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Effectiveness of Virtual Laboratories in Teaching and Learning Biology: A Review of Literature

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Abstract. Scholars have debated whether virtual laboratories are educationally effective tools and if they should be continuously developed. In this paper, we comprehensively review literature about the effectiveness of virtual labs in teaching and learning biology to identify the topics often taught and the linked learning outcomes. We used Google Scholar, ERIC, and Web of Science electronic databases to access journal articles and conference proceeding papers. Through a systematic analysis, we obtained 26 articles solely related to virtual lab use in biology education. The overall findings from the reviewed literature indicated that virtual laboratories are often used on topics that seem abstract. These include cell and molecular biology topics, followed by microbiology, genetics, and other practical topics such as dissection and biotechnology. This review study revealed that virtual labs are effective as they improve students' conceptual understanding, laboratory or practical skills, and motivation and attitudes towards biology. We recommend the use of virtual labs in teaching as a means of actively involving students in safer and more cost-effective scientific inquiry.

Keywords: Biology topics; computer simulations; learning outcomes; virtual laboratories/labs

1. Introduction
1.1 Background
Information and communication technology is increasingly penetrating almost all domains of human life, including education. In addition, with the current global trend of achieving twenty-first century learning skills, where digital literacy is one of the core goals, there is an increasing, understandable desire to bring more educational technologies into the classroom (Dakhi et al., 2020; Smetana & Bell, 2012; Tarbutton, 2018). Globally, researchers and practitioners agree that educational technology can transform the learning process by providing teachers and students with access to relevant resources when integrated into teaching. However, to be successful, educational technology should enhance the achievement of learning objectives (Griffin, 2003), because effective technology should enable students to achieve critical thinking by creating a shift from memorizing factual knowledge to understanding principles and applications.

Like any other science subject, the teaching of biology inevitably requires laboratory exercises as a part of the practical skills acquisition process (Borgerding et al., 2013). Indeed, most biology topics heavily rely on practical activities, especially in laboratories (Cavanagh et al., 2005; Çimer, 2012; Vijapurkar et al., 2014). In addition, research has shown that laboratory activities can potentially develop students' intellectual abilities, such as critical thinking, scientific inquiry, and practical skills. For instance, Hofstein and Mamlok-Naaman (2007) revealed that science cannot be significant to students without practical experiences in the school laboratory. When students have no access to laboratory activities and experiences, they often meet with difficulties in the learning of biology, especially in molecular biology topics (Boulay et al., 2010; Öztap et al., 2003; Sammet & Dreesmann, 2017; Tibell & Rundgren, 2009).

Literature has shown that technology can provide students with laboratory experience and enhance learning (Keller & Keller, 2005). However, the question to be asked is which kind of technology can provide students with authentic scientific practice and help them move from memorization to a deeper understanding of concepts and applications. Research has shown that using inquiry-based and learner-centered technologies that allow students to manipulate and observe scientific phenomena (Flick & Bell, 2000; Sivin et al., 2000) bring about a deeper understanding of concepts and applications. Virtual laboratories, commonly called virtual labs, meet the criteria in this context.

Virtual lab technologies were proposed by the National Science Foundation's (NSF) task force to upgrade the state of STEM education as a dynamic response to the sustainable preparation of the population for complex global challenges in the twenty-first century (Borgman et al., 2008). Researchers have shown that virtual labs could help make science concepts in general and biology in particular more concrete (Olympiou et al., 2013) and meaningful for students without requiring complex and costly equipment (Elangovan & Ismail, 2014; Makransky et al., 2019; Marbach-Ad et al., 2008).

Several pedagogical advantages have been highlighted regarding virtual lab use in education. For instance, by using virtual labs, teachers can easily explain complex theoretical concepts through a visual and immersive experience that can make it simpler for students to understand the subject (Smetana & Bell, 2012). With virtual labs, students try various experiments in risk–free environments without fear of damaging equipment. In addition, students can conduct the same experiment multiple times to ensure an understanding of the concept. Virtual labs allow teachers to capture students' attention and ensure their engagement and motivation (Babateen, 2011). Furthermore, virtual labs help students to learn at their own pace as they can prepare and perform laboratory experiments at any time and place. With virtual lab technology, teachers and students can explore topics that would otherwise be unworkable in conventional classes (Smetana & Bell, 2012).

Radhamani et al. (2014) and Pearson and Kudzai (2015) emphasized the need for virtual labs in teaching biology, especially in developing countries. They argued that, generally, science education in developing countries faces many limitations. These include shortage of laboratory equipment and reagents, space and time constraints, insufficient laboratory protocol, inadequate technical support, and safety, among other limitations. According to Radhamani et al. (2014), virtual labs are asset tools to mitigate the challenges of insufficient laboratory equipment needed in teaching biology topics such as biotechnology. This is despite some drawbacks of virtual labs, such as students not being able to feel, smell, or touch as in a physical laboratory.

While physical laboratories are absent or not fully equipped in many schools due to the high costs of their equipment and maintenance, virtual labs have been affirmed to lessen financial constraints related to laboratory equipment, space, and maintenance (Fisher et al., 2012). These potential advantages have triggered research interest, and a good number of empirical studies have been conducted about the effectiveness of virtual laboratories (Breakey et al., 2008; Dyrberg et al., 2017; Muhamad et al., 2010, 2012; Pope et al., 2017; Radhamani et al., 2014; Ray et al., 2012; Triola & Holloway, 2011).

Along this vein, several review studies on the effect of virtual laboratories in teaching sciences have been carried out (Brinson, 2015; De Jong et al., 2013; Ma & Nickerson, 2006; Smetana & Bell, 2012; Udin et al., 2020). However, most reviews only included laboratory practices of many other disciplines, such as physics, chemistry, and engineering, with few review studies about the effectiveness of virtual laboratories in teaching and learning biology (Udin et al., 2020). There is a need to know for which topics of biology virtual labs are more useful and what outcomes are brought about by virtual labs in the teaching and learning of biology. Therefore, we assume that this study will shed light on the effectiveness of virtual labs and in which preferred topics teachers are called to use the virtual labs. This relates especially to those biology topics which seem difficult to be taught by teachers and those which are too hard to understand for students because they are too abstract. The following specific questions guide this literature review:

1. In which topics of biology are virtual laboratories the most useful?
2. What learning outcomes are best achieved using virtual laboratories in biology?

1.2 Theoretical Context

The use of virtual laboratories in teaching and learning is based on David Kolb's (1984) experiential learning theory, which is rooted in the constructivist approach and John Dewey's work (Ouyang & Stanley, 2014). Around 1938, Dewey showed that no learning happens without practice and the active involvement of students. Kolb advocated and applied Dewey's concept of "learning by doing", believing that learning occurs through cognitive and experiential learning (Kolb & Kolb, 2005). The core of experiential learning theory is the individual learner's participation and experiences (Ouyang & Stanley, 2014). The application of virtual labs in teaching ensures students' active learning (Evans et al., 2004). The use of virtual labs allows learners to experiment with immediate feedback and interactivity (Dyrberg et al., 2017; Tan & Waugh, 2013). Thus, virtual labs help students to learn by doing and to become more engaged in their studies (Gallagher et al., 2005; Marchevsky et al., 2003).

2. Methodology

We applied preferred reporting items for systematic reviews and meta-analyses (PRISMA) principles and guidelines in our review (Moher et al., 2009). PRISMA guidelines assist researchers in conducting transparent and comprehensive systematic review reporting. These guidelines help researchers define research strategies, eligibility criteria, the selection process, and the data collection process.

2.1. Literature Search

We used an open federated search in this review study to find relevant articles from trusted databases. This type of search involves searching various electronic databases for information relevant to the review study. We used certain keywords to search and retrieve articles related to our study. These included "biology laboratory", "virtual laboratory in teaching biology", "virtual labs and biology topics", "biology education and virtual laboratory", "virtual and physical laboratory", "virtual lab and real lab", and "effectiveness of virtual labs in biology education". We used trusted electronic databases such as Google Scholar, ERIC, and Web of Science to access reliable articles and conference proceedings.

2.2 Inclusion and Exclusion Criteria

Using a systematic selection process and the elimination of duplicates, the first stage of searching yielded 161 papers. Manual filtering was applied based on how an article is relevant to our study. In selecting the relevant articles for inclusion in the review, we screened the titles and abstracts of all recorded articles. We used several inclusion and exclusion criteria to filter irrelevant articles (Table 1).

Table 1: Inclusion and exclusion criteria used to select relevant studies

Inclusion criteria	Exclusion criteria
Empirical studies in peer-reviewed journals, and conference proceedings	Reviews in non-peer-reviewed journals
Virtual labs used for biology education	- Virtual lab development procedures, design, or architecture - Virtual labs used for medical biology
Articles published in English	Articles that are not in English

The screening of titles and abstracts yielded 38 publications. The publications were further subjected to screening by checking their full-text content. The articles that focused only on biology virtual lab development procedures, design, or architecture without any relation to teaching biology were excluded. In this regard, 12 publications were filtered out. Eventually, we gathered 26 studies relevant to our review study, and each study was recorded to categorize information for further analysis (see Table 2 and Figure 1). The PRISMA diagram in Figure 1 shows the selection process. The obtained articles are dated from 2002 to 2019

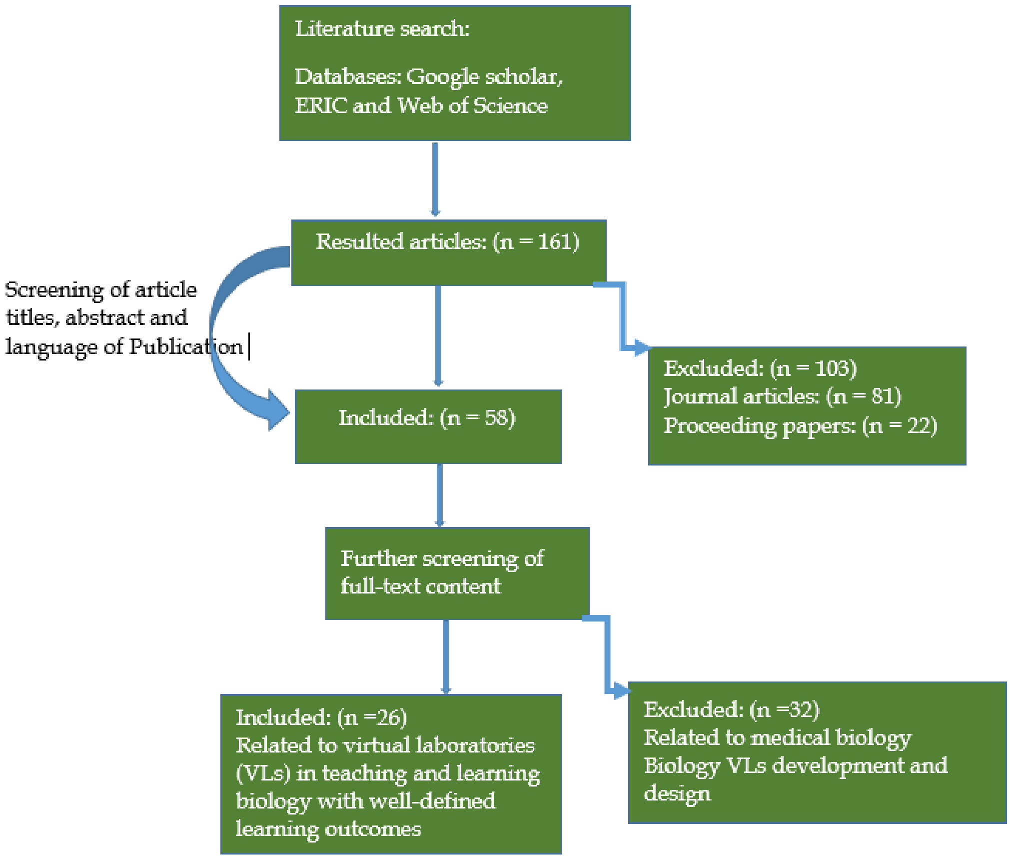

Figure 1: PRISMA diagram of the selection process of the reviewed studies

3. Results and Discussion

3.1. The Use of Virtual Laboratories in Teaching Biology Topics

In response to the first research question, we present in Table 2 the biology topics in which virtual laboratories are most commonly used for effective teaching. We also present the related learning outcomes that are most commonly enhanced by the use of virtual labs.

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

SN	Study	Biology topic	Measured learning outcome
1	Akhigbe and Ogufere (2019)	Genetics	Student attitudes and academic achievement in genetics
2	Akpan and Strayer (2010)	Frog dissection	Actual dissection practices and attitudes towards dissection
3	Breakey et al. (2008)	Genetics	Understanding of experimental genetics procedures
4	Collier et al. (2012)	Histology	Content mastery and time management
5	Diwakar et al. (2011)	Biotechnology	(No learning outcomes were identified)
6	Dyrberg et al. (2017)	Microbiology and pharmaceutical toxicology	Enhanced student positive attitudes, motivation, and self-efficacy
7	Elangovan and Ismail (2014)	Cell division	Student conceptual understanding of cell division
8	Flowers (2011)	Various topics, most of which are related to cell and molecular biology (DNA, cell structure, enzyme-controlled reaction, cell reproduction)	Student perceptions of biology
9	Havlícková et al. (2018)	Dissection	Student motivation
10	Huppert et al. (2002)	Microbiology	Student science process skills and academic achievement
11	Ismail et al. (2016)	Microbiology (dissolving pathogenic bacteria)	Enhancing student scientific literacy
12	Kiboss et al. (2006)	Cell division	Conceptual understanding and perceptions
13	Makransky et al. (2016)	Microbiology	Knowledge transfer and practical skills
14	Makransky et al. (2019)	Microbiology	Student knowledge, motivation, and self-efficacy in microbiology
15	Marbach et al. (2008)	Molecular biology	Enhanced student achievement
16	Meir et al. (2005)	Introductory biology (osmosis and diffusion)	Student understanding of how these processes work at a molecular level

17	Muhamad et al. (2012)	Cell division	Student understanding of cell division, specifically applications of mitosis in cloning
18	Oser and Fraser (2015)	Genetics	Student perception of the learning environment, attitudes towards the topic, and achievement
19	Pope et al. (2017)	Evolution	Student understanding of natural selection concepts
20	Radhamani et al. (2014)	Biotechnology	Enhanced student achievement
21	Shelden et al. (2019)	Cell division	Understanding of cell division phases
22	Stuckey-Mickell and Stuckey-Danner (2007)	Introductory biology	Enhanced student perceptions
23	Tan and Waugh (2013)	Molecular biology	Student conceptual understanding and attitudes in molecular biology
24	Toth et al. (2009)	DNA and gel electrophoresis	Student understanding and laboratory skills
25	White et al. (2007)	Genetics	Conceptual understanding
26	Whitworth et al. (2018)	Enzyme kinetics	Conceptual understanding

Table 2 displays the topics in which virtual labs were used and the learning outcomes that were attained as a result of their use. The reviewed articles are dated from 2002 to 2019. We did not find literature for the years 2020 to 2022. In the reviewed studies, virtual labs were used to teach genetics, dissection, microbiology, cell division, osmosis, DNA and gel electrophoresis, enzyme kinetics, biotechnology, evolution, histology, and introduction to biology. Virtual labs were used most frequently in teaching microbiology and cell division. Moreover, some of the learning outcomes that were attained using virtual labs included conceptual understanding, knowledge transfer, practical skills acquisition, and enhanced positive attitudes, motivation, and self-efficacy among students. The topics and learning outcomes are further described in the following sections, respectively.

3.2. Topics in Which Virtual Labs are the Most Useful

We analyzed the reviewed studies to identify which biology topics were most taught using virtual labs. Figure 2 shows the different topics that were facilitated using virtual labs.

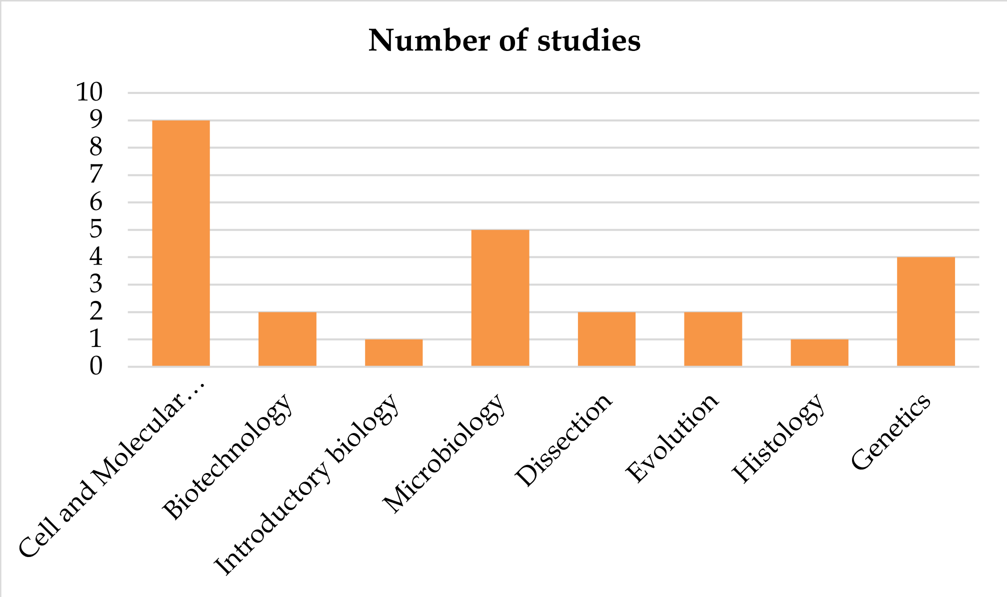

Figure 2. Biology topics in which virtual labs were used as per the reviewed studies

It is not by coincidence that the identified topics in Figure 2 employ virtual laboratories. The listed topics are perceived by both teachers and students to be difficult, abstract, and daunting due to their complexity, difficulty to visualize, and not being practicable in normal physical school laboratories. For instance, before conducting their study on developing and implementing a scenario-based biology virtual lab, Muhamad et al. (2012) carried out a preliminary investigation of a survey type involving 72 students and 10 high school teachers. Their investigation aimed to identify the biology topic that was most difficult to teach and learn and to focus on developing a virtual lab for it. Their preliminary study findings indicated cell division as the most difficult topic for both teachers and students (Muhamad et al., 2010).

Tan and Waugh (2013) undertook research employing virtual reality simulations in teaching and learning molecular biology in Singapore high schools. Teachers claimed that the topic of molecular biology was challenging and difficult to teach. They also indicated different complaints by students about teaching materials used by their teachers, such as diagrams and 2D presentations, which do not enable them to see DNA and protein molecules. Tan and Waugh (2013) argued that before studying molecular biology by use of virtual reality simulations, it was difficult for students to relate the structure and molecular interactions for cell functioning. Radhamani et al. (2014) reported that after virtual lab classes, 44% of the students who participated in their study scored 90%, with an average class score of about 70% in the post-test evaluation. In the pre-test evaluation, the majority of the students (88%) had scored below 70%.

Indeed, the topic to be taught with the use of virtual labs depends on the nature of the experiment. For instance, considering the topic of dissection, this topic raises many debates and disagreements regarding ethical issues among researchers, educators, and animal rights activists. Virtual laboratories that dissect animal specimens provide a viable alternative to real dissections and relieve ethics-related issues. Studies comparing the value of virtual frog dissections with traditional dissections using real specimens have revealed mixed results, however. Some supported that real dissections in the physical laboratory are effective (Cross & Cross, 2004), while others agreed that the simulated dissections are effective for improving students' performance in the virtual laboratories (Akpan & Strayer, 2010).

3.3. Learning Outcomes Enhanced by the Use of Virtual Laboratories

The learning outcomes identified in the reviewed studies were grouped into three categories (Figure 3). These are: 1) knowledge and conceptual understanding; 2) laboratory skills, knowledge transfer, and self-efficacy in laboratory activities; and 3) students' motivation, perceptions, and attitudes towards biology and the learning environment. Some of the reviewed studies assessed more than one of the above learning outcomes. The total number of studies indicated in Figure 3 therefore exceed the number of reviewed studies. The overall findings indicated that the learning outcomes varied, but in most studies, knowledge and conceptual understanding were frequently assessed.

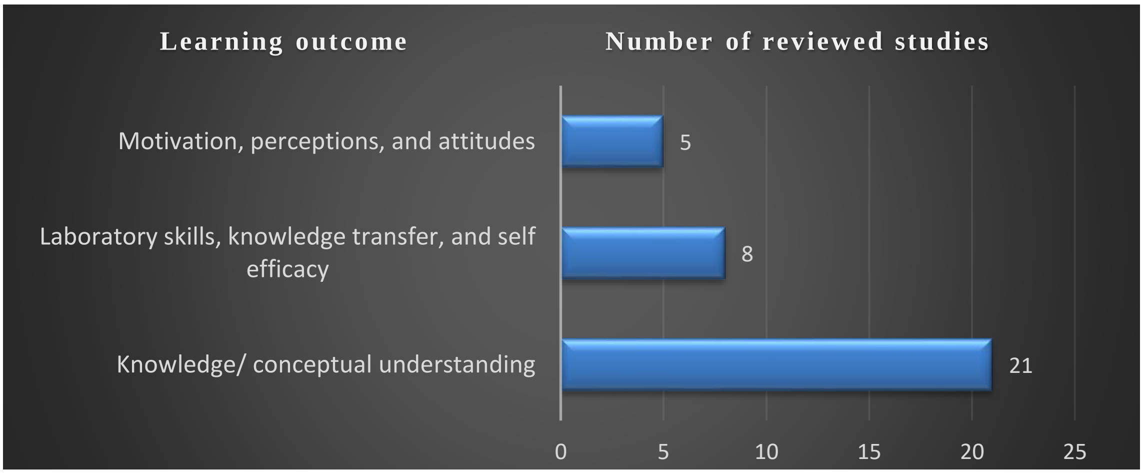

Figure 3: Learning outcomes identified in the reviewed studies

3.3.1 Knowledge and conceptual understanding

From our analysis, 21 out of the 26 reviewed studies reported that the use of virtual labs enhances students' conceptual understanding (Figure 3). Indeed, virtual lab exercises have been proven essential for students to understand biology concepts. Virtual labs present multiple opportunities for students to gain access to learning resources easily, and to get enough time to do and repeat activities, thereby nurturing deeper learning (Muhamad et al., 2012).

Furthermore, biology is a molecular science; most of its topics require visualizations, videos, and illustrations for students to understand how processes work at the molecular level (Evans et al., 2004; Muhamad et al., 2012). Many studies have shown that virtual laboratories are effective, low-cost tools to enhance students' understanding of biology concepts. This is because they provide students with visualizations of abstract concepts through animations, simulations, and virtual practices of simulated laboratory experiments for some topics, which could not be done even in normal classes (Akhigbe & Ogufere, 2019; Collier et al., 2012; Makransky et al., 2016; Oser & Fraser, 2015; Špernjak & Šorgo, 2018; Tan & Waugh, 2013).

In the study conducted by Tan and Waugh (2013), students admitted that before exposure to visualization exercises, molecular biology was a dry topic, too abstract and daunting for them. This resulted in some of them giving up biology altogether. Nonetheless, Tan and Waugh confirmed that after viewing the animations and participating in the visualization exercises, the students demonstrated increased interest, understanding, and engagement in the subject. 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. The experimental group was taught using standard lab instruction coupled with simulated lab instruction, while the control group was taught with only standard lab instruction. The increased post-test scores of the experimental group had an average standard deviation of 1.59. Based on their study results, Whitworth et al. (2018) concluded that computer simulations improve students' conceptual understanding of enzyme kinetics.

Moreover, various studies have shown that virtual labs are adequate for improving understanding of biology topics that are difficult to observe directly in the classroom context (Collier et al., 2012; Pope et al., 2017; Radhamani et al., 2014). For example, evolution by natural selection has been shown to be notoriously difficult for students to understand, and its processes have been described as not directly observable (Krist & Showsh, 2007; Nehm & Schonfeld, 2008; Plunkett & Yampolsky, 2010). However, Pope et al. (2017) clearly showed that simulations of natural phenomena are effective tools that support an active teaching approach to help students overcome natural selection misconceptions.

3.3.2 Laboratory skills, knowledge transfer, and self-efficacy in laboratory activities

Eight out of the twenty-six reviewed studies indicated that virtual laboratories enhance students' laboratory skills, knowledge transfer, and self-efficacy (Figure 3). 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 (Makransky et al., 2016). Research has affirmed that for meaningful laboratory learning to occur, students should be prepared before performing the required laboratory tasks (Jones & Edwards, 2010). According to O'Brien and Cameron (2008), laboratory practices help students to move from abstract to concrete settings. However, if students are not prepared, they could experience stress and confusion during laboratory activities instead of expected manipulative and process skills. The students become overloaded with too much information about the assigned task and may become overwhelmed as they try to handle new manipulative tasks as well as master new concepts (Pogačnik & Cigić, 2006).

Virtual labs are crucial for the preparation of students before embarking on a physical experiment. Researchers have affirmed that to perform the required practical tasks, science classes should blend real and virtual experiments so that students acquire the skills necessary. Several of the reviewed studies suggested the desirability of integrating hands-on laboratories with virtual ones and the effectiveness of engaging in virtual experiences before the real, hands-on investigation (Akpan & Strayer, 2010; Toth et al., 2009). In addition, other researchers have indicated that students prepared using virtual labs do not waste time on how to handle apparatus in organizing the experiment; rather, they focus on testing hypotheses through practicing and making important observations (Johnstone & Al-Shuaili, 2001). Prepared students begin the procedures faster and ask questions on a higher level than those who are less or not prepared (Dyrberg et al., 2017).

In their post-test, Akpan and Strayer (2010) discovered that students who engaged first in simulated dissection outperformed their peers who only performed conventional dissection. Similarly, Maldarelli et al. (2009) found that visual demonstration of laboratory techniques via instructional videos before the actual physical laboratory activity was sufficient to mediate significant increases in knowledge, self-efficacy, and experience in basic biology laboratory procedures. However, not surprisingly, some studies found that students believed that traditional labs offer more effective pedagogical techniques in teaching them how to use biology laboratory equipment than virtual labs (Flowers, 2011). Researchers have also criticized virtual labs, claiming that they have limited potential for teaching students how to handle specimens and perform techniques such as fixing, staining, and thin sectioning (Scheckler, 2003). However, other scholars have indicated that with simulations, students have opportunities to repeatedly learn all steps of an experiment, enabling them to transfer knowledge and skills gained from virtual learning to physical applications (Makransky et al., 2016).

3.3.3 Students' motivation, perceptions, and attitudes towards biology and the learning environment

In this study, 5 out of the 26 reviewed studies reported about virtual laboratories as related to students' motivation, perceptions, and attitudes towards biology and the learning environment (Figure 3). According to these studies, virtual labs are important for enhancing students' attitudes, stimulating interest and enjoyment, and motivating them to learn biology, improving their performance. Toth et al. (2009) performed a study about myDNA by using virtual labs to show the separation of DNA fragments. They found that students were happy to learn and efficiently repeated experiments and studied the effects of the variables. In a recent study, Akhigbe and Ogufere (2019) 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.

The majority of the reviewed studies revealed that students have positive perceptions towards virtual labs. Stuckey-Mickell and Stuckey-Danner (2007) made a contrary finding in their qualitative study analyzing open-ended qualitative responses by students after completion of several virtual lab sessions in human biology. This allowed them to investigate how students perceive virtual labs as compared to hands-on laboratory activities. They found that with virtual labs, students lacked the enjoyment of student-teacher interaction and the ability to ask questions and receive direct feedback from the instructor.

4. Conclusion and Recommendation

Based on the study's findings, we conclude that virtual laboratories are commonly effective in teaching difficult and abstract biology topics related to cell and molecular biology. Furthermore, conceptual understanding is the learning outcome most enhanced when using virtual labs. Studies have further affirmed that virtual labs improve students' motivation, self-efficacy, and attitudes towards learning biology topics. Virtual laboratories deserve the attention of researchers, teachers, and instructional designers due to their appealing nature as a means of actively involving students in safer and more cost-effective scientific inquiry. We suggest that future research assesses teachers' preparedness to use virtual labs in teaching and learning processes. The effectiveness of virtual labs, like any other instructional tool, may be greatly influenced by how they are used in the classroom. This study did not address the limitations of the virtual laboratory in teaching and learning biology. Thus, we recommend further research into the negative effects of using virtual laboratories in teaching and learning.

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