accessible sources, the review was able to achieve thorough and focused coverage of the existing literature.

2.2. Search and Identification Strategies

The following searches were run for the individual databases:

Table 2.2-1 Search Prompts Used

Database	Search Query	Date
SCOPUS	(ALL ("Engineering") AND ALL ("Biomedical" OR "Biology" OR "Bioinstrumentation" OR "bioscience" OR "bio" *) AND TITLE-ABS-KEY ("Educational Kit" OR "Teaching Kit" OR (("Hands-on" OR "lab" * OR "device" OR "equipment" OR "experiential") AND ("teach" * OR "learn" *))))	7-14-2024
ERIC	engineering AND biology AND noft(("kit" OR "manipulative" OR "hands on" OR "lab" OR "device" OR "equipment" OR "experiential"))	7-14-2024 2-18-2025
WoS	ALL=("Engineering") AND ALL=("Biomedical" OR "Biology" OR "Bioinstrumentation" OR "bioscience" OR "bio" *) AND (TI = (("Educational Kit" OR "Teaching Kit" OR (("Hands-on" OR "lab" * OR "device" OR "equipment" OR "experiential") AND ("teach" * OR "learn" * OR "education")))) OR AK = (("Educational Kit" OR "Teaching Kit" OR (("Hands-on" OR "lab" * OR "device" OR "equipment" OR "experiential") AND ("teach" * OR "learn" * OR "education"))))OR AB = (("Educational Kit" OR "Teaching Kit" OR (("Hands-on" OR "lab" * OR "device" OR "equipment" OR "experiential") AND ("teach" * OR "learn" * OR "education")))))	7-14-2024 2-18-2025
Education Source	TX engineering AND TX bio* AND ("Educational Kit" OR "Teaching Kit" OR lab*) AND (open* OR "open source" OR "affordable" OR "low-cost")	7-14-2024 2-18-2025

The author remains up to date on searches by reviewing new editions of key journals (specifically Journal of Engineering Education and Biomedical Engineering Education). No filters or automatic exclusion criteria were included in the search strategy, aside from excluding key words from specific sections (this is visible in the search prompt section in the table above).

2.3. Inclusion and Exclusion Criteria and User Identification

Following the search, the articles were screened based on their abstracts to ensure alignment with the study's focus and objectives. Given the diverse and often non-standard terminology used in education-related research, a substantial number of papers were excluded from full-text review. These excluded papers included those that were either incoherent or completely irrelevant to the subject matter. Additionally, studies that primarily focused on K-12 education, emphasized course design rather than the use or development of educational equipment, or lacked rigorous peer review, such as catalogues or whitepapers, were also screened out. This process was conducted to ensure only relevant research was included for further analysis.

In the full-text review phase papers were excluded for focusing on course design over kit design (n =19), focused on the technical development of a remote lab server (n=15), did not appear to be applicable to engineering students (n = 10), were for a demographic that is younger than the scope of this review (n=10), did not have significant relevance to BME or engineering students (n = 11), did not have significant educational use (n = 5) or were not formatted in a way that was compatible with the review (e.g. a magazine article that does not adequately describe the presented kit; n = 7). In addition, (n = 2) papers were excluded due to multiple papers being present for the same kit.

The ideal end user of a kit is a) a student in an accredited biomedical engineering program, b) a student in a different discipline cross-enrolled in a bioengineering course, c) a student in an outreach program with a skill level similar to that of a or b, or d) an educator that works primarily with students in a, b or c. This assumes that the end user has sufficient cognitive and physical ability to enroll and participate in laboratory-based activities at the post-secondary level. This does not exclude students who abstain from these activities due to financial, geographic or illness (provided they have an appropriate level of physical and cognitive ability) related constraints.

2.4. Managing Records

All articles were screened by a single reviewer, a streamlined approach that allowed for efficient processing within the available resources. While peer review was not incorporated at this stage due to practical considerations (mostly personnel availability), the process was conducted with careful attention to the exclusion criteria mentioned in section 2.3 to ensure consistency and accuracy. This approach aligns with common practices in resource-conscious reviews and provides a solid foundation for the subsequent stages of the systematic review.

Duplicates were primarily identified and removed automatically using the reference management software Covidence, which streamlined the data management process and ensured an efficient and accurate deduplication procedure. Covidence is widely recognized for its reliability in systematic reviews, and its use provided a streamlined and efficient approach to conducting the review while minimizing screening errors. A total of (n = 1,279) records were initially retrieved across multiple databases and sources. Specifically, records were retrieved from Web of Science (n = 556), Education Source (n = 554), Scopus (n = 103), ERIC (n = 60). In addition, some articles were retrieved from hand searching key journals, specifically: Biomedical Engineering Education (BEE; n = 5), and Engineering Studies (n = 1).

Following the deduplication process, the retrieved records were screened to determine their relevance to the study. This screening phase led to the removal of (n = 1,019) studies, mostly due to the lack of standard terminology and inconsistent choice of publishing format present in engineering education research. The following PRISMA diagram describes the search and screening process in more detail:

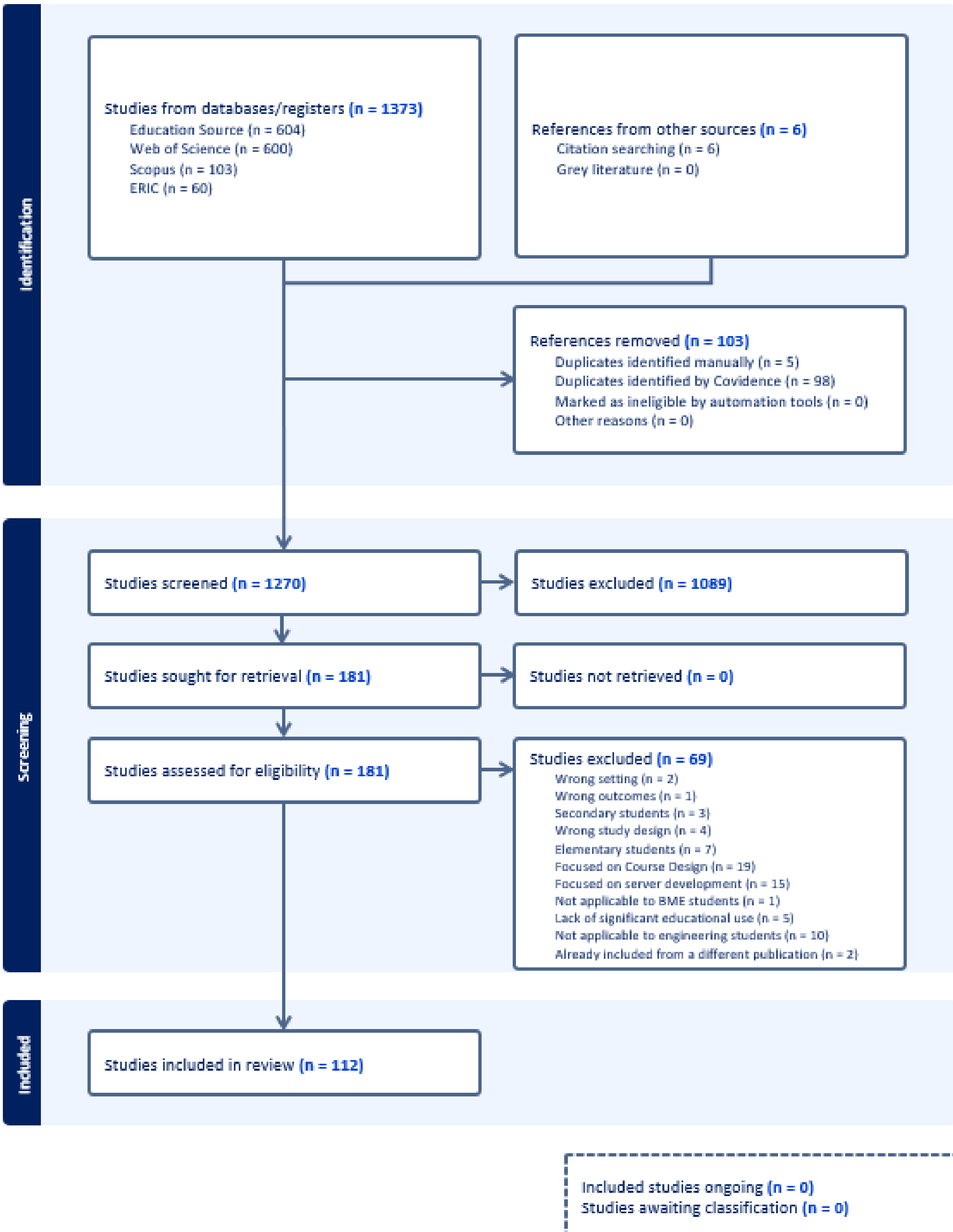

Figure 2.1: PRISMA Flow Diagram

3. Results

The systematic review of teaching kits for biomedical engineering provides a comprehensive analysis of their distribution and characteristics across multiple dimensions. The results highlight geographical trends in kit availability and adoption, as well as changes over time in their development and use. Additionally, the review examines the task hierarchy embedded in these kits, revealing how they scaffold learning experiences. Further, it categorizes the target demographics these kits are designed for, the modalities through which they are delivered, and the diverse subject matters they cover. Together, these findings offer valuable insights into the evolution and current state of biomedical engineering education through hands-on instructional tools.

3.1. Geographical Location

During the investigation, geographical information from the reviewed papers was considered, recognizing the variations in educational standards across different regions. To illustrate these geographical trends, Figure 3.1 below presents a heatmap depicting the locations of the papers included in the review.

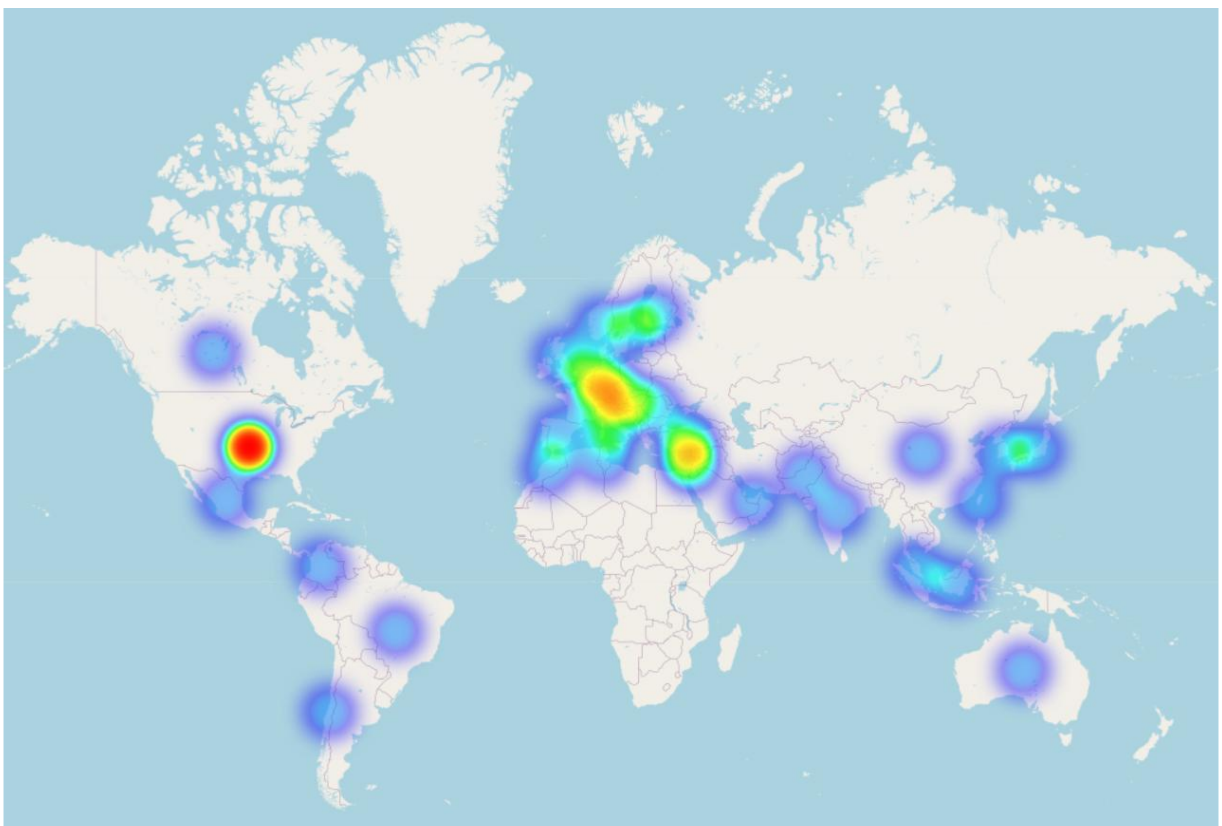

Figure 3.1: Heatmap of Paper Locations

The majority of the papers reviewed (n = 60) originated from the United States, with additional contributions from Asia (n = 13), Europe (n = 19), South/Latin America (n = 3), North Africa (n = 5), Australia (n = 3), and Canada (n = 4). This distribution is unsurprising given the size of these regions and the availability of research funding. Additionally, some international papers originally intended for K-12 education were recategorized as undergraduate-level based on the author's frame of reference. For example, Hsu et al.'s development of an open-source Arduino-based glucose sensor teaching module, designed for middle school students and delivered as a teacher's workshop [2], was reassessed as more aligned with undergraduate-level learning in many institutions outside its country of origin

3.2. Time Period

The review encompasses a diverse range of papers published between 2000 and 2025, providing a broad perspective on the development and evolution of teaching kits for biomedical engineering. The distribution of these papers over time is illustrated in Figure 3.2 below.

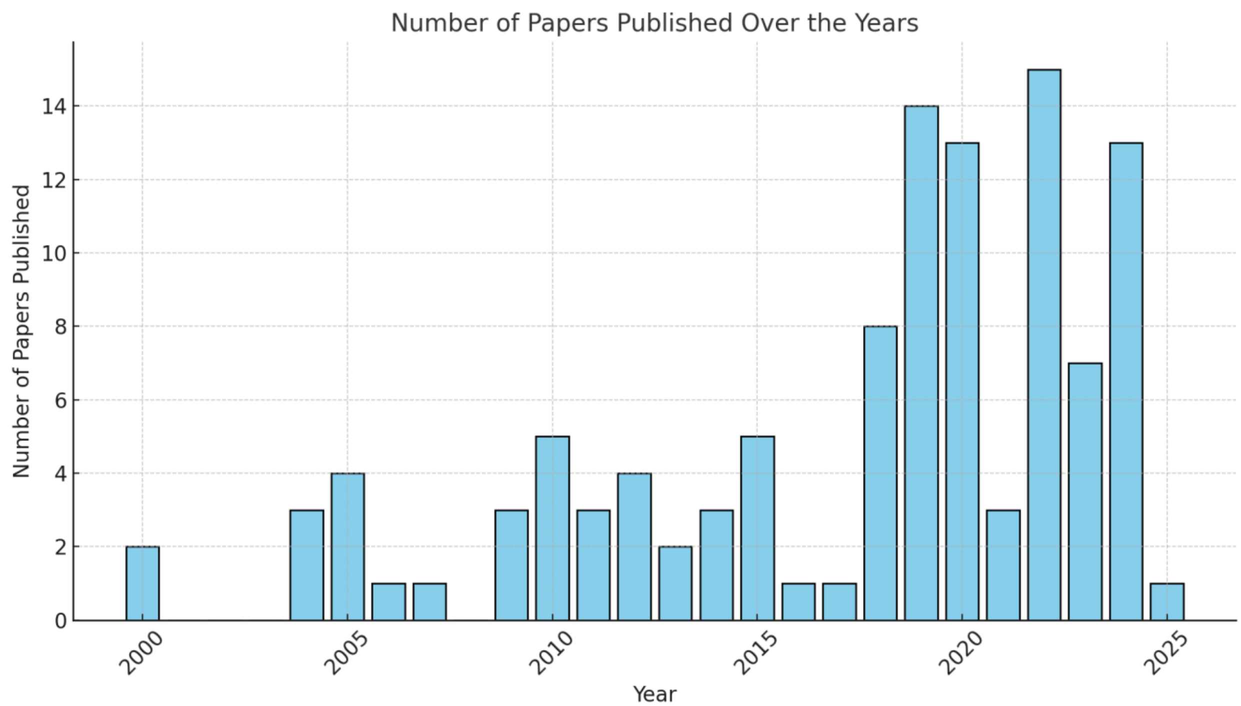

Figure 3.2 Number of Papers Published by Year

A significant increase in the number of papers published after 2019 likely reflects the impact of the COVID-19 pandemic, which heightened demand for remote learning activities, however this rise started in 2018 prior to the pandemic which indicates the presence of other factors. Student attitudes toward remote learning also shifted dramatically in the post-COVID era. Earlier studies, such as Bhargava et al. (2005), found that 65.0% of students preferred physical lab work over virtual alternatives, with only 19.2% favoring online labs and 14.5% expressing no preference [3]. Similarly, Estriegana et al. (2019) reported low engagement with an online learning environment (OLE), noting that only 46% of students completed at least 75% of OLE activities, while 8% engaged with less than 25%. Additionally, they identified a link between student satisfaction and the behavioral intention to use OLEs, with 18.53% of uptake attributed to satisfaction [4]. However, by 2021, Devine and May's study using the MUSIC® model of academic motivation showed a significant shift, with students rating their interest in remote lab activities at 4.77 ± 0.94 on a 5-point Likert scale [5]. This change is likely due to rapid advancements in remote lab technology since 2019, along with increased familiarity among students and educators with online learning environments.

3.3. Task Hierarchy

Figure 3.3 below illustrates the traditional task hierarchy used in most papers to introduce their teaching kit to students, specifically in cases where the kit was evaluated within a student population. This hierarchy reflects common instructional approaches and the sequence in which students engaged with the kits during their learning experience.

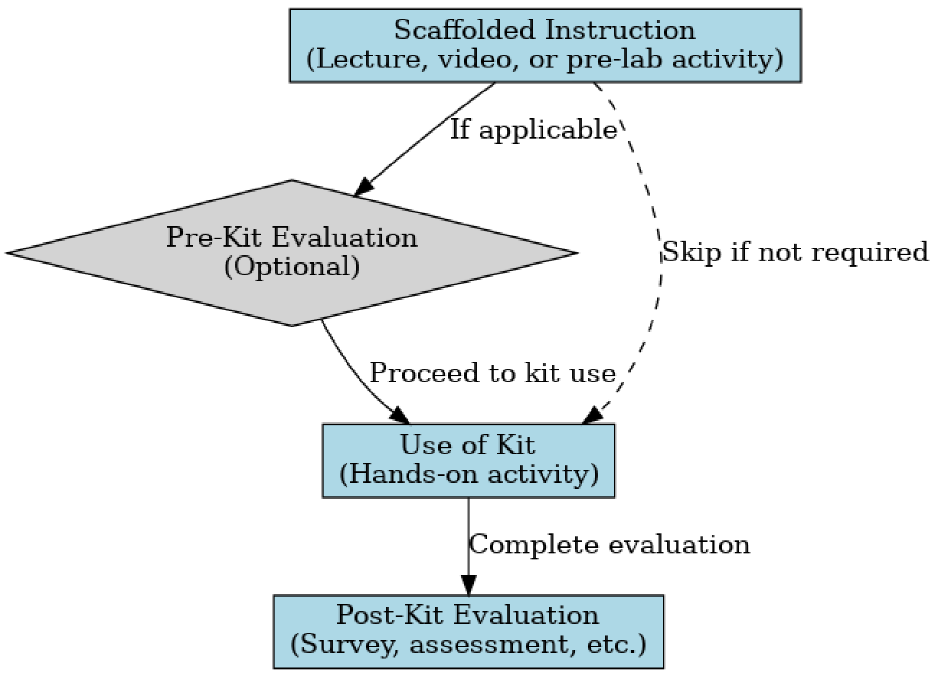

Figure 3.3: Task Diagram of Typical Teaching Kit Introduction

In most papers reviewed, the introduction of teaching kits followed a structured format consisting of three main stages: (1) a form of scaffolded instruction, such as a lecture, video, or pre-lab activity to prepare students, (2) hands-on use of the kit, and (3) a post-kit evaluation, which could take the form of a survey, formal academic assessment, or other measures. Additionally, many studies incorporated a short pre-assessment before students engaged with the kit to establish a baseline for evaluating learning outcomes.

However, there were notable exceptions to this traditional approach. Garcia-Gonzalez experimented with a problem-based learning (PBL) method, in which students actively engaged with the kit without following a pre-formulated set of instructions. The results indicated a slight but statistically insignificant improvement in learning outcomes for the PBL group, with a median score of 85.62 (lower quartile: 82.25, upper quartile: 86.18, min: 81, max: 90.5), compared to the traditional learning group's median score of 83.75 (lower quartile: 81, upper quartile: 87.37, min: 76, max: 90) (P = 0.436). This study involved 14 fifth-semester biotechnology engineering students randomly assigned to traditional learning (n = 8) or PBL (n = 6) groups [6].

Another alternative approach was explored by Williams et al., who integrated the kit-based activity as a replacement for some lecture content. Instead of providing a preparatory video before the lab, students watched a short video covering additional content after completing the activity. Despite this deviation from the standard instructional sequence, both groups still demonstrated a statistically significant improvement in assessment results [7], highlighting the flexibility of instructional design in effectively incorporating teaching kits into biomedical engineering education.

3.4. Demographic

Figure 3.4 below illustrates the distribution of target demographics for the teaching kits reviewed. The screening process was conducted with a primary focus on undergraduate-level kits, which is reflected in the results, with 64 kits identified as specifically targeting this demographic. However, the review also includes materials adapted from graduate-level activities and university outreach programs, demonstrating some overlap in the application of these kits across different educational levels.

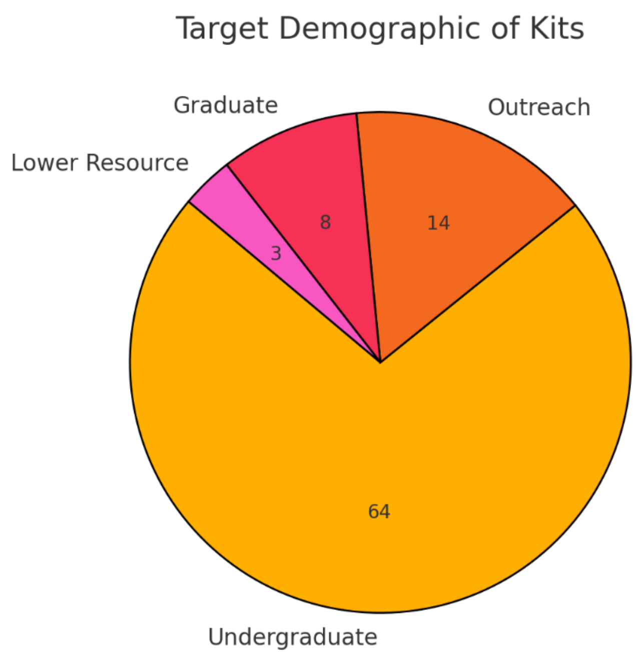

Figure 3.4: Target Demographic of Teaching Kits

A distinct category labeled "lower resource" is also included in the review, representing universities that have shared teaching kits with partner community colleges to expand access to hands-on learning opportunities. Additionally, this category includes initiatives such as the EngStarter kit by de Freitas et al., which was distributed to refugees with the aim of enhancing education in refugee camps [8]. This initiative not only provided educational opportunities but also sought to empower refugees to innovate and develop solutions to challenges within their communities.

3.5. Modality

Figure 3.5 below describes the different modalities of the teaching kits included in the review. Virtual kits are entirely digital, requiring no physical components, allowing them to be used anywhere with an internet connection. “At home” kits, while still portable, consist of physical components that can be constructed and used in various settings outside of a traditional laboratory.

Lab-based kits are further categorized based on their design and purpose. Purpose-made lab-based kits consist of equipment specifically designed for educational use, such as the iWorks bioinstrumentation system or the BioRadio™. In contrast, lab-based (industry) kits incorporate equipment originally developed for industrial applications but adapted for teaching purposes. Finally, lab-based (custom) kits include specialized equipment designed for exclusive use within a laboratory setting, limiting their accessibility outside of structured learning environments.

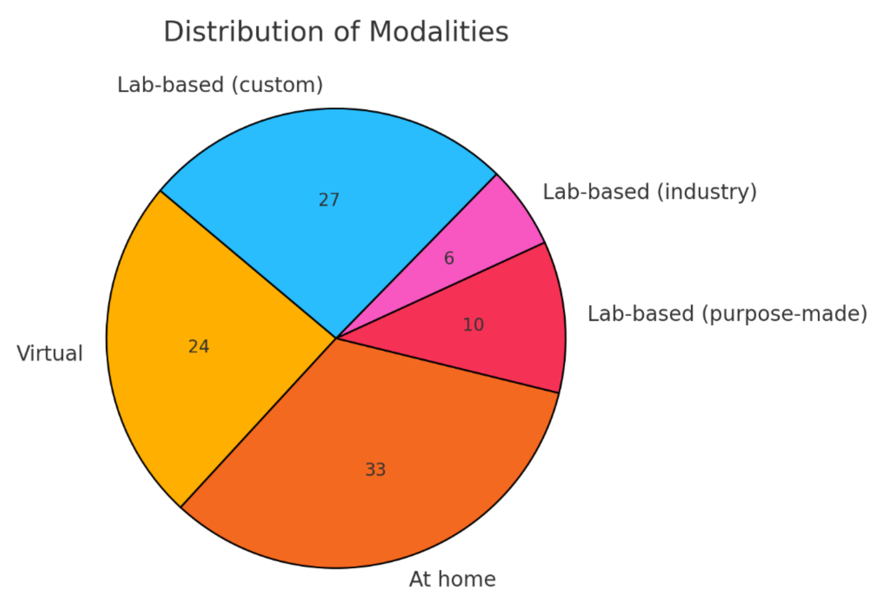

Figure 3.5: Modality of teaching kits

The majority of the kits reviewed are either virtual or designed for at-home use, a trend that likely stems from the increased adoption of remote learning during and after the COVID-19 pandemic. The flexibility and accessibility of these modalities have made them popular choices for biomedical engineering education, allowing students to engage with hands-on learning outside of traditional lab environments.

In contrast, very few papers incorporate industry equipment for teaching purposes. This is likely due to the high costs associated with such equipment, which can be a significant barrier in the context of biomedical engineering education. The expense of acquiring and maintaining industry-grade tools makes them less practical for widespread educational use, leading most educators to rely on purpose-made or custom-designed teaching kits instead.

Alkhasawneh et al. surveyed the satisfaction of engineering students accessing remote labs (with use TutorTims simulator). Surveys were administered to 31 students who attended either lab online. Twenty students responded to the survey of which 45% were females. All students were enrolled in at least one of the labs online during the pandemic (Analog communications lab or Digital communications lab). About 54.5% of male students preferred to be in-person and mentioned they would have done better being physically in the lab and learning how to use the actual tool and lab equipment. For those who responded with “no” or “no difference”, their responses focused on the quality of the simulator used in the lab and how close it was to the actual lab tools. In addition, flexibility and learning as a team had a great impact on their online experience. As for female students, 6 out of 9 students responded with a “no” or “no difference”[9].

Asiskoy et al. conducted a survey of 240 introductory physics students in 2023 on their perceptions of remote learning using a 5-point Likert scale, " the total mean score of the positive expression items was 3.95 (SD = 1.16), which indicates that students have positive perceptions about simulation-based experiments. From the answers students gave to the positive items, it was revealed that they wanted all lab activities to be virtual (M = 3.95, SD =1.20). They also stated that simulation-based experiments increased their motivation (M = 3.85, SD = 1.25) and learning speed (M = 3.96, SD = 1.20).” [10].

3.5.1. A Note on Virtual Reality (VR) and Augmented Reality (AR)

Reviews on the use of virtual reality (VR) as a teaching tool in biomedical engineering education have been mixed. Some studies indicate that VR enhances student engagement and performance, while others highlight concerns about discomfort and its limited impact on learning outcomes. For example, Ismael's survey of 15 students in a principles of surveying course found that 80% of participants viewed hands-on components in engineering courses as exciting and beneficial for learning, and 73.34% believed that VR or augmented reality (AR) would enhance their hands-on learning experiences [11]. Similarly, Rossoni's study of 10 engineering design students showed that novice students using a VR-based CAD simulation performed at a similar level to expert students, with final assessment scores of 77.7% and 78.5%, respectively [12]. However, other studies raise concerns. Tandon et al. found that 39.39% of students with prior VR experience reported discomfort before engaging with VR labs, with a slight decrease to 28.29% after completing the labs. More critically, their study concluded that VR did not significantly improve student engagement, material understanding, retention, or transferability of skills compared to traditional labs [13].

Wilkerson et al. found some evidence that VR may enhance learning, reporting an increase in student pre-lab quiz scores from 76.90% (±12.95) to 83.18% (±11.72%) when VR videos were introduced. Post-lab quiz scores also improved from 77.59% (±13.65) to 81.00% (±11.07%). However, student satisfaction results were mixed, with only 25% of students agreeing and 7% strongly agreeing that they wanted VR videos in future labs, while 27% disagreed and 18% strongly disagreed [14]. On the other hand, Singh et al. surveyed 34 biomedical engineering students in a clinical practice course and found that all students (100%) felt that VR closely simulated their in-person experience, and 60% believed it could serve as an alternative to in-person simulation labs [15]. Overall, these findings suggest that while VR can provide valuable learning experiences, it may also cause discomfort and is not always well-received by students.

Some interesting applications of VR in education have been developed despite its challenges. Kumar et al. found that VR simulations increase access to educational activities but are costly to acquire and develop [16]. Boettcher et al. presented a virtual simulation for an undergraduate fluid mechanics laboratory, and Han et al. created a simulated pipetting laboratory, demonstrating the versatility of VR-based instructional tools [17].

In contrast to VR, augmented reality (AR) has generally been viewed as a positive addition to teaching activities. Martin-Gutierrez et al. found that in a study of 25 mechanical engineering students, an AR-based technical drawing simulator significantly improved student scores, with gains of 8.04 ± 5.31 or 9.02 ± 4.08 points, compared to 4.64 ± 4.63 or 5.12 ± 7.13 points in the control group [18]. Similarly, Chen & Liu reported significant grade improvements in a study of 112 introductory chemistry students, with scores increasing from 40.19 ± 15.93 to 52.08 ± 18.75 for students who performed a hands-on AR activity and from 40.98 ± 14.14 to 47.45 ± 12.54 for those who had the AR activity demonstrated to them. Additionally, student satisfaction with the learning module improved, as reflected in 5-point Likert scale ratings increasing from 2.96 ± 0.94 to 3.22 ± 0.85 in the hands-on group and from 3.09 ± 0.78 to 3.31 ± 0.80 in the demo group [19]. Other studies further support the effectiveness of AR in education. Wildan et al. received entirely positive ratings for their AR bacteria growth lab, with all high school and undergraduate students agreeing or strongly agreeing that AR enhanced their biology learning experience [20]. Alptekin & Temmen also successfully developed an introductory electronics lab featuring an AR oscilloscope [21], showcasing the potential of AR to improve practical engineering education.

3.6. Subject Matter of Kit

Figure 3.6 below illustrates the distribution of the various subject matters covered by the teaching kits. Notably, some of the papers included in this review are review papers or surveys rather than original studies presenting specific kits. As a result, not all 112 papers are represented in the chart, which focuses solely on those that introduced and evaluated hands-on learning kits.

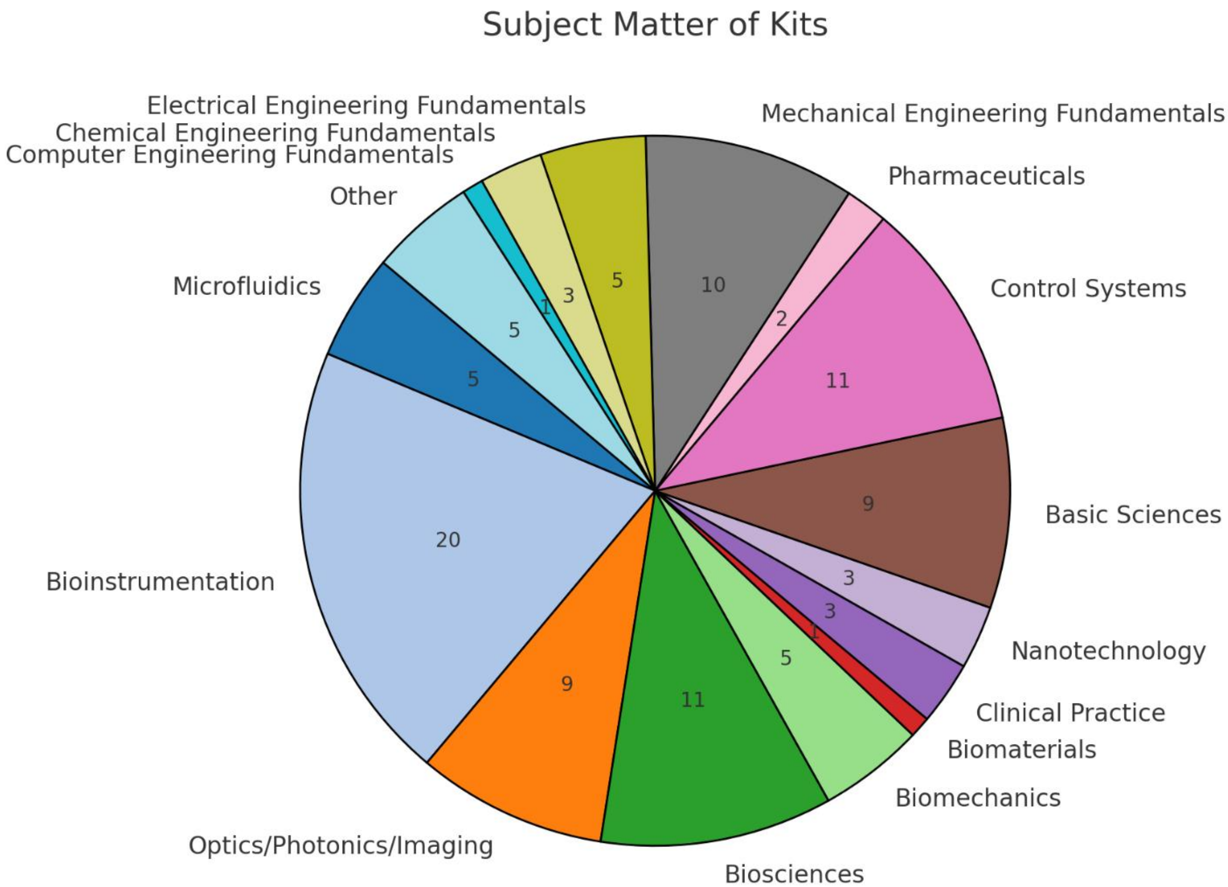

Figure 3.6: Subject Matter of Kits

3.6.1. Bioinstrumentation

Bioinstrumentation emerged as the most common subject area among the reviewed teaching kits, with 20 kits focused on this topic. Many papers centered around the use of commercially available teaching kits, such as the iWorx and CleveLabs BioRadio™ systems. For example, Andritol et al. compared the iWorx kit to traditional experiments and found that 52% of students reported it as easy to use, while only 9% found it difficult. Additionally, 15% of students achieved a perfect score on the activity, while only 3% scored a 5, with the rest evenly distributed between these values [22]. Schmidt and Giuffida provided a detailed account of teaching with the BioRadio™ [23], [24], while Dewilde et al. attempted to develop a low-cost, Arduino-based alternative to the iWorx system [25]. Feedback from students indicated that this system allowed for self-paced learning. Similarly, Al-Nahhas et al. created a low-cost, interchangeable bioinstrumentation kit [26], while Giuffrida et al. developed a virtual version of a similar system [27].

Beyond commercially available kits, many papers focused on developing low-cost bioinstrumentation devices. Jin et al. demonstrated the Einthoven Triangle using only a box and batteries in a highly cost-effective manner [28]. Haase et al. created a do-it-yourself (DIY) Arduino-based electrocardiogram (EKG) [29], while Opuszynski et al. developed a low-cost ECG device [30], with Mohamad and Noor offering a virtual version of the same concept [31]. Tepe & Savaster took a different approach by designing an EEG system using a Raspberry Pi [32]. These innovations highlight the ongoing efforts to make biomedical engineering education more accessible through affordable alternatives to expensive laboratory equipment.

Several other notable studies explored unique educational applications in bioinstrumentation. Bartocci et al. developed a teaching kit focused on cardiovascular physiology, specifically arrhythmias and spiral wave dynamics. Student satisfaction with the kit was high, with 15 students rating it a mean score of 4.6 on a 5-point Likert scale [33]. Bjorn et al. examined gender differences in motivation when using an EEG simulator and found that 92% of female students, compared to only 60% of male students, were unmotivated to use the simulator [34]. Their findings aligned with GenderMag predictions, suggesting that women prefer additional theoretical background before engaging with hands-on simulations [35]—an observation supported by student responses, where 54% of female students felt they needed theoretical knowledge first, compared to just 20% of male students [34].

Other innovative studies demonstrated the versatility of teaching kits in biomedical engineering education. Pennes et al. developed a mechatronic pump, and half of the 28 students surveyed reported that it enhanced their understanding of mechatronic systems [36]. Luo et al. used a cochlear implant model to teach signal processing, with most students agreeing or strongly agreeing that anchoring skills and concepts in a physical system made learning easier [37]. Lott et al. introduced a MATLAB-based oscilloscope for neurophysiology instruction [38], while Campbell & Pozzi leveraged an inexpensive video game to teach neural interface and device control [39]. Hsu et al. developed an Arduino-based glucose sensor for educational use [2]. Olansen et al pioneered one of the first remote bioinstrumentation labs in 2000, highlighting early efforts to expand access to hands-on learning[40]. Adorno et al. explored inquiry-based learning for electroretinography (ERG) and functional near-infrared spectroscopy (fNIRS) [41]. Franz et al. conducted a transcutaneous electrical nerve stimulation (TENS) and electromyography (EMG) lab, where 95.8% of students (n = 24 third-year biomedical engineering students) demonstrated improved learning outcomes [42]. Finally, Montesinos et al. investigated the use of wearable devices in the classroom, finding that student interest and motivation were identical between the control and intervention groups, suggesting that wearables did not significantly impact engagement levels [43].

3.6.2. Optics/Photonics/Imaging

The primary focus for many teaching kits in this field was affordability, likely due to the high cost of industry-standard equipment. Researchers explored various low-cost alternatives to provide accessible educational tools. For example, Fagerstrom demonstrated sinograms using simple paper blocks [44], while Haidekker designed a DIY tomography scanner [45]. Brown et al. created a compact desktop MR scanner [46], and Luo et al. and Gatkine et al. developed a DIY spectrograph [37], [47]. In virtual learning environments, Zhao et al. introduced a virtual imaging simulator [48]. Klinger contributed to multiple low-cost solutions, including a model of the human eye and an affordable microscope [49], while Walzik et al. designed a portable, low-cost cell imaging platform [50]. Grier et al. designed a low-cost DIY microscope. In a poll of 22 secondary students during an outreach program "22.7% of students agree and 77.3% strongly agree with the statement 'I think the microscope lesson was interesting'"[51]. These innovations reflect a broader effort to make imaging and bioinstrumentation education more widely accessible.

Control systems teaching kits predominantly followed two major approaches: LEGO® NXT-based systems and Arduino temperature control kits. Studies on LEGO-based kits suggest mixed results regarding their effectiveness. Wu et al. reported that while over 80% of students faced technical difficulties with LEGO labs, half still found them helpful for learning system dynamics [52]. Additionally, while confidence levels increased across all topics, no significant differences were found for modeling second-order systems or root locus diagrams. Similarly, Moor & Piergiovanni observed that over 80% of students responded positively to questions assessing their experience with LEGO-based labs, describing them as useful, engaging, and fun [53]. Elamvazuthi et al. also developed a system following this model [54].

The second major category, Arduino-based temperature control kits, showed strong student approval. Takas developed a system called HeatShield [55], while Ibrahim & Abu Hansa found that nearly all students (97%) strongly agreed that a microcontroller-based temperature control kit improved their understanding of controller design and implementation (n = 18 third-year students in a controls engineering course)[56]. Similarly, Tran et al.'s students rated a comparable system 4.14 on a 5-point Likert scale [57], and Oliveira et al. introduced a similar approach [58].

Some studies explored alternative approaches beyond the two dominant models. Javaid et al. developed a haptic paddle for control systems education [59], while Stoleo et al. created LabTech@Home, a low-cost Arduino-based PID control education kit utilizing a photoresistor [60]. Sanchez & Bucio designed a LEGO® prototype that did not rely on an NXT brick [61], expanding the accessibility of this teaching method. Reck et al. implemented a Raspberry Pi and DC motor system, though they could not reject the null hypothesis regarding its impact on student learning outcomes [62]. However, they did find a statistically significant improvement in student satisfaction, suggesting that while the learning impact was unclear, students still valued the system as an educational tool.

3.6.3. Biosciences

A significant portion of the reviewed papers in the biosciences section, as well as in the basic sciences category, focused on fluorescence-based teaching tools. Ding et al. developed a handheld portable fluorescence detector [63], while Stark et al. introduced the synthetic fluorescent BioBits® teaching kit [64], both aimed at enhancing hands-on learning in biosciences.

PCR and gel electrophoresis were also prevalent topics in bioscience education. Maurye designed a low-cost gel electrophoresis kit for outreach purposes, which received positive feedback from students, with 56 participants rating its effectiveness for improved learning at an average of 4.0 and overall satisfaction at 4.1 on a 5-point Likert scale [65]. Similarly, Yu et al.

developed a budget-friendly gel electrophoresis teaching activity using food dye as an accessible alternative for resource-limited environments [66].

Beyond fluorescence and electrophoresis, several other notable bioscience teaching kits were explored. Garcia-Gonzalez introduced a 3D cell culture experiment, providing students with a more interactive approach to cell biology [6]. Low and Ellefson created an educational game for teaching basic genetics, which significantly improved student performance and engagement. After playing the game, students' scores on a 16-question multiple-choice assessment increased from an average of 61.4% to 86.6% ($p < 0.001$), and their reported interest in learning genetics rose by 79.5%, with post-intervention ratings improving from 4.0 to 7.2 ($p < 0.001$) [67].

Other innovative bioscience teaching kits included Kaiphanliam et al.'s low-cost blood separator [68] and Nguyen et al.'s proposal for using loop-mediated isothermal amplification (LAMP) to engage undergraduates in research [69]. Jawad et al. developed an at-home lab activity for teaching micropipetting [70], while Rayment et al. designed take-home pipetting kits. Their results showed that 98.2% of students successfully completed the pipetting learning outcome on their first attempt, a success rate comparable to previous years (95.4%) [71]. Finally, Han et al. developed a VR bio training laboratory, exploring how virtual simulations can enhance bioscience education by providing immersive, interactive learning experiences [17].

3.6.4. Basic Sciences and Engineering Fundamentals

The reviewed teaching kits covered a wide range of fundamental science and engineering topics, with a strong emphasis on classical mechanics and introductory physics, as explored by Medina Uzcátegui et al. [72], Bhargava [3], Howard & Meier [73] and Laouina [74]. Rossini experimented with ways of teaching CAD [12]. Yusof et al. introduced machine learning through CAD [75]. Fluid mechanics was addressed by Goodman et al. [76], while heat transfer concepts were explored in studies by Diller & Bairaktarova [77], Khan et al.[78], Reynolds et al. [79] and Mehrotra et al.[80].

Beyond physics and engineering fundamentals, process control and basic chemistry were also popular topics, with Chen & Liu examining chemistry education through hands-on simulations [19]. In biology, Williams et al. focused on genetics [7], Wildan et al. explored bacterial growth [20], and Beltramini et al. developed a DNA modeling activity [81]. Other biological and biochemical applications included Piergiovanni et al.'s study on absorption kinetics and Dewan et al.'s research on microbial fuel cells [82], [83] and Kaushik focused on characterizing microbial growth [84]. Radhamani et al. also introduced microbiology concepts, but with the use of a virtual lab [85]. Tanabashi et al. created an interactive museum exhibit for teaching cell biology [86] and Ahmad et al. created a remote process control laboratory [87].

Several studies also addressed fundamental electronics and computing topics. Silva et al., Alptekin & Temmen, Fuada and Mohammad et al. developed teaching kits for basic electronics equipment [88] [19] [75] [90], while Lim et al. investigated computer architecture education [91] and Ham et al. developed hands-on programming activities [92]. These studies demonstrate the breadth of subjects covered in teaching kits, supporting hands-on learning across multiple disciplines within biomedical engineering and related fields.

3.6.5. Microfluidics and Nanotechnology

Microfluidics and nanotechnology are rapidly emerging fields in biomedical engineering education, and several studies have explored innovative teaching kits in these areas. Gerber et al. developed a microfluidic assembly kit based on laser-cut building blocks designed for education and fast prototyping. The kit received high student satisfaction ratings, with an average score of 8.3/10 from 35 outreach students [93].

Several researchers have focused on developing lab-on-a-chip teaching tools. Rackus et al. and Moraes et al. both created teaching labs using microfluidic chips [94], [95], with Moraes' study reporting that more than 85% of 61 surveyed students found the lab to be a fun and practical hands-on learning experience[95]. Hossain et al. expanded on this concept by developing a remote-access lab-on-a-chip system, allowing students to engage with microfluidic experiments virtually [96]. Similarly, Wu et al. leveraged microfluidics to teach cell adhesion using a microfluidics-based cell adhesion assay [97].

In nanotechnology education, Rodriguez introduced Oxford Nanopore's MinION device to help students learn about genetic variants, providing hands-on experience with cutting-edge sequencing and analysis techniques [98]. Vahedi & Farnoud developed an activity to teach nanoparticle characterization which resulted in 50% of students strongly agreeing with and 22.2% of students agreeing with the statement "I have improved upon my knowledge in NGS technologies due to participating in this module" [99]. Gimm et al. compiled a collection of nanoscience teaching kits, with their most notable being a nickel nanowire lab, which demonstrated high student success rates. Their broader set of video lab manuals also included an optical transform kit and an LED color strip kit, further expanding the educational resources available for teaching nanoscience concepts [100] .

These studies highlight the growing integration of microfluidics and nanotechnology into biomedical engineering education, providing students with early exposure to these advanced technologies through hands-on, interactive learning experiences.

3.6.6. Biomaterials and Biomechanics

Several studies in the review explored innovative teaching kits for biomaterials and biomechanics education, incorporating both virtual simulations and hands-on experimental setups. Ural introduced a virtual biomechanics simulation activity using finite element analysis (FEA) [101], allowing students to explore biomechanical principles in a digital environment.

In hands-on biomechanics education, Gao et al. developed an artificial finger [102], while Garofalo et al. created a simulated snake jaw robot to demonstrate biomechanical movement [103]. Daidié et al. designed a snap-together set of one-degree-of-freedom (1 DoF) models to analyze different gait patterns, providing a modular and interactive approach to understanding human movement [104]. Similarly, Rokbani et al. constructed a low-cost biped robot, enabling students to study the mechanics of human-like locomotion [105].

In biomaterials education, Kitto et al. investigated the use of biomaterials as sample materials in traditional mechanical engineering materials testing labs [106]. By incorporating biomaterials into standard engineering experiments, this approach provided students with a deeper understanding of how biological materials compare to conventional engineering materials in terms of mechanical properties.

These studies demonstrate a range of approaches to teaching biomaterials and biomechanics, from cost-effective physical models to advanced computational simulations, enriching student learning experiences in these fields.

3.6.7. Clinical Practice

Several studies explored the integration of clinical practice simulations into biomedical engineering education, using both high-fidelity physical simulations and virtual reality (VR) environments. Singh et al. introduced high-fidelity mannequins to 68 biomedical engineering students, with 94% of students in the immersion group reporting that the simulation lab experience helped them identify an unmet clinical need. Even among students who did not visit the simulation lab, 74% believed that such an immersion could have been beneficial in the need-finding phase, highlighting the perceived value of hands-on clinical exposure [107].

Singh et al. developed a VR-based simulation for biomedical engineering students to explore patient care scenarios (see Section 3.5.1 for further details) [15]. This approach allowed students to engage with clinical concepts in a virtual environment, offering an alternative to in-person training.

Backstrom et al. introduced low-cost surgical simulations to 15 graduate students, providing them with hands-on exposure to surgical procedures. Their findings indicated strong student engagement, with over 80% of participants agreeing or strongly agreeing that the activity improved their understanding of the procedure [108].

These studies demonstrate the growing use of both physical and virtual clinical simulations in biomedical engineering education, emphasizing the importance of immersive learning experiences in preparing students for real-world clinical challenges.

3.6.8. Pharmaceuticals

Kaste et al. utilized Python simulations to teach metabolic modeling to a group of seven graduate students. Their study found a significant improvement in students' perceived understanding of metabolic modeling; however, students reported no significant change in their confidence in applying these techniques to research [109]. Similarly, Allen et al. developed modeling software designed to support computer-aided drug design education, providing students with tools to enhance their understanding of pharmaceutical development processes [110].

3.6.9. Other

Boskovic et al. developed a teaching kit focused on acoustic trapping, providing students with hands-on experience in manipulating particles using sound waves [111]. Pajpack et al. created an open-source machine vision kit, expanding access to computer vision education [112]. Farrel and Cavanaugh introduced a lifecycle design activity, where student evaluation scores significantly improved from 26.8% to 82.8% after completing the activity (n = 24 undergraduates) [113]. Haj-

Hosseni et al. developed a remote electronics safety course, which received an average rating of 3.17/5 from students who participated in the evaluation (n = 35) [114]. Lastly, de Freitas et al. designed a general-purpose educational kit aimed at supporting refugee learners, promoting accessibility to STEM education in resource-limited environments [8].

4. Future Work

This systematic review represents a thorough initial examination of the landscape of teaching kits in biomedical engineering education, focusing on the technologies, pedagogical strategies, and reported outcomes. The comprehensive search and screening process has laid the groundwork for a deeper investigation into this topic. The next steps involve developing a set of requirements for developing future kits as well as an evaluation framework, which aims to provide a robust synthesis of current practices and offer actionable recommendations for the design and implementation of effective teaching kits in biomedical engineering education. By continuing to build on this work, this review aspires to make a meaningful contribution to the field and support the development of innovative and impactful educational tools.

References

[1] M. L. Rethlefsen *et al.*, “PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews,” *Syst. Rev.*, vol. 10, no. 1, p. 39, Jan. 2021, doi: 10.1186/s13643-020-01542-z.

[2] S. Hsu, C. Sung, and H. Sheen, “Developing an Interdisciplinary Bio-Sensor STEM Module for Secondary School Teachers: An Exploratory Study,” *Vopr. Obraz.-Educ. Stud. Mosc.*, no. 2, pp. 230–251, 2020, doi: 10.17323/1814-9545-2020-2-230-251.

[3] P. Bhargava, J. Antonakakis, C. Cunningham, and A. T. Zehnder, “Web-based virtual torsion laboratory,” *Comput. Appl. Eng. Educ.*, vol. 14, no. 1, pp. 1–8, Jan. 2006, doi: 10.1002/cae.20061.

[4] R. Estriegana, J.-A. Medina-Merodio, and R. Barchino, “Student acceptance of virtual laboratory and practical work: An extension of the technology acceptance model.,” *Comput. Educ.*, vol. 135, pp. 1–14, 2019.

[5] R. Devine and D. May, “Work in Progress: Pilot Study for the Effect of a Simulated Laboratories on the Motivation of Biological Engineering Students,” presented at the CROSS REALITY AND DATA SCIENCE IN ENGINEERING, 2021, pp. 429–436. doi: 10.1007/978-3-030-52575-0_35.

[6] M. Garcia-Gonzalez *et al.*, “A PBL strategy for incorporating 3D cell culture into the classrooms of undergraduate biotechnology engineering students,” *Res. Sci. Technol. Educ.*, 2024, doi: 10.1080/02635143.2024.2423077.

[7] L. C. Williams *et al.*, “The Genetic Code Kit: An Open-Source Cell-Free Platform for Biochemical and Biotechnology Education,” *Front. Bioeng. Biotechnol.*, vol. 8, 2020, doi: 10.3389/fbioe.2020.00941.

[8] C. C. S. De Freitas and J. Deboer, “A Mobile Educational Lab Kit for Fragile Contexts,” presented at the 2019 IEEE Global Humanitarian Technology Conference, GHTC 2019, 2019. doi: 10.1109/GHTC46095.2019.9033133.

[9] R. Alkhasawneh, R. Al-Nsour, and M. Akho-Zahieh, “Measuring Online Engineering Laboratory Satisfaction During COVID-19 Pandemic.,” *J. Eng. Educ. Transform.*, vol. 37, no. 3, pp. 157–164, 2024.

[10] G. Asiksoy, “Effects of Virtual Lab Experiences on Students’ Achievement and Perceptions of Learning Physics,” *Int. J. ONLINE Biomed. Eng.*, vol. 19, no. 11, pp. 31–41, 2023, doi: 10.3991/ijoe.v19i11.39049.

[11] D. Ismael, “Enhancing Online Hands-On Learning in Engineering Education: Student Perceptions and Recommendations,” presented at the ASEE Annual Conference and Exposition, Conference Proceedings, 2023. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85172105437&partnerID=40&md5=4a115de901b9cb21e3a51cb81c004269

[12] M. Rossoni, E. Spadoni, M. Carulli, C. Barone, G. Colombo, and M. Bordegoni, “Virtual Reality in Education to Enable Active Learning and Hands-on Experience,” *Comput.-Aided Des. Appl.*, vol. 21, no. 2, pp. 258–269, 2024, doi: 10.14733/cadaps.2024.258-269.

[13] I. Tandon, V. Maldonado, M. Wilkerson, A. Walls, R. Rao, and M. Elsaadany, “Immersive virtual reality-based learning as a supplement for biomedical engineering labs: challenges faced and lessons learned,” *Front. Med. Technol.*, vol. 6, 2024, doi: 10.3389/fmedt.2024.1301004.

[14] M. Wilkerson, V. Maldonado, S. Sivaraman, R. Rao, and M. Elsaadany, “Incorporating immersive learning into biomedical engineering laboratories using virtual reality,” *J. Biol. Eng.*, vol. 16, no. 1, 2022, doi: 10.1186/s13036-022-00300-0.

[15] A. Singh, D. Ferry, A. Ramakrishnan, and S. Balasubramanian, “Using Virtual Reality in Biomedical Engineering Education,” *J. Biomech. Eng.-Trans. ASME*, vol. 142, no. 11, 2020, doi: 10.1115/1.4048005.

[16] V. V. Kumar, D. Carberry, C. Beenfeldt, M. P. Andersson, S. S. Mansouri, and F. Gallucci, “Virtual reality in chemical and biochemical engineering education and training.,” *Educ. Chem. Eng.*, vol. 36, pp. 143–153, 2021.

[17] P. Han, G. Li, S. Sunilkumar, and Y. Cao, “A Virtual Learning Platform for Biomedical Laboratory Scientists Using Unity3D,” presented at the 2023 11TH INTERNATIONAL CONFERENCE ON CONTROL, MECHATRONICS AND AUTOMATION, ICCMA, 2023, pp. 320–325. doi: 10.1109/ICCMA59762.2023.10374813.

[18] J. Martín-Gutiérrez, J. L. Saorín, M. Contero, and M. Alcañiz, “AR-Dehaes: An educational toolkit based on augmented reality technology for learning engineering graphics,” presented at the Proceedings - 10th IEEE International Conference on Advanced Learning Technologies, ICALT 2010, 2010, pp. 133–137. doi: 10.1109/ICALT.2010.45.

[19] S.-Y. Chen and S.-Y. Liu, “Using augmented reality to experiment with elements in a chemistry course.,” *Comput. Hum. Behav.*, vol. 111, p. N.PAG-N.PAG, 2020.

[20] A. Wildan, B. H.-P. Cheong, K. Xiao, O. W. Liew, and T. W. Ng, “Growth measurement of surface colonies of bacteria using augmented reality.,” *J. Biol. Educ. Routledge*, vol. 54, no. 4, pp. 419–432, 2020.

[21] M. Alptekin and K. Temmen, “Design Concept and Prototype for an Augmented Reality based virtual preparation laboratory training in Electrical Engineering,” presented at the PROCEEDINGS OF 2018 IEEE GLOBAL ENGINEERING EDUCATION CONFERENCE (EDUCON) - EMERGING TRENDS AND CHALLENGES OF ENGINEERING EDUCATION, 2018, pp. 963–968.

[22] D. ANDRIȚOI, C. LUCA, and R. FUIOR, “Modern Teaching Methods Used in the Study of Sensors and Transducers in the Biomedical Field.,” *ELearning Softw. Educ.*, vol. 3, pp. 261–266, 2019.
[23] R. Schmidt, “Clinical application driven physiology in biomedical engineering laboratory course education,” presented at the 2005 27TH ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY, VOLS 1-7, 2005, pp. 367–370. doi: 10.1109/IEMBS.2005.1616421.
[24] J. Giuffida, “Bridging biomedical basics with practical applications in BME laboratory education,” presented at the PROCEEDINGS OF THE 26TH ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY, VOLS 1-7, 2004, pp. 5180–5183.
[25] A. H. Dewilde and Y. Li, “Using Arduinos to Transition a Bioinstrumentation Lab to Remote Learning,” *Biomed. Eng. Educ.*, vol. 1, no. 2, pp. 313–316, 2021, doi: 10.1007/s43683-020-00042-9.
[26] M. Al-Nahhas, H. Yassine, N. Baassiri, R. Halabi, M. Sabbah, and M. Diab, “Physio-Vibes: A Biomedical Engineering Educational Kit for Highschool and Sophomore Students,” presented at the International Conference on Advances in Biomedical Engineering, ICABME, 2019. doi: 10.1109/ICABME47164.2019.8940272.
[27] J. Giuffrida, “Virtual clinical engineering: From biomedical basics to practical applications,” presented at the PROCEEDINGS OF THE IEEE 30TH ANNUAL NORTHEAST BIOENGINEERING CONFERENCE, 2004, pp. 224–225.
[28] B. E. Jin, H. Wulff, J. H. Widdicombe, J. Zheng, D. M. Bers, and J. L. Puglisi, “A simple device to illustrate the Einthoven triangle.,” *Adv. Physiol. Educ.*, vol. 36, no. 4, pp. 319–324, 2012.
[29] E. Haase, R. O’Hara, and A. Maybhate, “The Do-It-Yourself Electrocardiogram,” *Biomed. Eng. Educ.*, vol. 2, no. 1, pp. 83–90, 2022, doi: 10.1007/s43683-021-00061-0.
[30] M. Opuszynski, R. Andrews, J. Potvin, T. BouRamia, and Y. Sun, “Experiential Learning in an Undergraduate Biomeasurement Course: Heart-Rate Meter,” presented at the 2009 35TH ANNUAL NORTHEAST BIOENGINEERING CONFERENCE, 2009, pp. 258–259.
[31] A. Mohamad and H. Noor, “DEVELOPMENT OF SMART ECG MACHINE USING LABVIEW FOR BIOMEDICAL ENGINEERING STUDENTS,” presented at the 2014 4TH INTERNATIONAL CONFERENCE ON ENGINEERING TECHNOLOGY AND TECHNOPRENEURSHIP (ICE2T), 2014, pp. 320–323.
[32] C. Tepe and E. Savastaer, “A computer-aided educational device and toolbox for biomedical signal processing at the undergraduate level,” *Comput. Appl. Eng. Educ.*, vol. 30, no. 6, pp. 1725–1738, 2022, doi: 10.1002/cae.22552.
[33] E. Bartocci *et al.*, “Teaching cardiac electrophysiology modeling to undergraduate students: laboratory exercises and GPU programming for the study of arrhythmias and spiral wave dynamics.,” *Adv. Physiol. Educ.*, vol. 35, no. 4, pp. 427–437, 2011.
[34] M. H. Björn, W. Ravyse, C. Botha-Ravyse, J. M. Laurila, and T. Keinonen, “A Revised Pedagogy Model for Simulator-Based Training with Biomedical Laboratory Science Students.,” *Educ. Sci.*, vol. 11, no. 7, p. 328, 2021.
[35] M. Burnett *et al.*, “GenderMag: A Method for Evaluating Software’s Gender Inclusiveness,” *Interact. Comput.*, vol. 28, no. 6, pp. 760–787, Nov. 2016, doi: 10.1093/iwc/iwv046.

[36] A. Pennes *et al.*, “A Hands-on Medical Mechatronics Exercise to Pump Up Student Learnings,” *Biomed. Eng. Educ.*, vol. 3, no. 2, pp. 235–242, 2023, doi: 10.1007/s43683-022-00100-4.

[37] C. Luo, J. McClellan, and P. Bhatti, “INTRODUCTORY SIGNAL PROCESSING LABS BASED ON FILTERBANK APPLICATIONS,” presented at the 2011 IEEE DIGITAL SIGNAL PROCESSING WORKSHOP AND IEEE SIGNAL PROCESSING EDUCATION WORKSHOP (DSP/SPE), 2011, pp. 90–94.

[38] G. Lott, B. Johnson, R. Bonow, B. Land, and R. Hoy, “Real-Time Development of Data Acquisition and Analysis Software for Hands-On Physiology Education in Neuroscience: g-PRIME,” presented at the 2009 ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY, VOLS 1-20, 2009, pp. 2019-+. doi: 10.1109/IEMBS.2009.5334424.

[39] B. Campbell and A. Pozzi, “Work In Progress: Adapting Inexpensive Game Technology to Teach Principles of Neural Interface Technology and Device Control,” presented at the 2013 ASEE ANNUAL CONFERENCE, 2013.

[40] J. Olansen, F. Ghorbel, J. Clark, and A. Bidani, “Using Virtual Instrumentation to Develop a Modern Biomedical Engineering Laboratory,” *Int. J. Eng. Educ.*, vol. 16, no. 3, pp. 244–254, 2000.

[41] D. Adorno, “Inquiry-based environments for bio-signal processing training in engineering education,” *Int. J. Mech. Eng. Educ.*, vol. 50, no. 3, pp. 629–647, 2022, doi: 10.1177/03064190211026207.

[42] K. Franz, K. Patel, and D. Kilkenny, “A biomedical Engineering Laboratory module for exploring involuntary muscle reflexes using Electromyography,” *J. Biol. Eng.*, vol. 14, no. 1, 2020, doi: 10.1186/s13036-020-00248-z.

[43] L. Montesinos, A. Santos-Diaz, D. Salinas-Navarro, and L. Cendejas-Zaragoza, “Experiential Learning in Biomedical Engineering Education Using Wearable Devices: A Case Study in a Biomedical Signals and Systems Analysis Course,” *Educ. Sci.*, vol. 12, no. 9, 2022, doi: 10.3390/educsci12090598.

[44] J. M. Fagerstrom, “Computed tomography, sinograms, and image reconstruction in the classroom.,” *Phys. Educ.*, vol. 55, no. 3, pp. 1–6, 2020.

[45] M. A. Haidekker, “A Hands-on Model-computed Tomography Scanner for Teaching Biomedical Imaging Principles.,” *Int. J. Eng. Educ.*, vol. 21, no. 2, pp. 327–334, 2005.

[46] D. Brown, D. Spence, and S. Wright, “A transceiver for an inexpensive desktop MR microscope,” presented at the PROCEEDINGS OF THE 22ND ANNUAL INTERNATIONAL CONFERENCE OF THE IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY, VOLS 1-4, 2000, pp. 2390–2393.

[47] P. Gatkine, G. Zimerman, and E. Warner, “A Do-it-yourself Spectrograph Kit for Educational Outreach in Optics and Photonics,” presented at the OPTICS EDUCATION AND OUTREACH V, 2018. doi: 10.1117/12.2321640.

[48] W. Zhao, A. Bessell, N. Erdol, A. McGoron, and W. Rhodes, “Collaborative Development of Internet-Accessible, Interactive, Medical Imaging Teaching Courseware and Application to Undergraduate Curricula,” presented at the 2013 ASEE ANNUAL CONFERENCE, 2013.

[49] T. Klinger, C. Kreiter, J. Klinger, T. Steinmetz, and I. Krumphals, “A Remote Lab for School Students that Explores the Function of the Human Eye,” presented at the TOWARDS A HYBRID, FLEXIBLE AND SOCIALLY ENGAGED HIGHER EDUCATION, VOL 1, ICL 2023, 2024, pp. 231–238. doi: 10.1007/978-3-031-51979-6_24.

[50] M. Walzik *et al.*, “A portable low-cost long-term live-cell imaging platform for biomedical research and education,” *Biosens. Bioelectron.*, vol. 64, pp. 639–649, 2015, doi: 10.1016/j.bios.2014.09.061.

[51] Z. Grier *et al.*, “A low-cost do-it-yourself microscope kit for hands-on science education,” presented at the Proceedings of SPIE - The International Society for Optical Engineering, 2018. doi: 10.1117/12.2320655.

[52] Y. Wu, C. de Vries, and Q. Dunsworth, “Using LEGO kits to teach higher level problem solving skills in system dynamics: A case study,” *Adv. Eng. Educ.*, vol. 6, no. 3, pp. 1–20, 2018.

[53] S. S. Moor and P. R. Piergiovanni, “Process control kits: A hardware and software resource.,” *Comput. Appl. Eng. Educ.*, vol. 21, no. 3, pp. 491–502, 2013.

[54] I. Elamvazuthi *et al.*, “Implementation of a New Engineering Approach for Undergraduate Control System Curriculum using a Robotic System,” presented at the 2015 IEEE INTERNATIONAL SYMPOSIUM ON ROBOTICS AND INTELLIGENT SENSORS (IEEE IRIS2015), 2015, pp. 34–39. doi: 10.1016/j.procs.2015.12.272.

[55] G. Takács *et al.*, “HeatShield: A low-cost didactic device for control education simulating 3d printer heater blocks,” presented at the IEEE Global Engineering Education Conference, EDUCON, 2019, pp. 374–383. doi: 10.1109/EDUCON.2019.8725201.

[56] D. IBRAHIM and J. F. A. HASNA, “Teaching PID Auto-Tuning Using a Low-Cost Control Kit.,” *Int. J. Eng. Educ.*, vol. 29, no. 1, pp. 239–247, 2013.

[57] L. Q. Tran, P. Radcliffe, and L. Wang, “A low budget take-home control engineering laboratory for undergraduate.,” *Int. J. Electr. Eng. Educ.*, vol. 59, no. 2, pp. 158–175, 2022.

[58] P. Oliveira, J. Hedengren, and J. Rossiter, “Introducing Digital Controllers to Undergraduate Students using the TCLab Arduino Kit,” presented at the IFAC PAPERSONLINE, 2020, pp. 17524–17529. doi: 10.1016/j.ifacol.2020.12.2662.

[59] A. Javaid, H. Munawar, and M. A. Mohyuddin, “A Low Cost 1-DoF Encounter Type Haptic Device for Use in Education,” presented at the 2019 International Conference on Robotics and Automation in Industry, ICRAI 2019, 2019. doi: 10.1109/ICRAI47710.2019.8967395.

[60] D. Sotelo *et al.*, “Lab-Tec@Home: A Cost-Effective Kit for Online Control Engineering Education,” *Electron. Switz.*, vol. 11, no. 6, 2022, doi: 10.3390/electronics11060907.

[61] A. Sanchez and J. Bucio, “Improving the Teaching of Discrete-Event Control Systems Using a LEGO Manufacturing Prototype.,” *IEEE Trans. Educ.*, vol. 55, no. 3, pp. 326–331, 2012.

[62] R. M. RECK, R. S. SREENIVAS, and M. C. LOUI, “Evaluating the Effectiveness of an Affordable and Portable Laboratory Kit for an Introductory Control Systems Course.,” *Adv. Eng. Educ.*, vol. 7, no. 3, pp. 1–35, 2019.

[63] B. Ding *et al.*, “Feasible and economic DIY procedures of a hand-held fluorescence detector set—FluorDetector to assist laboratory course development.,” *Biochem. Mol. Biol. Educ.*, vol. 52, no. 5, pp. 580–587, 2024.

[64] J. Stark *et al.*, “BioBits^{TM} Bright: A fluorescent synthetic biology education kit,” *Sci. Adv.*, vol. 4, no. 8, 2018, doi: 10.1126/sciadv.aat5107.

[65] P. Maurye, A. Basu, S. Sen, J. K. Biswas, T. K. Bandyopadhyay, and M. Naskar, “User-friendly tool kits for protein gel electrophoresis techniques: A training program for high school students.,” *Biochem. Mol. Biol. Educ.*, vol. 46, no. 5, pp. 566–577, 2018.

[66] J. H. Yu, “Gel Electrophoresis on a Budget to Dye for,” *Sci. Teach.*, vol. 77, no. 1, pp. 50–54, 2010.

[67] H. G. H. Low and M. Ellefson, “Punnett Farms: Developing An Immersive Educational Game-Based Platform for Learning Genetics.,” *Simul. Gaming*, vol. 55, no. 2, pp. 302–322, 2024.
[68] K. M. Kaiphanliam, O. O. Adesope, and B. J. Van Wie, “Assessment of a particle sedimentation hands-on learning tool with application in blood cell separations.,” *Educ. Chem. Eng.*, vol. 45, pp. 28–40, 2023.
[69] A. Nguyen *et al.*, “Loop-Mediated Isothermal Amplification (LAMP) as a Rapid, Affordable and Effective Tool to Involve Students in Undergraduate Research,” *Front. Microbiol.*, vol. 11, 2020, doi: 10.3389/fmicb.2020.603381.
[70] M. Jawad, A. Bhattacharjee, R. Lehmann, A. Busza, P. Perez-Pinera, and K. Jensen, “Remote Laboratory Exercise to Develop Micropipetting Skills,” *J. Microbiol. Biol. Educ.*, vol. 22, no. 1, 2021, doi: 10.1128/jmbe.v22i1.2399.
[71] S. Rayment *et al.*, “Investigating Student Engagement and Making Science Real during a Pandemic: Bioskills at Home, a Case Study.,” *Educ. Sci.*, vol. 12, no. 2, p. 106, 2022.
[72] L. U. Medina Uzcátegui, C. Müller-Karger Pereda, and E. Casanova Medina, “The Virtual Rotor Kit Project: A virtual rotor test rig for balancing experiments.,” *Int. J. Mech. Eng. Educ.*, vol. 52, no. 4, pp. 429–456, 2024.
[73] D. Howard and M. Meier, “Meeting Laboratory Course Learning Goals Remotely via Custom Home Experiment Kits.,” *Phys. Teach.*, vol. 59, no. 6, pp. 404–409, 2021.
[74] Z. Laouina, L. Ouchaouka, M. Moussetad, S. Mordane, and M. Radid, “Remote Lab Experiments in Mechanic: The Compound Pendulum,” *Int. J. ONLINE Biomed. Eng.*, vol. 19, no. 2, pp. 23–41, 2023, doi: 10.3991/ijoe.v19i02.37061.
[75] N. Yusof *et al.*, “Development of an Educational Kit Using CAD Software for Simple Machine Learning,” *J. Adv. Res. Appl. Sci. Eng. Technol.*, vol. 44, no. 2, pp. 11–24, 2025, doi: 10.37934/araset.44.2.1124.
[76] N. Goodman, B. J. Leege, and P. E. Johnson, “An improved de Laval nozzle experiment.,” *Int. J. Mech. Eng. Educ.*, vol. 50, no. 2, pp. 513–537, 2022.
[77] T. DILLER and D. BAIRAKTAROV, “Evaluation of the Effectiveness of Individual Hands-on Workshops in Heat Transfer Classes to Specific Student Learning Outcomes.,” *Int. J. Eng. Educ.*, vol. 40, no. 1, pp. 5–15, 2024.
[78] A. I. KHAN *et al.*, “Effectiveness of Hands-on Desktop Learning Modules to Improve Student Learning in Fluid Mechanics and Heat Transfer across Institutions and Program Types.,” *Int. J. Eng. Educ.*, vol. 38, no. 3, pp. 849–872, 2022.
[79] O. M. REYNOLDS *et al.*, “Teaching Fluid Mechanics and Heat Transfer in Hands-on and Virtual Settings with Low Cost Desktop Learning Modules.,” *Int. J. Eng. Educ.*, vol. 38, no. 5, pp. 1536–1549.
[80] A. K. Mehrotra, N. N. Nassar, and A. S. Kasumu, “A novel laboratory experiment for demonstrating boiling heat transfer,” *Educ. Chem. Eng.*, vol. 7, no. 4, pp. e210–e218, 2012.
[81] L. M. Beltramini, A. P. U. Araújo, and T. H. Gonçalves de Oliveira, “A New Three-dimensional Educational Model Kit for Building DNA and RNA Molecules.,” *Biochem. Mol. Biol. Educ.*, vol. 34, no. 3, pp. 187–193, 2006.
[82] P. R. Piergiovanni, “Adsorption Kinetics and Isotherms: A Safe, Simple, and Inexpensive Experiment for Three Levels of Students.,” *J. Chem. Educ.*, vol. 91, no. 4, pp. 560–565, 2014.
[83] A. Dewan, B. Van Wie, H. Beyenal, and Z. Lewandowski, “The Microbial Fuel Cell as an Education Tool,” *Chem. Eng. Educ.*, vol. 44, no. 2, pp. 157–165, 2010.

[84] K. Kaushik, A. Kessel, N. Ratnayeke, and V. Gordon, “A Low-Cost, Hands-on Module to Characterize Antimicrobial Compounds Using an Interdisciplinary, Biophysical Approach,” *PLOS Biol.*, vol. 13, no. 1, 2015, doi: 10.1371/journal.pbio.1002044.
[85] R. Radhamani *et al.*, “Virtual Laboratories in Biotechnology are Significant Educational Informatics Tools,” presented at the 2018 INTERNATIONAL CONFERENCE ON ADVANCES IN COMPUTING, COMMUNICATIONS AND INFORMATICS (ICACCI), 2018, pp. 1547–1551.
[86] S. Tanabashi, “STE(A)M Education of Cell Biology Using Advanced 3D Technology for K-12 Learning,” presented at the PROCEEDINGS OF 2020 IEEE INTERNATIONAL CONFERENCE ON TEACHING, ASSESSMENT, AND LEARNING FOR ENGINEERING (IEEE TALE 2020), 2020, pp. 922–924. doi: 10.1109/TALE48869.2020.9368441.
[87] S. Ahmad, S. Alhayyas, M. Almansoori, N. Almenhali, F. Alsudain, and A. Alkhaldi, “Remote Control of the FESTO MPS PA Compact Workstation for the Development of a Remotely Accessible Process Control Laboratory,” *Int. J. ONLINE Biomed. Eng.*, vol. 16, no. 5, pp. 84–103, 2020, doi: 10.3991/ijoe.v16i05.12809.
[88] J. Silva, J. Simao, M. Cristiano, P. Nicolete, C. Heck, and K. Coelho, “A DC Electric Panel Remote Lab,” *Int. J. ONLINE Eng.*, vol. 12, no. 4, pp. 30–32, 2016, doi: 10.3991/ijoe.v12i04.5096.
[89] S. Fuada, “Development of Educational Kit for Practical Course in the Topic of Phase-Shift RC Oscillator,” *Int. J. Online Biomed. Eng.*, vol. 18, no. 5, pp. 112–130, 2022, doi: 10.3991/ijoe.v18i05.29131.
[90] Z. O. Mohammad, Z. A. Amar Faiz, H. M. Syahrul, K. A. Nur Dalila, and N. Ismail, “E-logic trainer kit: Development of an electronic educational simulator and quiz kit for logic gate combinational circuit by using arduino as application,” *Int. J. Online Biomed. Eng.*, vol. 15, no. 14, pp. 67–77, 2019, doi: 10.3991/ijoe.v15i14.11410.
[91] J. Lim, J. Cho, S. Kim, S. Kim, T. Nam, and O. Oh, “Development of a self-tutoring multimedia contents for microcontroller instruction set,” presented at the Healthcom 2005: 7th International Workshop on Enterprise Networking and Computing in Healthcare Industry, Proceedings, 2005, pp. 350–353. doi: 10.1109/HEALTH.2005.1500479.
[92] T. Ham, S. Rezvanifar, V. Thomas, and R. Amini, “Using Hands-On Physical Computing Projects to Teach Computer Programming to Biomedical Engineering Students,” *J. Biomech. Eng.-Trans. ASME*, vol. 140, no. 8, 2018, doi: 10.1115/1.4040226.
[93] L. C. Gerber, H. Kim, and I. H. Riedel-Kruse, “Microfluidic assembly kit based on laser-cut building blocks for education and fast prototyping,” *Biomicrofluidics*, vol. 9, no. 6, 2015, doi: 10.1063/1.4935593.
[94] D. Rackus, I. Riedel-Kruse, and N. Pamme, “‘Learning on a chip:’ Microfluidics for formal and informal science education,” *BIOMICROFLUIDICS*, vol. 13, no. 4, 2019, doi: 10.1063/1.5096030.
[95] C. Moraes, K. Wyss, E. Brisson, B. Keith, Y. Sun, and C. Simmons, “An Undergraduate Lab (on-a-Chip): Probing Single Cell Mechanics on a Microfluidic Platform,” *Cell. Mol. Bioeng.*, vol. 3, no. 3, pp. 319–330, 2010, doi: 10.1007/s12195-010-0124-0.
[96] Z. Hossain, A. Chung, and I. Riedel-Kruse, “Real-time and turn-based biology online experimentation,” presented at the PROCEEDINGS OF 2015 12TH INTERNATIONAL CONFERENCE ON REMOTE ENGINEERING AND VIRTUAL INSTRUMENTATION (REV), 2015, pp. 86–89.

[97] Y. Wu *et al.*, “An educational kit for introducing microfluidics-based cell adhesion assay in undergraduate laboratory (work in progress),” *ASEE Annu. Conf. Expo. Conf. Proc.*, vol. 2017-June, 2017, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85030570512&partnerID=40&md5=3b36df2bb4287a7b8d2087a7e69e82e7

[98] P. D. Rodriguez *et al.*, “A guided-inquiry investigation of genetic variants using Oxford nanopore sequencing for an undergraduate molecular biology laboratory course.,” *Biochem. Mol. Biol. Educ.*, vol. 49, no. 4, pp. 588–597, 2021.

[99] A. Vahedi and A. Farnoud, “Novel Experimental Modules To Introduce Students to Nanoparticle Characterization in a Chemical Engineering Course,” *J. Chem. Educ.*, vol. 96, no. 9, pp. 2029–2035, 2019, doi: 10.1021/acs.jchemed.9b00423.

[100] J. A. Gimm, A. Bentley, M. Farhoud, A. B. Ellis, G. C. Lisensky, and W. C. Crone, “Video laboratory manuals and kits that explain nanoscale science and engineering concepts,” presented at the ASEE Annual Conference and Exposition, Conference Proceedings, 2005, pp. 15651–15658. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-22544458199&partnerID=40&md5=e6aaaeac6fb4ee17aba79e8b8eca9088

[101] A. URAL, “A Virtual Biomechanics Laboratory Incorporating Advanced Image Processing and Finite Element Modeling.,” *Int. J. Eng. Educ.*, vol. 34, no. 2,Part A, pp. 505–513, 2018.

[102] R. Z. Gao, P. S. Lee, A. Ravi, C. L. Ren, C. R. Dickerson, and J. Y. Tung, “Hybrid Soft-Rigid Active Prosthetics Laboratory Exercise for Hands-On Biomechanical and Biomedical Engineering Education,” *J. Biomech. Eng.*, vol. 146, no. 5, 2024, doi: 10.1115/1.4065008.

[103] L. Garofalo, S. Sandler, and D. Seth, “Evaluation of a Snake Jaw Robot to Teach Integrated Biology, Mathematics, and Engineering,” presented at the 2020 9TH IEEE INTEGRATED STEM EDUCATION CONFERENCE (ISEC 2020), 2020.

[104] D. Daidié *et al.*, “The DoF-box project: An educational kit for configurable robots,” presented at the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM, 2007. doi: 10.1109/AIM.2007.4412571.

[105] N. Rokbani, A. Zaidi, and A. M. Alimi, “Prototyping a biped robot using an educational robotics kit,” presented at the 2012 International Conference on Education and e-Learning Innovations, ICEELI 2012, 2012. doi: 10.1109/ICEELI.2012.6360682.

[106] K. Kitto, “Enhancing fundamental materials engineering education using biomedical devices and case studies,” presented at the ASEE Annual Conference and Exposition, Conference Proceedings, 2009. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029060524&partnerID=40&md5=54912acfc85fe1d20aafff02d493d7f1

[107] A. Singh, D. Ferry, and S. Balasubramanian, “Efficacy of Clinical Simulation-Based Training in Biomedical Engineering Education,” *J. Biomech. Eng.-Trans. ASME*, vol. 141, no. 12, 2019, doi: 10.1115/1.4045343.

[108] C. Backstrom, A. Chandra, J. Hale, and D. Mooradian, “DEVELOPMENT AND EVALUATION OF SIMULATION EDUCATION FOR UNIVERSITY OF MINNESOTA MASTER OF MEDICAL DEVICE INNOVATION STUDENTS IN A POST-COVID WORLD,” presented at the Proceedings of the 2022 Design of Medical Devices Conference, DMD 2022, 2022. doi: 10.1115/DMD2022-1066.

[109] J. A. M. Kaste, A. Green, and Y. Shachar-Hill, “Integrative teaching of metabolic modeling and flux analysis with interactive python modules.,” *Biochem. Mol. Biol. Educ.*, vol. 51, no. 6, pp. 653–661, 2023.

[110] P. Allen, N. Nguyen, N. Humphrey, J. Mao, D. Chavez-Bonilla, and E. Sorin, “A Hands-On Collaboration-Ready Single- or Interdisciplinary Computational Exercise in Molecular Recognition and Drug Design,” *Educ. Sci.*, vol. 14, no. 2, 2024, doi: 10.3390/educsci14020139.
[111] A. Boskovic *et al.*, “Acoustic trapping in the undergraduate laboratory.,” *Am. J. Phys.*, vol. 92, no. 1, pp. 59–64, 2024.
[112] M. Pajpach, O. Haffner, E. Kučera, and P. Drahoš, “Low-Cost Education Kit for Teaching Basic Skills for Industry 4.0 Using Deep-Learning in Quality Control Tasks,” *Electron. Switz.*, vol. 11, no. 2, 2022, doi: 10.3390/electronics11020230.
[113] S. Farrell and E. Cavanagh, “An introduction to life cycle assessment with hands-on experiments for biodiesel production and use.,” *Educ. Chem. Eng.*, vol. 9, no. 3, pp. e67–e76, 2014.
[114] N. Haj-Hosseini, H. Jonasson, M. Stridsman, and L. Carlsson, “Interactive remote electrical safety laboratory module in biomedical engineering education,” *Educ. Inf. Technol.*, 2024, doi: 10.1007/s10639-024-12636-9.