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Implementation of Low-Cost Laboratory in Education: A Systematic Literature Review

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ABSTRACT

The availability of educational facilities is still a problem in many countries. Inadequate laboratory equipment will affect student learning outcomes and the quality of graduates. Therefore, many studies have developed low-cost laboratories as an alternative solution. This article aims to study the development of low-cost laboratories and their implementation in learning. This study used the systematic literature review (SLR) method. The articles used in this study were published from 2017–2021 and obtained from the IEEE Xplore database. After the papers were accepted, we were selected using inclusion and exclusion criteria. Thirty-two articles were used. The results show that a low-cost laboratory can be an alternative solution to the high price of commercial equipment and a learning tool to improve learning outcomes. The methods used in implementing low-cost laboratories are design, research and development, and experimentation. Using low-cost laboratories in learning activities improves the quality of learning outcomes.

***Keywords**: low-cost, laboratory, implementation, education*

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INTRODUCTION

In developing countries, educational facilities and infrastructure availability is still a problem in educational scope (Prieto et al., 2017). Inadequate facilities in educational institutions (Ekin et al., 2021), the disproportionate number of available tools and students (Ong & Ling, 2020; Oteri, 2020; Trabelsi & Saleous, 2019) force students to practice activities in groups (Berman et al., 2021), and the high price of tools or machines that meet industrial standards (Fukumoto et al., 2021) becomes a burden for schools. Sometimes the commercial equipment available on the market is unsuitable for educational purposes (Dias et al., 2020). Strategies for fulfilling laboratory/ workshop facilities, including optimizing their use by teachers in learning, have become alternative solutions to improve the quality of learning (Sajidan et al., 2018).

The COVID-19 pandemic has significantly impacted social order, affecting education, especially the learning process. The social distancing policy has forced students to learn from home, and they cannot attend face-to-face learning at school, including laboratory practice activities (Bekasiewicz et al., 2021). However, on the other hand, practice learning activities cannot be eliminated, especially in vocational subjects (Huertas et al., 2020).

Practice learning is essential to improving students' competence (Slamnik-Krijestorac et al., 2021). The "learning by doing" method can increase the student's understanding of learning materials by up to 70%. They do what they hear and see (Khaing et al., 2018). Three kinds of practice learning activities are simulation, emulation, and hands-on practice (Uyanik & Catalbas, 2018). Laboratory experiments are essential to achieving learning objectives and enriching students' cognitive, affective, and psychomotor abilities. Through this practical learning activity, students will observe and verify the concepts and theories learned in the classroom using hands-on experiments (Firdaus et al., 2019). Teaching facilities are one factor supporting that learning activity's success (Bima et al., 2021).

Various educational institutions have made various efforts to resolve the limitations of practical learning facilities in the laboratory. One of them is the development of low-cost laboratory equipment as an alternative solution to the availability of suitable equipment and to overcome social distancing policies during the pandemic (Tahiru, 2021). A practical and appropriate learning approach should also be explored so that the quality of learning continues to improve (Lee et al., 2020; Sanfilippo & Austreng, 2018). So, in this study, we are trying to explain the implementation of low-cost laboratories in education.

Low-cost laboratories support practical learning activities developed using more straightforward, cheaper, and more affordable equipment. For example, using Arduino for a control system to replace a PLC or Raspberry Pi for network servers is relatively cheaper than using a computer CPU. Simulation software to simulate the operation of commercial equipment, which is expensive. To support the learning process, especially for practicum teaching at universities and schools, researchers, lecturers, and teachers have been developing low-cost laboratory kits (Chowdhury et al., 2019).

Although low-cost laboratory kits have limitations and are not as comprehensive as high-cost laboratory kits, there are several identifiable advantages 1) Affordable price; 2) Primary and beginner education; 3) Portability and flexibility; 4) the simplicity and ease to use; and 5) Initiate an interest in science. This low-cost laboratory kit can also be an alternative solution for schools in fulfilling adequate practicum equipment considering the price of commercial equipment is fairly expensive (Mukarramah, 2020). Students can conduct experiments similar to commercial laboratory equipment at a reduced cost and gain hands-on experience in their learning. Low-cost laboratories can be categorized into physical laboratories (learning kits, portable trainer kits), virtual laboratories, and remote laboratories.

Here is a comparison between low-cost and high-cost laboratory kits:

Table 1. Comparison of Low-cost with High-cost laboratory kit

Criteria	Low-cost Laboratory Kit	High-cost Laboratory Kit
Price	More affordable	Expensive

Criteria	Low-cost Laboratory Kit	High-cost Laboratory Kit
Goal	Primary education	Professional Research
Equipment	Simple basic equipment	Advanced, precise, and specialist
Ability	Simple Experiment	More complex experiment
Material quality	Cheaper, simpler	High quality
Durability	Relatively Short	Durable
Precision and accuracy	Wider tolerances	Higher in measurement and analysis
Application	Basic education, home experiments, scientific concepts	Scientific research, product development, or advanced testing

This systematic literature review offers an overview of the development and implementation of low-cost laboratories in learning. We study research methods, technology types, and instructional learning design. So, the research questions in this study are:

RQ1: What are the research objectives, methods, and outcomes of implementing low-cost education laboratories?

RQ2: At which level of education has a low-cost laboratory been implemented?

RQ3: What technology has been used in the development of low-cost laboratories?

RQ4: What instructional design has been applied to low-cost laboratories?

Through this study, we hope that it can motivate teachers and students to develop low-cost laboratories as an alternative solution to increase the availability of learning facilities at schools.

RESEARCH METHODS

This systematic literature review (SLR) study was carried out to get an overview of the implementation of low-cost laboratories in the learning process. The systematic literature review synthesizes scientific articles to answer specific research questions transparently and reproducibly while combining all published articles on related topics and assessing the article's quality (Lame, 2019). SLR research aims to identify, review, evaluate, and interpret all available studies on interesting phenomena with specific relevant research questions (Triandini et al., 2019). The synthesis of articles refers to the PRISMA 2020 guidelines (Page et al., 2021). This guide helps researchers provide transparent and complete reports on SLR (Chan et al., 2021). The author must decide on a search strategy, selection criteria, and data collection procedure.

Database and keyword

The first stage of the SLR is searching for literature in the database. The literature search for this study was carried out on the IEEE Xplore database using the terms (low cost OR Affordable OR portable) AND (laboratory OR kit) AND (teaching OR learning OR education) in the Abstract field with publications between 2017 to 2021. This search returned 228 articles.

Inclusion and exclusion criteria

Table 2. Criteria for Inclusion and Exclusion

Inclusion	Exclusion
Journal and proceeding.	Articles are reviews, literature reviews, bibliometrics, manuscripts
Development of Low-cost laboratory for learning purposes	Low-cost laboratory for research or industrial purpose
Published in English	Published not in English
Implemented in learning	Has not been implemented in the learning
	The full text cannot be downloaded

The next step is to select an article related to the issue under consideration for review. The article selection process refers to PRISMA 2020 (Page et al., 2021). This synthesis stage consists of four stages: identification, screening, eligibility, and inclusion. Article selection started with screening the article title and abstract and obtaining as many as 108 articles. After that, we continued with full-text screening, referring to the inclusion and exclusion criteria as in Table 1 above, so that 32 articles were obtained.

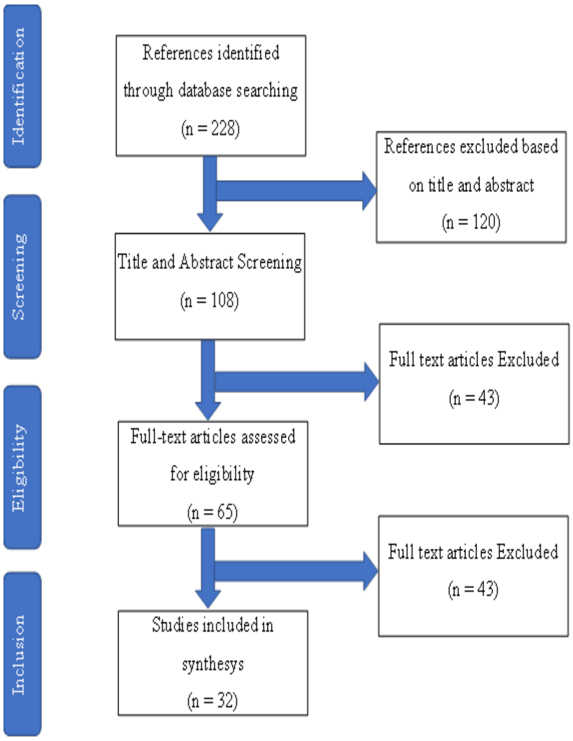

Figure 1. The PRISMA flow diagram.

Data analysis and coding

The final step is to analyze 32 articles to find information corresponding to the research questions.

1. Research Objective

An analysis of the purpose of the research was to get answers to RQ1 about the low-cost laboratory implementation's research purpose. In this case, we group the research objectives into three categories: action research, experimentation, and research and development. Analysis of the study's intention was to get answers to RQ1 about the low-cost laboratory implementation's research purpose. In this case, we group the research objectives into three categories: action research, experimentation, and research and development.

Action research focuses on research to improve learning. Experiment Research focuses on research conducted to try, find out, and confirm, while Research and Development is a research program to develop products used in education.

2. Research Methods

At the Research Methods stage, an analysis was carried out to answer RQ1 about the methods used to research low-cost laboratories' implementation.

3. Research Outcome

An analysis was conducted to answer RQ1 about the research results used in low-cost laboratory implementation research. The variables in the group fall into three categories: affective, cognitive, and skill-based.

4. Education Level

The level of education is reviewed to determine how this low-cost laboratory research has been applied. The term used refers to the level of formal and informal education.

5. Technology Type

The review of the types of technology aims to find out what types of low-cost laboratories are used in learning.

6. Instructional Design

Instructional design is an analysis that identifies learning models that use the low-cost laboratory used in this publication.

THE RESULTS OF THE RESEARCH AND DISCUSSION

1. Research Objectives

Table 3. Categories of research objectives

Research Objectives	Number of Articles	Reference
Action Research	8	2; 3; 4; 5; 11; 14; 15; 19.
Experiment	12	6; 8; 9; 10; 13; 16; 17; 21; 22; 24; 29; 32.
Research and Development	12	1; 7; 12; 18; 20; 23; 25; 26; 27; 28; 30; 31.

Research in low-cost laboratories is still focused on development and experimentation. In this case, the development of low-cost laboratories (n = 12 or 37.5%) is driven by the limited availability of practicum equipment in educational institutions, so it is necessary to find alternative solutions. This limitation is due to the high price of commercial laboratory instruments, and sometimes the kits on the market are unsuitable for use in educational institutions. Meanwhile, various experiments were also carried out (n = 12 or 37.5%) to find the right way to use these tools in the learning process, whether as a learning tool or as a learning medium, especially during the implementation of social distancing in the pandemic period. However, there are still few studies to see the results or impact of the implementation of low-cost laboratories on improving the quality of learning (action research) (n = 8 or 25%).

2. Research Methods

Table 4. Research methods

Research Methods	Number of Articles	Reference
Experiment	7	4; 13; 14; 16; 19; 28; 30.
Exploration	2	8; 10
Comparison	1	2
Qualitative	2	3; 15
Mixed Methods	1	11
Quasi-experiment	16	1; 5; 6; 7; 9; 12; 17; 20; 21; 22; 23; 24; 27; 29; 31; 32.
Research & Development	3	18; 25; 26

The quasi-experiment method predominates (n = 16, or 50%) as a reference method. In its implementation, this method does not use random assignments but existing groups. This method is widely used because researchers do not need to create certain conditions to conduct research, and they can take advantage of the students they are teaching to provide feedback on the tools used in learning. Other methods were used, such as experiments (n = 7 or 22%) and R&D (n = 3 or 10%). The rest are exploration, comparison, quantitative, triangulation, and mixed methods.

3. Research Outcomes

Table 5. An Overview of the research outcome

Research Outcomes	Number of Articles	Reference
Affective	20	1; 2; 3; 4; 5; 6; 7; 9; 10; 11; 15; 16; 21; 22; 24; 27; 29; 30; 31; 32.
Cognitive	11	2; 3; 5; 6; 7; 8; 12; 15; 19; 21; 22.
Skill-based	26	1; 2; 3; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; 22; 23; 24; 25; 26; 27; 28.

Most studies measure this skills-based aspect (n = 26 or 46%). Most studies are conducted with quasi-experiments to see how low-cost laboratories can be an alternative solution for students to do practical activities. Either in hands-on practice due to limited facilities or remotely and virtually due to enacting social distancing policies during a pandemic, even with project-based learning. Practicum learning activities in the laboratory aim to train and improve students' skills for specific jobs, especially in engineering schools. In addition, the study also examined affective aspects (n = 20 or 35%) by asking students for responses using low-cost laboratories. This feedback can be used for comfort, motivation, effectiveness, and confidence in learning. At the same time, the cognitive aspect, 19% (n = 11) of the whole, does it. Research that measures cognitive aspects is generally carried out if the tool has been used in the course and the learning steps are well planned. Note: In this part of the results, many researchers have examined more than one aspect.

4. Education Level

Table 6. The level of education

Education Level	Number of Articles	Reference
Secondary School	1	29
High School	3	3; 8; 26
Undergraduate	26	1; 2; 4; 5; 6; 7; 8; 9; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; 22; 23; 24; 25; 28; 30; 31; 32.
Postgraduate	2	23; 30.
College	1	27
Training Course	1	10

Most of the research on low-cost laboratories was implemented at the undergraduate university level (n = 26, or 76%). As for other levels of education, there are very few. Postgraduate 6% or two articles; high school 9% or three articles; secondary school, college, and the training course 3% each or 1 article.

5. Technology Type

Table 7. The type of technology

Technology Type	Number of Articles	Reference
Cloud Laboratory	1	2
Learning Kit	2	3; 11.
Physical Laboratory	12	2; 6; 9; 18; 20; 21; 22; 23; 25; 28; 30; 32.
Portable kit	6	5; 7; 12; 13; 15; 31
Remote Laboratory	5	1; 4; 10; 16; 17
Virtual Laboratory	7	8; 14; 19; 24; 26; 27; 29;

Since low-cost laboratories generally aim to provide adequate practicum facilities in educational institutions, the development of physical laboratory types is found in many referenced publications (n = 12, or 37%). After the COVID-19 pandemic, the development of low-cost laboratories began to shift towards equipment that could support distance learning. So, the development of portable kits (n = 6 or 18%), remote laboratories (n = 5 or 15%), virtual laboratories (n = 7 or 21%), and cloud laboratories (n = 1 or 3%) began to be done a lot. In addition, there is also equipment designed as a project for students, where they can devote their creativity to the project. Here we term the learning kit discussed through (n = 2 or 6%) articles.

6. Instructional design

Table 8. Instructional Design

Instructional Design	Number of Articles	Reference
Activity Based Learning	1	29
Blended Learning	1	14
Hands-on Experiment	12	5; 6; 7; 9; 13; 15; 20; 21; 23; 28; 31; 32
Online Learning	1	8
Project Based Learning	7	2; 3; 11; 12; 18; 25; 30
Remote Experiment	5	1; 4; 10; 16; 17

Instructional Design	Number of Articles	Reference
Simulation	4	19; 22; 24; 26
Virtual Experiment	1	27

From the literature review results, the most widely used instructional design is a hands-on experiment (n = 12, or 37%). As previously mentioned, the type of equipment most widely used is the physical laboratory. Next are the project-based learning designs (n = 7 or 21%), remote experiments (n = 5 or 15%), and simulation learning (n = 4 or 12%). Only one article was found for designs such as activity-based learning, blended learning, online learning, and virtual experiments.

RQ1. Research Methods for the Implementation of low-cost laboratory

In this study, we found that research on the application of low-cost laboratories is generally carried out to develop tools to find solutions to inadequate educational facilities and infrastructure in educational institutions. This situation is due to the high price of practicum equipment on the (commercial) market, so the school is not able to provide it in sufficient quantities for each student. Sometimes the equipment on the market is not necessarily suitable for use in the learning process.

Educational resources must be adequate to achieve educational goals. However, Limited funds, the high price of commercial equipment, and large class sizes can be an obstacle. To overcome these problems, low-cost laboratory kits were developed as low-cost and affordable learning equipment to support the teaching and learning process. Small-scale labor is suitable for schools with large student ratios because it is cheaper and can serve more students in practicum.

Quasi-experimental research is widely conducted to review the impact of the developed equipment on the learning activities it supports and find effective ways to use it so that this equipment can provide the expected learning benefits. Researchers use many quasi-experimental methods where they do not need to design special conditions to test the tools and learning strategies to be learned. They research students who take lectures in the courses they teach.

The development of low-cost laboratory kits in educational institutions aims to optimize learning. To check the results, it is necessary to test practically to the students. Quasi-Experimental methods are used to implement tools in education and see changes before and after. Quasi-experimentation is a type of research that does not use randomization in the formation of subject groups. The goal is to test hypotheses about causal relationships between independent and dependent variables. Advantages of quasi-experiments: flexible in research, controlling certain factors without limiting other variables. This allows researchers to be more flexible, adapt research designs to suit the situation and address ethical concerns. Quasi-experiments are used if an actual experiment is unethical or detrimental to a research subject, such as humans or animals, and helps researchers gather data. Quasi-experiments are commonly used in real-world situations such as in health, education, social, or economic fields. Thus, researchers can study everyday phenomena and make relevant and applicable conclusions.

The skill aspect is one of the most emerging as a result of research on the application of low-cost laboratories. Practicum in the laboratory aims primarily to train and improve students' skills for specific jobs. However, affective and cognitive aspects are often involved in research because these three aspects of learning go hand in hand. Many research results reveal that cheap equipment makes its users comfortable and confident in using it, increasing interest and motivation in learning. In addition, it will undoubtedly improve student learning outcomes regarding skills and knowledge.

The development of low-cost laboratory kits increases student competence in science learning with cheap and easily obtained materials, allowing students to conduct experiments independently, creatively, and innovatively. Students become more excited and optimistic in the science learning process, and their ability to develop curiosity increases.

- Knowledge competence. Students can better understand science concepts by using practice tools that are affordable and readily available.
- Skill competence. Students can develop good science practice skills using effective and efficient practice tools.
- Affective competence. Students use low-cost lab practice tools and have a positive attitude to science, including confidence, honesty, responsible, criticalness, cooperation, and environmentally caring. Also, appreciate the process/deliverable, and acknowledge the advantages/disadvantages of practical tools.

Students who use low-cost laboratory-based practice tools can gain better knowledge than conventional methods. Students improve their science skills with a deeper and more integrated understanding, as well as being able to carry out the science process. Low-cost laboratories can improve students' 21st-century skills in the era of globalization, such as communicating, collaborating, critical thinking, creativity, innovation, and solving problems. Students can express oral and written ideas, work collaboratively with groups or cross-groups, and create alternative solutions and useful new products.

RQ2. Education level that implements low-cost laboratory

The development and implementation of low-cost laboratories still dominate higher education. Very little research addresses the development of low-cost laboratory implementation at the secondary education level. Research is needed related to the implementation of low-cost laboratories at the secondary education level. The problem of limited learning facilities and infrastructure does not only occur at the higher education level, but this limitation is more common in secondary and vocational schools.

The development of low-cost laboratory kits is one of the efforts to improve the quality of science education. Low-Cost Laboratory Kit is a simple lab kit that can be made at a low cost and easily obtained materials. Low-cost laboratory kits can be used to demonstrate basic science concepts, such as electricity, magnetism, waves, optics, chemistry, and biology. The low-cost laboratory kit can not only be applied at the university level but also at the high school level. By using a low-cost laboratory kit, students can learn science actively, creatively, and with fun. Low-cost laboratory kits can also increase students' interest and motivation in science, as well as develop critical and scientific thinking skills. For this reason, there needs to be efforts and encouragement for teachers in secondary schools to actively develop learning kits based on low-cost laboratories so that equipment availability is no longer an obstacle to improving the quality of learning.

RQ3. Technology that is used in implementing low-cost laboratory

Low-cost laboratory kits as an alternative to expensive commercial equipment still dominate as a widely applied technology in learning. This equipment is generally developed based on Arduino, Raspberry Pi, and other simple electronic devices. After the COVID-19 pandemic, low-cost laboratory research began to be directed toward supporting developments for online learning. This equipment is designed as a virtual laboratory, portable kit, and remote laboratory. This design aims to provide skills aspects to students in social distancing policies where students cannot carry out practicum activities directly in the laboratory.

One example of a low-cost laboratory developed is a virtual laboratory. A virtual laboratory is a web-based application that allows users to simulate scientific experiments without having to have physical equipment. Virtual labs can provide benefits such as saving costs, time, and resources, improving accessibility and student engagement, and reducing safety and environmental risks. Virtual labs can also support distance learning and collaboration between students and teachers from different locations.

RQ4. Instructional Design in implementing low-cost laboratories in learning

Instructional design in the form of hands-on practicum is commonly found in these studies. Much of this instructional design refers to the design of learning using both conventional and commercial equipment that seeks to be implemented on low-cost laboratory-based equipment. However, learning methods are also created and pursued in existing technological conditions and developments. That way, existing low-cost laboratories are implemented using new instructional designs and are expected to deliver better results and impact.

Low-cost laboratories can be implemented in learning activities in schools with the following steps:

1. Determine learning materials that follow the curriculum and essential competencies to be achieved.
2. Develop a learning plan that includes objectives, methods, media, learning resources, and evaluation.
3. Prepare low-cost laboratory tools and materials needed following learning materials. Teachers or students themselves can make these tools and materials by utilizing used or inexpensive items available around the school or home environment.
4. Conduct learning activities using the low-cost laboratory as a medium to explain, demonstrate, or conduct experiments related to learning materials.
5. Provide opportunities for students to interact, discuss, and explore low-cost laboratories independently or in groups.
6. Evaluate learning using instruments that follow the learning objectives and the low-cost laboratory used.

Implementing a low-cost laboratory in learning activities at school is expected to increase students' understanding, creativity, and interest in science and save the cost of procuring expensive laboratory equipment.

CONCLUSIONS AND SUGGESTIONS

Conclusion

The availability of inadequate educational facilities and infrastructure is still a problem in many countries, and to fulfill it requires a lot of money. The high cost of commercial equipment on the market and the large number of students burden the institution. The condition has been exacerbated by the COVID-19 pandemic, which has limited laboratory activities. This pandemic will undoubtedly affect the quality of learning outcomes and graduates, especially in technical and vocational education.

Various studies were conducted to find solutions to reduce this limitation. One of them is research, development, and experiments carried out to develop low-cost laboratory equipment, which is expected to be an alternative solution. Low-cost laboratories are meant to be laboratory facilities to support practical learning activities designed using more straightforward equipment, making them cheaper and more affordable. Low-cost laboratories include physical (learning and portable trainer kits), virtual laboratories, and remote laboratories. The device is implemented in the learning process at various levels of education, from elementary school, high school, university, college, and training courses through hands-on experimental learning, project-based learning, remote experiments, and simulations.

Implementing low-cost laboratories in learning can positively impact supporting learning activities and improve the quality of student learning outcomes. This impact is felt in the skill, affective, and cognitive aspects of learning because these three aspects go hand in hand. Practicum in the laboratory using low-cost equipment mostly shows results that can improve students' skills for a specific job. The developed tools can be accepted and used well by learners. They become more confident and motivated to do learning activities using these tools, and the learning outcomes also show improvement.

Suggestion

This review identifies studies investigating low-cost laboratory implementations that are still being conducted at the undergraduate level. However, there are still very few at the other educational levels. Therefore, it is also necessary to study the implementation of low-cost laboratories in the middle grades, such as in vocational high schools. In addition, it is necessary to explore the instructional design in implementing the low-cost laboratory in the course so that the development and implementation of this low-cost laboratory in education can be duplicated by other educational institutions so that it can also improve the quality of graduates. It is necessary to encourage institutions at different levels to do the same so that laboratory practice facilities' needs are met, and teachers can carry out learning activities with varied methods.

Limitation

The limitations of this literature study are that only one database source is used. Because of that, many publications that should be included in this review may be neglected. Nevertheless, these limitations should not affect our conclusions too much. In addition, the IEEE Xplore database generally contains electronic and electrical engineering publications. Most articles used in this literature study implement low-cost electrical engineering laboratories.

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Appendix: Coding scheme of the 32 reviewed publications

No.	Study	Author	Years
1	Application of Open-Hardware-Based Solutions for Rapid Transition from Stationary to the Remote Teaching Model During Pandemic	Bekasiewicz, A Pankiewicz, B Wojcikowski, M Klosowski, M Koziel, S	2021
2	Cloud-based virtual labs vs. low-cost physical labs: what engineering students think	Slamnik-Krijestorac, Nina Langenbergh, Raf Van Den Huybrechts, Thomas Gutierrez, Sergio Martin Gil, Manuel Castro Marquez-Barja, Johann M.	2021
3	A Do-It-Yourself (DIY) LightWave Sensing and Communication Project: Low-Cost, Portable, Effective, and Fun	Ekin, S O'Hara, J F Turgut, E Colston, N Young, J L	2021
4	Developing a Remote Laboratory System of Stepper Motor for Learning Support	Fukumoto, Hisao Yamaguchi, Takashi Ishibashi, Makoto Furukawa, Tatsuya	2021
5	Utilizing Portable Learning Technologies to Improve Student Engagement and Retention	Carlson, Charles Peterson, Garrett Day, Dwight	2020
6	Low-Cost DC Motor System for Teaching Automatic Controls	Cook, Michael D. Bonniwell, Jennifer L. Rodriguez, Luis A. Williams, Daniel W. Pribbernow, Jacob	2020
7	A Portable Lab for the Practical Study of Modern Computer Engineering	Dias, Tiago Sampaio, Pedro Matutino, Pedro Miguens	2020
8	Low-cost and high-precision labs to promote active learning in online learning environments	Huertas, Jose I. Vazquez-Villegas, Patricia DIaz-Ramirez, Jenny Tejeda, Santa	2020
9	Cost-efficient Hands-on Learning Design for Computer Organization Course	Lee, Suk Jin Jung, Andrew Park, Jinsook Yun, Mira	2020
10	A Low-Cost Remote Laboratory for Photovoltaic Systems to Explore the Acceptance of the Students	Martin, Aranzazu D. Cano, Juan M. Vazquez, Jesus R. Lopez-Garcia, Diego A.	2020
11	Low-Cost Educational Robotics Car Promotes STEM Learning and 21st-Century Skills	Ong, Sing Ling Ling, Jill Pei Wah	2020
12	The Application of IoT layer one Based Mobile Labs in Engineering, Science, and Technology Education	Oteri, Omae Malack	2020
13	Freewheeling Electronic Laboratory Learning with Pocket Instruments	Ren, Yanpin Wu, Min	2020

14	Mobile Technologies in Blended Learning of Engineering Students in Digital Measurements on Geodetic Equipment	Solnyshkova, Olga Dudysheva, Elena	2020
15	Enhancing practical skills in the electronics classroom with portable labs	Valiente, David Rodriguez, Fernando Ferrer, Juan Carlos Alonso, Jose Luis De Avila, Susana Fernandez	2020
16	Remote Implementation of Microcomputers Laboratory Practices: A Case Study	Wong, W. K. Juwono, Filbert H. Loh, W. N.	2020
17	Programming logical controllers using remote labs and virtual reality	Alvarez, Jorge Díaz, Gabino Macías, Manuel	2019
18	Design and Building of an Automatic Alternator Synchronizer Based on Open-Hardware Arduino Platform	Riedemann, Javier Peña, Rubén Pino, Rubén Perez, Martín Jara, Werner Pesce, Cristián Melín, Pedro	2019
19	Exploring the Opportunities of Cisco Packet Tracer for Hands-on Security Courses on Firewalls	Trabelsi, Zouheir Saleous, Heba	2019
20	Development and Outcomes of Teaching PID Control in Classroom with Hands-on Learning Experience	Tran, Long Quang Sun, Yifeng Guan, Robin Saeed, Junaid Wang, Liuping Radcliffe, P. J.	2019
21	Integrating Hardware Prototyping Platforms into the Classroom	Al-Masri, Eyhab	2019
22	A low-cost approach to simulate real-world automotive platforms in systems engineering education for non-computer science majors	Meyer, Dany Bergande, Bianca Seyser, Dominik	2018
23	A Flexible Laboratory Environment Supporting Honeypot Deployment for Teaching Real-World Cybersecurity Skills	Eliot, Neil Kendall, David Brockway, Michael	2018
24	Affordances of Virtual and Physical Laboratory Projects for Instructional Design: Impacts on Student Engagement. IEEE Transactions on Education	Nolen, Susan Bobbitt Koretsky, Milo D.	2018
25	Enhancing Teaching Methods on Embedded Systems with Project-Based Learning	Sanfilippo, Filippo Austreng, Kolbjorn	2018
26	Development and Application of Nursing Operation Virtual Simulation Training System	Yang, Xueqin Li, Yazhen Wang, Lan Li, Deli	2018
27	Experiences with Multi-modal Collaborative Virtual Laboratory (MMCVL)	Desai, Kevin Belmonte, Uriel Haile Hernndez Jin, Rong Prabhakaran, Balakrishnan Diehl, Paul	2017

		Ramirez, Victor Ayala Johnson, Vinu Gans, Murry	
28	Reconfigurable devices-based experimentation supports teaching introductory digital systems	Gomes, Luís Costa, Anikó Moutinho, Filipe Maló, Pedro	2017
29	Benefits of Activity-Based Learning Pedagogy with Online Labs (OLabs)	Nedungadi, Prema Prabhakaran, Malini Raman, Raghu	2018
30	Learning autonomous systems — An interdisciplinary project-based experience	Page, Brian R Ziaeefard, Saeedeh Moridian, Barzin Mahmoudian, Nina	2017
31	Portable Electrical Capacitance Tomography Device for Teaching and Learning of Engineering Instrumentation in Electrical Engineering Laboratory	Phang, Fatin Aliah Pusppanathan, Jaysuman Rahim, Ruzairi Abdul	2018
32	A modern, versatile and low-cost educational system for teaching DC/DC converter control with analog, digital and mixed-signal methods	Ulrich, Burkhard	2017