



ORIGINAL RESEARCH ARTICLE

The Potential of Virtual Laboratories in Enhancing Biology Learning

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ABSTRACT

The ICT integration has transformed education, with virtual labs emerging as potential tools to enhance biology learning. This study conducted a comprehensive review to investigate the impact of virtual laboratories on student learning outcomes across various biology topics. A systematic review protocol was employed to identify and select relevant articles from Google Scholar, ERIC, Web of Science, Civilica, and SID. These databases were searched for journal and conference papers on the use of virtual laboratories in biology education. The review revealed that virtual laboratories are effective tools for teaching biology, particularly in abstract areas like cellular and molecular biology, genetics, and microbiology, as well as practical subjects such as dissection and biotechnology. These labs enhance students' conceptual understanding, practical skills, motivation, and attitudes. Realistic simulations within virtual laboratories were found to be particularly beneficial. However, a combination of virtual and real laboratories is recommended for optimal outcomes. While realistic simulations within virtual laboratories are effective, combining virtual and real laboratory experiences is essential for maximizing student learning and providing safer, more cost-effective opportunities for scientific inquiry. ©authors

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## 1. Introduction

Information and Communication Technology (ICT) has emerged as a powerful tool, playing a pivotal role in shaping new learning environments and driving rapid societal changes. This technology has significantly impacted various aspects of life, including education. Recent developments in education, particularly in the field of educational technology, have introduced new approaches and environments, marking a significant transformation. Rapid advancements in ICT in the present era have extended beyond providing equal opportunities and facilitating learning for those who were previously unable to do so (Zaraii Zvaraki & Schneider, 2019). Moreover, the development of these tools and technologies has strengthened face-to-face learning environments while simultaneously giving rise to electronic and blended learning environments (Hatami et al., 2018). The absence of new technologies does not constitute a deficiency in education, but their presence in classrooms is necessary for educational transformation (Abbasi et al., 2024).

On the other hand, learning science (acquiring knowledge and skills in science) is essential for successful participation in today's knowledge-based society and is crucial for forming informed opinions and making informed decisions. Consequently, science learning has become a fundamental goal of science education. In this context, the experimental nature of basic sciences and the possibility of understanding natural phenomena empirically for students, in the integration of theoretical and practical education, provide suitable conditions, considering the possibility of using simple and accessible science activities to address the six dimensions of education (Mirzaei et al., 2020).

In this context, laboratories have long been considered the domain for practical work and learning; however, in many schools, students either lack a formal laboratory program or their lab work is often unscheduled and conducted only when there is extra time (Hatami et al., 2018).

It seems that technology and innovative computer programs, particularly simulations and virtual laboratories, play a significant role in this regard and can have positive impacts on learners' acquisition of knowledge, skills, and motivation (Farrokhnia et al., 2010). A virtual laboratory is a system that can be used to support traditional apprenticeships (Zatomy et al., 2020). This type of laboratory uses computer technology to simulate laboratory experiments on a computer (Ravista et al., 2021) and can have positive impacts on learners' acquisition of knowledge, skills, and motivation. Research has shown that virtual laboratories can be an effective tool for science education, especially in countries facing a shortage of equipment and educational resources (Radhamani et al., 2014; Pearson & Kodzas, 2015).

Therefore, virtual laboratories have become increasingly important as a new tool in basic science education, particularly in the fields of science, technology, engineering, and mathematics. This enhances learning effectiveness, allowing students to gain a deeper and more tangible understanding of the content, which can support learning in scientific fields (McCranskey et al., 2016).

In this regard, several review studies have been conducted on the effects of virtual laboratories in science education (Brinson, 2015; De Jong et al., 2013; Ma & Nickerson, 2006; Smetana & Bell, 2012; Udin et al., 2020). Additionally, the results of Ahmadi Gol & Hatami, (2016) showed that multimedia-based instruction with pre-training according to Mayer's principles had a positive effect on students' learning in biology. The results of this study are consistent with the findings of Zarei et al. (2015), Shakari et al. (2014), Zaraii Zvaraki, & Gharibi, (2012), Gharibi, (2009) and Zaraii Zavaraki, & Jafar Khani, (2007). However, most reviews have only included laboratory exercises in many other fields such as physics, chemistry, and engineering, and there are few review studies on the effectiveness of virtual

laboratories in biology education and learning (Udin et al., 2020). Therefore, there is a need to know:

1. In which biology topics are virtual laboratories most beneficial?
2. What learning outcomes with the use of virtual laboratories in biology yield the best results?

## **2. Literature Review**

The use of virtual laboratories in education and learning is grounded in David Kolb's (1984) experiential learning theory, which has its roots in constructivism and the work of John Dewey (Ouyang & Stanley, 2014). This new approach to science education seeks to combine the strengths of various methods and approaches, thereby addressing the weaknesses of each (Hatami et al., 2018; Zarei et al., 2019). It emphasizes creating an active learning environment, promoting inquiry-based learning, considering cognitive levels, focusing on interactive learning, and adhering to principles of understanding and comprehension.

Science education inherently requires laboratory exercises as part of acquiring practical skills (Borgerding et al., 2013). In fact, most scientific topics, especially in laboratories, rely on hands-on activities (Cavanagh et al., 2005; Çimer, 2012; Vijapurkar et al., 2014). Furthermore, research has shown that when students lack access to laboratory activities and experiences, they often struggle with learning (Oztap et al., 2003; Samat & Dersmen, 2017).

Virtual laboratories are increasingly permeating science education, as they can enhance access to relevant resources for both teachers and students and transform the learning process (Dahi et al., 2020; Smetana & Bell, 2012; Tarabazon, 2018). Using virtual laboratories allows learners to experiment with immediate feedback and interaction (Dieberg et al., 2017; Tan & Waugh, 2013). Thus, virtual laboratories help students learn by doing and become more engaged in their studies (Gallagher et al., 2005; Marchevski et al., 2003).

In recent years, analog forms of experimentation have been augmented or even replaced by digital technologies (e.g., Becker et al., 2020; Brinson, 2015; De Jong, 2006). Specifically, students have been asked to conduct experiments using virtual labs or simulations, which are claimed to enhance learning (De Jong & Van Joolingen, 1998; Geelan & Fan, 2014). These are presented as an exciting way to prepare students for practical exercises such as laboratory work (McCranskey et al., 2016).

A number of studies have shown that virtual laboratories are beneficial for improving student learning outcomes in cognitive, affective, and psychomotor domains (Capicchi et al., 2019; Maxum & Saragi, 2020; Siswanto et al., 2021; Udin & Ramli, 2020). Additionally, results have indicated that the effects of using virtual laboratories in learning can be beneficial for conceptual understanding and attitudes (Bogusevschi et al., 2020; Dieberg et al., 2017; Hurtado-Bermúdez & Romero-Abrio, 2020). Boulay et al. (2010) emphasize the importance of higher-level teacher training to improve student learning and conclude that blended learning programs can be an effective way to enhance teachers' knowledge and skills. However, it is important that instructional materials are designed based on the needs of both teachers and students.

The existing literature presents diverse advantages and disadvantages of real or virtual experiments, suggesting that both may offer unique aspects for fostering scientific literacy (De Jong et al., 2013). In line with this argument, several researchers such as Al-Khalidi et al. (2016), Brinson (2015), De Jong et al. (2013), and Hofstein and Lunetta (2004) suggest that a combination of real and virtual experiments may be more effective for science learning - but they leave open the order in which they are conducted.

### *Benefits of Virtual Laboratories in Education*

Virtual laboratories offer a range of advantages for education, including:

- **Safety:** Virtual laboratories eliminate the risks associated with real experiments, providing a safer learning environment. This is particularly important for experiments involving hazardous chemicals or complex equipment (Freire et al., 2009).
- **Easy access:** Virtual laboratories allow learners to access and conduct scientific experiments anytime, anywhere. This provides greater flexibility in scheduling and eliminates time and location constraints (Gamidge et al., 2020). By providing rich and immersive experiences, they can also simplify complex scientific concepts for students (Smentana & Bell, 2012).
- **Repeatability and minimization of errors:** Experiments in virtual environments are completely controllable and repeatable, which increases the accuracy and validity of results. Students can repeat experiments multiple times and modify different variables to gain a deeper understanding of scientific concepts (Hatami et al., 2018).
- **More engaging and enjoyable learning process:** Virtual laboratories can make learning activities more engaging and interactive, leading to increased student motivation (Chen, 2010; Freire et al., 2009; Hadi, 2023).
- **Enhancing visualization of scientific concepts:** Virtual laboratories have been shown to improve students' ability to visualize abstract scientific concepts (Olivio et al., 2013).
- **Interaction and motivation:** Virtual laboratories can increase interaction and motivation among students by allowing them to perform experiments collaboratively and discuss and share their findings. This can lead to more active and effective learning (Babatin, 2011; Mastoor et al., 2017; Hadi, 2023).
- **Flexibility:** Students can learn at their own pace as they can set up and perform virtual lab experiments anytime, anywhere (Gamidge et al., 2020; Freire et al., 2009).
- **Cost:** Virtual laboratories reduce financial constraints associated with equipment, space, and laboratory maintenance (Fisher et al., 2012; Makransky et al., 2019).
- **Deeper understanding of concepts:** Research has shown that using inquiry-based, student-centered technologies that allow students to manipulate and observe scientific phenomena (Flick & Bell, 2000) leads to a deeper understanding of concepts and applications.
- Stimulating curiosity, exploration, and invention, and fostering critical thinking and problem-solving skills (Kellur & Kellur, 2005; Hofstein & Mamlok-Naaman, 2007; Hadi, 2023).

### *Challenges of Using Virtual Laboratories in Education*

Despite their numerous benefits, virtual laboratories also present certain challenges (Kapilan et al., 2021; Nirwana, 2016; Tracheli et al., 2019).

- **Technical issues:** Internet connectivity, software compatibility, and hardware limitations can hinder the effectiveness of virtual laboratories.
- **Lack of hands-on experience:** Virtual laboratories cannot fully replicate the tactile and sensory experiences of real-world experiments, potentially limiting learning.
- **Student engagement:** Maintaining student engagement in virtual laboratory environments can be challenging and requires innovative teaching approaches and interactive design.

## **3. Method**

This study followed a protocol outlined in guidelines for conducting systematic reviews (Moher et al., 2009). These guidelines were followed to determine inclusion and exclusion criteria, conduct the search process to extract data, and assess the quality of articles before writing this review.

First, the study aimed to report on the "*The Potential of Virtual Laboratories for Enhancing Biology Learning*" to answer the research questions. After scoping the review, the authors met twice to develop a protocol. This document organized all subsequent steps to minimize bias in selecting publications and processing data. The protocol ensured replicability and transparency by planning the strategy for conducting and guiding the review (Fink, 2019). Accordingly, the protocol included the research questions, search strategy for academic resources, inclusion criteria, study appraisal, data extraction, and a desired timeline (Kitchenham & Charters, 2007).

The inclusion and exclusion criteria for selecting studies were determined based on the research questions and informed by a previous review. All reviewed articles for inclusion had to utilize learning in virtual laboratories and meet the following inclusion and exclusion criteria:

- Publications in English or Farsi languages.
- Publication year for articles from 2010 onwards.
- Full articles, journals, conference proceedings, and book chapters. Therefore, we excluded editorials, conference abstracts, workshop proposals, and posters.
- The amount of references should have an acceptable reference.
- Empirical studies with collection and analysis of empirical data. Reviews and incomplete reports (e.g., articles with only abstracts or articles without methods and results) were excluded.

Databases and Search Strategy: The authors identified four reputable databases for searching: Scopus, Web of Science (WoS), ERIC, and Google Scholar. Both Web of Science databases utilize rigorous inclusion criteria for journals and conferences, have a vast data corpus, and are recognized as established venues for scholarly publications.

Google Scholar and ERIC are educational databases covering a broad range of educational resources.

We conducted multiple iterations of searches using various combinations of keywords; the following search formula yielded the best results in capturing all forms of the keywords (Table 1).

*Table 1. Keywords Used with Wildcards to Capture All Keyword Forms.*

Key word			Alternate characters		
Education	Teaching	Education			
Lab	Experiment	Multimedia	Clinic	Practical	
Virtual	Online	Simulate	Computer		
Biology	cellular and molecular biology	genetics	microbiology	biotechnology	anatomy

**(Education\* OR Teaching\* OR\* Learning) AND (Lab\* OR Experiment\* OR Multimedia\* OR Clinic \* OR Practical\*) AND (Virtual\* OR Online\* OR simulate\* OR computer\*) AND (Biology\* OR Biology Topics\*)**

This table lists the keywords used in the search along with wildcard characters to capture all variations of those keywords. These wildcard characters allow for a more comprehensive search, as they enable the search engine to consider similar terms.

This combination of keywords was used to search the titles, abstracts, or author keywords of articles. The search was conducted over two days following April 24, 2024, resulting in the retrieval of 513 articles from all specified databases: Web of Science, ERIC, Google Scholar, Civilica, SID, and other reputable Persian portals.

A total of 437 irrelevant and duplicate articles were removed based on screening the topic, content, and abstract. This left 76 articles, of which 51 were unavailable in full text or were not freely accessible. Therefore, 20 English articles and 5 Persian articles remained as full-text papers and were relevant to the protocol and inclusion criteria."

Researchers independently and in a joint session scanned and evaluated the abstracts, titles, and keywords of the 30 extracted articles. Consensus was reached, and any disagreements were discussed and resolved. In cases where two reviewers had different opinions about the classification of an article, they discussed it until a consensus was reached. Therefore, after filtering to discuss any uncertainties, scanning the titles and abstracts based on the inclusion and exclusion criteria identified 30 suitable publications for full-text review (Figure 1).

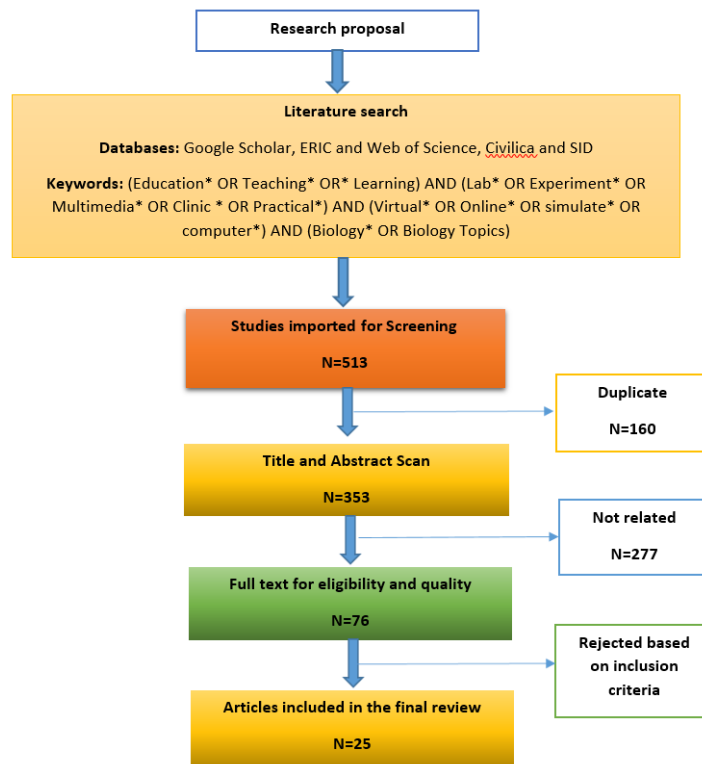


Figure 1. Diagram of the selection process of the reviewed studies

To obtain data from the selected articles, the relevant information was first collected in a coding scheme. This was done to reduce inter-rater variability. The following categories of information were extracted from each article: descriptive statistics, learning environments and levels, academic disciplines, approaches to learning analysis, and main findings of each study. The first ten articles were coded by two different coders, and then a meeting was held to discuss any discrepancies and finalize the coding before continuing with the coding of the articles. Finally, before starting the synthesis phase, the quality of the retrieved articles was assessed. At this stage, the authors are organizing all data within the framework of the research hypothesis (Webster & Watson, 2002). The data analysis provides a comprehensive overview from a learning analysis perspective.

#### 4. Findings

This review summarizes key findings from studies investigating the use of virtual laboratories in biology education, categorized by year of publication. The studies cover a wide range of biological topics and focus on various learning outcomes, including conceptual understanding, procedural skills, and attitudes.

**2010:**

- Muhamad et al. investigated students' understanding of cell division, particularly the applications of mitosis in cloning. The findings suggest that the proposed virtual laboratory will assist students in learning abstract concepts in biology, particularly the challenging topic of cell division.
- Akpan et al. compared traditional animal dissection to virtual simulations in biology classrooms. Results showed that students using simulations performed better on tests and maintained more positive attitudes towards the subject than those who performed dissections.

**2011:**

- Diwakar et al. studied the use of virtual labs in biotechnology. The findings of this study showed that realistic simulation (3D multimedia simulation) is more effective in learning biology than the non-realistic simulation (desktop virtual reality simulation). Realistic simulation (3D multimedia simulation) in Cell Division topic helped students to visualize and understand the abstract and difficult concepts such as mitosis and meiosis through the simulation.
- Flowers explored students' understanding of various cellular and molecular biology topics. Research findings indicate that students prefer to participate in virtual labs compared to traditional (e.g., face-to-face) labs. Data also indicated that students perceived higher learning gains as a result of participating in virtual labs compared to traditional hands-on labs.

**2012:**

- Collier et al. focused on students' mastery of content and time management in a virtual histology laboratory. This analysis showed that the teaching assistants found the virtual microscope to be an advantageous change in the classroom. They cite the ease of use of the virtual microscope, access to histology outside of designated laboratory time, and increasing student collaboration in class as the primary advantages.
- Muhamad et al. focused on virtual biology laboratory (VLab-Bio): Scenario-based learning approach. Findings show that learning area under focus is Cell Division, the learning objective is Understanding Mitosis and the learning outcome is the Application of Knowledge on Mitosis in Cloning. Thus, this topic will be the main contents of designing learning modules intended to serve as a learning support tool of the Scenario-based Learning Approach for Virtual Biology Laboratory (VLab-Bio).

**2014:**

- Therefore, virtual laboratories have become increasingly important as a new tool in basic (McCranskey et al., 2016).
- Elangovan and Ismail investigated students' conceptual understanding of cell division. The results show that realistic simulation is a more effective 3D computer simulation based teaching method than the non-realistic simulation and it improves Biology students' achievement and memory retention.
- Radhamani et al. explored the impact of virtual labs on student achievement in biotechnology. Usage analysis and surveys indicated that biotechnology virtual labs are significant elements in adaptive learning process in blended classroom environment.

**2015:**

- Oser and Fraser investigated students' perceptions of the learning environment, attitudes toward the subject, and academic achievement in a genetics context.

**2016:**

- Ismail et al. focused on promoting scientific literacy among students by using virtual labs to solve problems related to pathogenic bacteria. The results show that using the new STEM-based virtual lab can greatly improve students' science knowledge.
- Makransky et al. explored the transfer of knowledge and practical skills in microbiology using virtual labs. These studies suggested that virtual laboratories are

effective tools for pre-lab preparation and transferring knowledge and skills from an idealized environment into physical reality.

- Hatami et al. emphasized that virtual laboratories have a significant positive impact on student learning outcomes, including: "Increased student motivation and achievement" , "Facilitation of learning and cognitive load management" , "The ability to repeat content until mastery" , "Optimization of teaching and learning" , "Providing opportunities for personalized learning to meet the needs of individual students".

**2017:**

- Dyrberg et al. investigated the impact of virtual microbiology and pharmaceutical toxicology labs on students' positive attitudes, motivation, and self-efficacy. The study presents the results of a pilot study investigating students' attitudes, motivation, and self-efficacy while using the virtual laboratory program Labster, concluding that virtual laboratories can enhance students' pre-laboratory readiness.
- Sofian et al. focused on production of e-learning content and evaluating the effect of blended learning of cell and molecular biology laboratory in students learning. In this study, by production of E-Learning content of the Cellular and Molecular Biology Laboratory, the effect of E-Practical blended learning on students' teaching investigated in the Cellular and Molecular Lab of Payame Noor University.

**2018:**

- Havlíčková et al. focused on student motivation in a virtual dissection environment. With the advent of computers virtual dissection was recognized as a plausible option for the replacement of hands-on dissection. Based on survey data collected from 489 Czech Biology teachers it was revealed that teachers value positively both variants of dissection, even more, differences are small or even negligible. Differences on motivation scale toward both variants are small or negligible too.
- Whitworth et al. explored students' conceptual understanding of enzyme kinetics using virtual labs. Whitworth et al. (2018) reported a varied use of simulations in laboratory activities after seeing a significant increase in post-test scores of the experimental group of students over the control group of students. Based on their study results, Whitworth et al. (2018) concluded that computer simulations improve students' conceptual understanding of enzyme kinetics.

**2019:**

- Makransky et al. focused on equivalence of using a desktop virtual reality science simulation at home and in class. Makransky et al.'s research demonstrated that learning outcomes and motivation among biology students were equivalent when using virtual reality laboratory simulations at home compared to using them in a classroom setting under teacher supervision. Furthermore, the study found that virtual laboratories can save time and costs, while also increasing accessibility to high-quality education for students. Specifically, students in both the home and classroom groups achieved similar results on the final exam. There were no significant differences in intrinsic motivation or self-efficacy between the two groups.
- Sheldon et al. focused on students' understanding of the stages of cell division using virtual labs. This activity guides students through a virtual experiment that can be easily scaled for large introductory classes or low-resource settings. The activity focuses on experimentally determining the timing of the stages of cell division, directing the attention of students to the tasks that are completed at each stage and promoting understanding of the underlying mechanisms.
- Akhigbe and Ogufere explored students' attitudes and academic achievement in genetics. In a recent study, they assessed the effect of computer simulations on students' attitudes towards biology, finding that computer simulations improve students' attitudes towards genetics. A significant improvement in performance was

seen with the students who were exposed to the computer simulation instructional strategy over their counterparts who were taught using traditional methodologies.

**2021:**

- Farhadi moghaddam et al. focused on solutions and challenges of holding an active biology laboratory class, with a look at The future is based on the experience of the corona pandemic. In this research, it has been tried to study the scientific researches (from the past to the present), the challenges and The solutions for conducting an online laboratory based on active learning should be reviewed and presented. In general, identifying and using interactive tools, Accessible websites, virtual labs, problem-based methods and flipped classrooms, as well as the accompaniment of an assistant instructor can increase the motivation and raise the level of active learning in the learner.

**2022:**

- Sidic et al. focused on the application of virtual laboratory as an effort to improve 10th grade students' learning outcomes on environmental change topic. The application of virtual laboratories in learning environmental change material has a positive effect on student learning outcomes. Assessment of students' attitudes during learning using virtual laboratories is included in the very good category with an average score of 81%.
- Aladesus et al. focused on secondary school teachers' access to virtual laboratory for teaching biology in secondary schools in Minna, Niger State. The study concluded that activities that would require the use of ICT-based resources in secondary school should be given to both male and female since the findings of this study revealed that there was no significant difference between male and female teachers.

**2023:**

- Justin et al. stated that virtual biotechnology laboratories can be used as an effective alternative or complementary tool to perform real or physical laboratory experiments. despite the argumentation presented by some authors that it can never be used as a replacement. In considering learning outcomes of all domains such as cognitive, affective, and skill-based or psychomotor, virtual laboratories can provide better outcomes and it can be claimed that virtual laboratories are equally effective as the traditional media or sometime better that it.

**2024:**

- Zare et al. focused on investigating the effect of virtual education on the academic progress and satisfaction of biology student teachers (a case study of Plant Physiology Laboratory of Farhangian University). The research findings indicate that virtual physiology plant laboratory training has had a positive impact on the grades of pre-service teachers and has led to their satisfaction with learning in three areas: knowledge acquisition, skill acquisition, and attitude. The highest level of satisfaction was observed in the area of knowledge acquisition, while the lowest level of satisfaction was observed in the area of skill acquisition.

*Table 2. Biology topics in which virtual labs are used and related learning outcomes*

SN	Year	Study	Biology topic	Measured learning outcome
1	2010	Muhama d et al.	Cell division	Student understanding of cell division, specifically applications of mitosis in cloning
2	2010	Akpan et al.	Dissection	Actual dissection practices and attitudes towards dissection
3	2011	Diwakar et al.	Biotechnology	The effect of realistic simulation (3D multimedia simulation) in learning biology
4	2011	Flowers	Various topics, most of which are related to cell and molecular biology	Student perceptions of biology

5	2012	Collier et al.	Histology	Access to histology outside of designated laboratory time, and increased student collaboration in the classroom
6	2012	Muhamad et al.	Cell division	Understanding Mitosis and the learning outcome
7	2014	Elangovan and Ismail	Cell division	Student conceptual understanding of cell division
8	2014	Radhamani et al.	Biotechnology	Enhanced student achievement in blended classroom environment
9	2015	Oser and Fraser	Genetics	Student perception of the learning environment, attitudes towards the topic, and achievement
10	2016	Ismail et al.	Microbiology	Enhancing student scientific literacy
11	2016	Makransky et al.	Microbiology	Knowledge transfer and practical skills
12	2016	Hatami et al.	Biology	Increased student motivation and achievement ·Facilitation of learning and cognitive load management
13	2017	Dyrberg et al.	Microbiology and Pharmaceutical Toxicology	Enhanced student positive attitudes, motivation, and self-efficacy
14	2017	Sofian et al.	Cell and Molecular Biology	The effect of E-Practical blended learning on students
15	2018	Havlícková et al.	Dissection	Student motivation
16	2018	Whitworth et al.	Enzyme kinetics	Conceptual understanding
17	2019	Makransky et al.	Microbiology	Student knowledge, motivation, and self-efficacy in microbiology
18	2019	Shelden et al.	Cell division	Understanding of cell division phases
19	2019	Akhigbe and Ogufere	Genetics	Student attitudes and academic achievement in genetics
20	2021	Farhadimoghadam et al.	Biology	The motivation and raise the level of active learning in the learner
21	2022	Sidik et al.	Biology	Learning outcomes on environmental change topic
22	2022	Aladesus et al.	Biology	Virtual laboratory of biology education based on gender and school type
23	2023	Justin et al.	Biotechnology	Learning outcomes of all domains such as cognitive, affective, and skill-based or psychomotor
24	2024	Andriani et al.	Biology (the circulatory system)	improve the critical thinking skills and conceptual understanding
25	2024	Zare et al.	Plant Physiology	knowledge acquisition, skill acquisition, and attitude in plant physiology

Figure 2 shows the various topics that have been facilitated using virtual labs. It is no coincidence that the topics identified in Figure 2 utilize virtual laboratories. The mentioned topics are considered difficult, abstract, and daunting by both teachers and students due to their complexity, difficulty in visualization, and impracticality in regular physical school laboratories. For instance, Sofian and colleagues investigated the impact of an electronic biology laboratory content on students' learning gains in a cellular and molecular biology laboratory at Payame Noor University. Students were divided into experimental and control groups and underwent a one-semester training program. Both groups were assessed before and after the training using a practical skills checklist and a written test. Additionally, student satisfaction was evaluated using a standard questionnaire. Data was analyzed using SPSS statistical software. The results of the study indicated that the combined electronic-practical training in the cellular and molecular biology laboratory led to the transfer of practical knowledge, increased learning quality, and higher student satisfaction (Sofian et al. 2017).

Zare et al. (2024) conducted a study investigating the impact of virtual instruction in a plant physiology laboratory on the academic progress and satisfaction of pre-service biology teachers at the University of Culture during the COVID-19 pandemic. One of the major challenges faced during the pandemic was the delivery of laboratory courses in universities. The population of the study comprised all undergraduate pre-service biology teachers at Shahid Beheshti University of Culture, Tehran, who were enrolled in a plant physiology course during the first semester of the 2021-2022 academic year. A complete enumeration method was used to select the sample. The course content was designed and delivered virtually for one semester.

Data was collected using a researcher-made cognitive-skill test to assess academic achievement and a researcher-made satisfaction questionnaire. The validity of the questionnaires was established through content validity, and reliability was assessed using Cronbach's alpha (0.85).

The findings revealed that virtual instruction in the plant physiology laboratory positively influenced students' grades and increased their satisfaction with learning in three domains: knowledge acquisition, skill development, and attitude. The highest level of satisfaction was observed in the area of knowledge acquisition, while the lowest was in skill development.

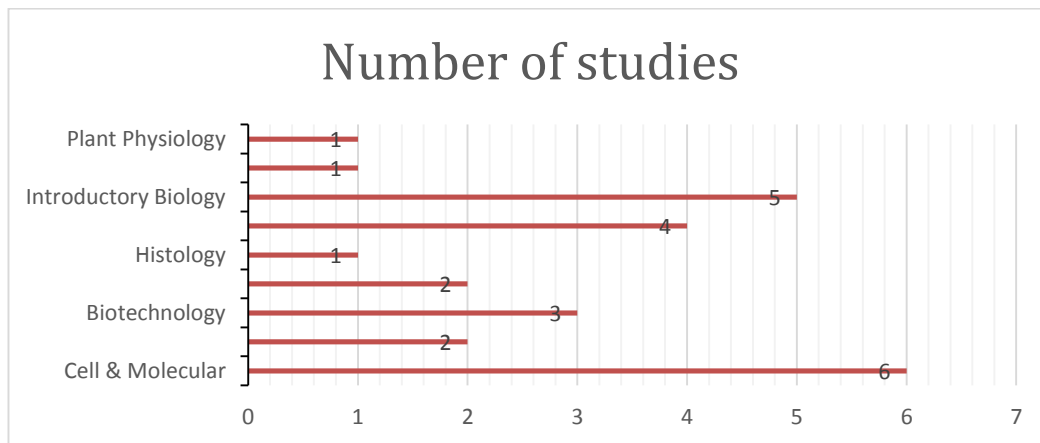


Figure 2. Biology topics in which virtual labs were used as per the reviewed studies

This review provides a snapshot of the growing body of research on the use of virtual laboratories in biology education. While the specific findings vary across studies, several common themes emerge, including:

- **Improved conceptual understanding:** Many studies have shown that virtual labs can enhance students' understanding of complex biological concepts.
- **Increased engagement:** Virtual labs can make learning more engaging and interactive, leading to increased student motivation.
- **Development of procedural skills:** Virtual labs can help students develop important laboratory skills, such as data analysis and interpretation.
- **Positive attitudes:** Virtual labs can foster positive attitudes towards science and learning.

#### Improved Conceptual Understanding

- Muhamad et al. (2010): Cell division
- Elangovan and Ismail (2014): Cell division
- Whitworth et al. (2018): Enzyme kinetics
- Sheldon et al. (2019): Cell division
- Farhadi moghadam et al. (2021)
- Andriani et al. (2024): Circulatory system

#### Increased Engagement

- Flowers (2011): Various cellular and molecular biology topics

- Dyrberg et al. (2017): Microbiology and Pharmaceutical Toxicology
- Havlícková et al. (2018): Dissection
- Akhigbe and Ogufere (2019): Genetics
- Sidiket al. (2022): Environmental change

**Development of Procedural Skills**

- Sofian et al. (2017): Cell and Molecular Biology
- Makransky et al. (2016): Microbiology
- Makransky et al. (2019): Microbiology

**Positive Attitudes**

- Akpan et al. (2010): Dissection
- Dyrberg et al. (2017): Microbiology and Pharmaceutical Toxicology
- Akhigbe and Ogufere (2019): Genetics
- Sidik et al. (2022): Environmental change

Category	Studies
Improved Conceptual Understanding	Muhamad et al. (2010), Elangovan & Ismail (2014), Whitworth et al. (2018), Shelden et al. (2019), Farhadi moghadam et al. (2021), Andriani et al. (2024)
Increased Engagement	Flowers (2011), Dyrberg et al. (2017), Havlícková et al. (2018), Akhigbe & Ogufere (2019), Raudlah et al. (2022)
Development of Procedural Skills	Sofian et al. (2017), Makransky et al. (2016), Makransky et al. (2019)
Positive Attitudes	Akpan et al. (2010), Dyrberg et al. (2017), Akhigbe & Ogufere (2019), Raudlah et al. (2022)

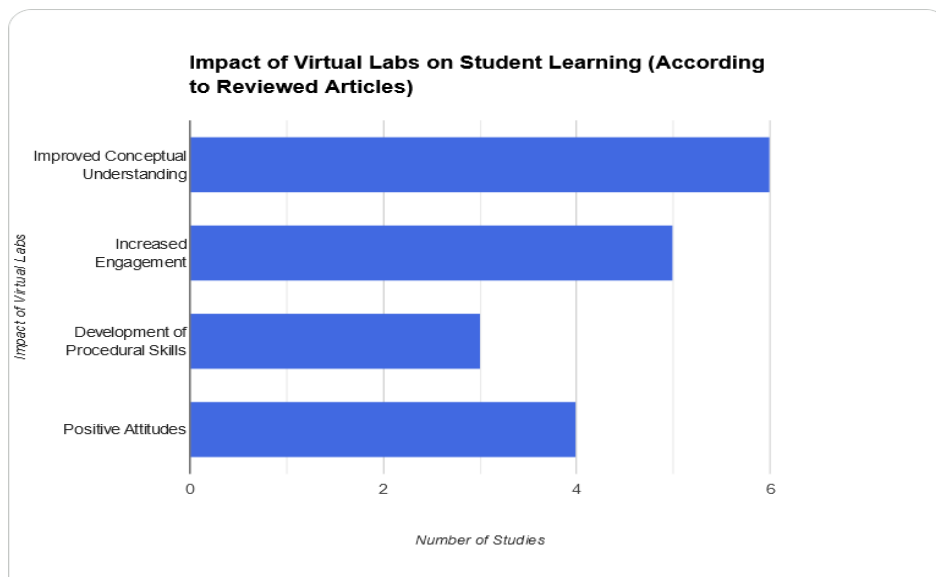


Figure 3. Learning outcomes identified in the reviewed studies

**6. Conclusion**

The integration of Information and Communication Technology (ICT), specifically through the use of virtual laboratories, has shown immense potential to enhance biology education. This review highlights the effectiveness of virtual labs in improving students' conceptual understanding, procedural skills, and overall attitude towards biology. While virtual labs demonstrate particular strengths in teaching abstract concepts in fields like cellular and molecular biology, genetics, and microbiology, their utility extends to practical areas such as dissection and biotechnology.

Nevertheless, for optimal learning outcomes, a judicious blend of virtual and real laboratories is often recommended. While virtual labs offer advantages in terms of safety, accessibility, and control, real laboratories provide indispensable hands-on experience and tactile learning opportunities.

Furthermore, research consistently indicates that virtual laboratories are particularly effective in teaching complex and abstract biological concepts. They have been shown to enhance students' motivation, self-efficacy, and overall positive attitudes towards biology. Due to their numerous benefits, including increased safety, cost-effectiveness, and accessibility, virtual laboratories warrant significant attention from researchers, educators, and instructional designers as tools for engaging students in scientific inquiry.

### Recommendations

Further research is needed to evaluate teachers' readiness to use virtual laboratories in teaching and learning processes. The effectiveness of virtual laboratories, like any other teaching tool, may be influenced by how they are used in the classroom. Therefore, further research is recommended on the negative effects of using virtual laboratories in teaching and learning. The development of inquiry-based virtual laboratories capable of assessing changes in students' conceptual understanding and scientific process skills is necessary. Combining virtual and real laboratories can be more effective in improving student learning outcomes. The use of virtual laboratories can be considered as an alternative method for pre-service elementary school teachers, especially in science education. To maximize conceptual mastery and critical thinking skills, students should be encouraged to develop habits of reading and using online technology to develop projects and improve their thinking skills. Future educators and researchers should seek alternative media to support learning. Educational institutions should improve their facilities and infrastructure to support innovative learning processes.

### Declaration of Competing Interest

The author declares that he has no competing financial interests or known personal relationships that would influence the report presented in this article.

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