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Alternatives to Traditional Physical Science Laboratory Experiences: A Review

Alternatives aux éxpériences de laboratoire traditionnelles en sciences physiques. Un examen

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Abstract

There is a lot of concern around the increasing difficulties faced in providing hands-on experiences for the science learner who is separated from the institution in space and time. This is evidenced by conflicting research reports on students' ability to manipulate laboratory equipment after participating in online experimentation. Since the importance of the laboratory practical cannot be ignored in distance delivery, there is a need to explore alternatives to the on-campus laboratory. The current research conducted a review of peer-reviewed empirical articles on these alternatives which include home kit labs, virtual labs, and remote labs. It included 70 selected articles published in English from 2006 to 2022. Although the review revealed a preference for the virtual and remote lab over the traditional one, the advantages of the latter cannot be ignored. A summary list of advantages (e.g., increased flexibility and access) and disadvantages (e.g., no face-to-face contact and some additional costs) outlined in the articles is presented.

Keywords: *online learning, virtual labs, home-lab kits, remote-controlled labs*

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Résumé

Les difficultés croissantes rencontrées pour fournir des expériences pratiques à l'apprenant en sciences qui est séparé de l'institution dans l'espace et le temps suscitent beaucoup d'inquiétude. Ceci est mis en évidence par des rapports de recherche contradictoires sur la capacité des étudiants à manipuler l'équipement de laboratoire après avoir participé à une expérimentation en ligne. L'importance des travaux pratiques en laboratoire ne pouvant être ignorée dans le cadre de la formation à distance, il est nécessaire d'explorer des alternatives au laboratoire sur le campus. La présente étude a passé en revue des articles empiriques évalués par des pairs sur ces alternatives, notamment les laboratoires en kit à domicile, les laboratoires virtuels et les laboratoires à distance. Elle a porté sur 70 articles sélectionnés, publiés en anglais entre 2006 et 2022. Bien que l'étude ait clairement révélé une préférence pour les laboratoires virtuels et à distance par rapport aux laboratoires traditionnels, les avantages de ces derniers ne peuvent être ignorés. Une liste récapitulative des avantages (par exemple, flexibilité et accès accrus) et des inconvénients (par exemple, absence de contact en face à face et certains coûts supplémentaires) décrits dans les articles est présentée.

Mots-clés *: apprentissage en ligne, laboratoires virtuels, kits de laboratoire à domicile, laboratoires télécommandés*

Introduction

Despite the transition to online delivery during the COVID-19 pandemic, including physical labs (Easdon, 2020), earlier research reports had cautioned that though computer simulations or virtual laboratories (VL) have been used to enable learners to gain experience in the use of apparatus and instruments, they should not replace practical laboratory experimentation entirely (Scheckler, 2003; Smetana & Bell, 2012; Sypsas & Kalles, 2018). According to them, while VL can boost access to education at a distance and facilitate interaction that promotes more meaningful science education, it should be preferably used in combination with face-to-face experiences and only be a substitute where the physical laboratory is not available. In addition to VL, educators have also used remote-controlled laboratories and home-study labs to support online science courses (Kennepohl, 2019). In remote-controlled labs one is carrying out real experiments on real samples without being in the same room, while home-study labs allow learners to physically carry out unsupervised experiments at home. Together VL, remote-controlled labs, and home-study labs represent three major modes of laboratory delivery commonly used as an alternative to the traditional on-campus mode. There have been a lot of studies to prove or refute the usefulness of alternative laboratory experiences (delivery modes) over the traditional in-person experience, which provide a worthwhile background to our review. Most comparative studies indicate that alternative laboratories provide equivalent learning compared with traditional in-person laboratories (Biel & Brame, 2016; Lindsay & Good, 2005; Smetana & Bell, 2012). Brinson provides a similar conclusion with an excellent review of empirical studies assessed by achievement of learning outcomes (2015). Still, this review reveals not all laboratory learning outcomes are tracked equally with most studies reporting on student perception and gain in knowledge and understanding. Studies on alternative laboratories primarily emphasise the cognitive domain and to a lesser extent the affective domain. The psychomotor domain is only mentioned when the experience is used as a pre-laboratory exercise for in-person work (Burewicz & Miranowicz, 2006; Hensen & Barbera, 2019). Also, previous assessments of alternative laboratories tend to just compare VL and remote control with traditional in-person laboratory experiences (Corter et al., 2011). This is seen as a gap and therefore includes in this meta-analysis the use of home-study labs, which is also a viable method to support online and distance coursework.

But with the pandemic that has kept people home and away from the physical laboratory, institutions may not have a choice but to look into alternatives to these traditional physical laboratories as supported by Easdon (2020) and Marincean and Scribner (2020). The range of assorted studies on alternative science laboratory experiences over the years seems to call for an analysis, which Sandelowski et al., (2006) viewed as a literature review approach that defines the parameters of research around a central question to select, evaluate, and synthesise findings to detect common themes, gain new insights, and construct greater meaning.

The purpose of this review is to analyse peer-reviewed articles that addressed various alternatives to the traditional laboratories including VL, remote, and home study. The review covers primary research conducted since 2006. The method and procedure of the current review, its results and the discussion of the findings are presented.

Teaching and Learning Context

First, teaching and learning science has a sound constructivist and experiential perspective (Bailey & Garratt, 2002). Post-secondary educators in the natural and physical sciences are also essentially practitioners who have little to no formal background in the scholarship of teaching and learning and are driven to improve learning by cultivating a better classroom environment for students. While they may have this in common with any number of other disciplines, it is primarily the culture and epistemology of science itself that frames their approach to teaching and learning. That process reflects scientific methodology where students state problems, form hypotheses, design and carry out experiments, perform calculations, make observations, ask questions, keep records, make deductions, and communicate results (Kennepohl, 2019). It is important to keep in mind for this meta-analysis that this teaching and learning approach is present in any science course, but comes out most explicitly in a laboratory component. Secondly, the off-campus nature of alternative laboratories also implies that some of the theoretical underpinnings come from the distance education literature. The two more notable concepts that help in the understanding of the approach to teaching and learning at a distance include Anderson's Equivalency Theorem (2003) and Moore's Theory of Transactional Distance (1997). Developed in the 1970s, Moore's theory proposed that the degree of psychological distance between learner and teacher was more significant than physical distance, essentially viewing all learning as distance learning. A couple of decades later, Anderson posited that deep and meaningful formal learning is supported as long as at least one of the three forms of interaction (student–teacher; student-student; student-content) is present at a high level. While there are other relevant concepts, those offered by Anderson and Moore provided a solid foundation for developing and running alternative laboratories, whether considered explicitly or intuitively.

Methodology

For the design and implementation of a systematic review, Sandelowski et al. (2006) methodological framework for conducting a meta-synthesis, which includes: (1) literature search; (2) quality appraisal; (3) analysis; and (4) synthesis, was used.

Literature search strategy

Several strategies were employed to locate and build a list of relevant research literature. First, manual browsing using Google and other online resources on empirical studies published in peer-reviewed journals with the search keywords "home laboratory kits," "alternative to physical labs," "alternative to traditional laboratory," as well as checking the reference lists of previous reviews from 2006-2022, generated 184 articles. Second, additional articles (176) were identified with the same search terms using ERIC and Web of Science.

Quality appraisal

After reading the abstract and conclusion, limiting to the last 16 years, and focusing on science laboratories, the articles were pared down to only 70 (Appendix A) from both rounds of searches. A large number that were not empirical research but based on perception, literature, discussions, and commercial lab advertisements were disqualified from consideration in the study. Although the initial proposal was to exclude articles at the lower level (high school), eight articles that did address high school students, but would be relevant to undergraduate-level work, were eventually included. The search strategy outlined above identified 51 articles that addressed various alternatives to the physical laboratory (Appendix A) from 12 different countries, published in English from 2006-2022. For the meta-analysis, four major categories were considered: (1) Motivation/interest/confidence/satisfaction and others of the learner to the alternative lab or learner's excitement and confidence; (2) General attitude of the learner to the alternative lab; (3) Learner's actual preference in the use of the alternative lab over the traditional; (4) Effectiveness of the alternative lab relative to the traditional lab.

Each article was reviewed individually to identify prevailing factors such as the type of alternative used, the year it was published, and the delivery strategies before coding for possible categories. This was then expanded for synthesis before recoding and looking into the similarities and differences. Before an article was included it had to meet the following criteria:

- be published within the time frame of 2006-2022
- report the research methodology used
- be conducted within an educational set-up
- report the effectiveness of the alternative lab
- report comparison relative to the traditional lab
- report the learner's attitude to the alternative lab

Conduct of Validation

Throughout the meta-synthesis, we implemented virtual weekly meetings where we compared notes, sought how to get more related articles, and reached a consensus on how best to organise the content for synthesis. As soon as the writing started, the authors met virtually twice a week to outline, write, review and restructure one another's work. A clear audit trail of the work progress was established, as suggested by Sandelowski et al. (2006).

Analysis and Synthesis

Of the 70 studies, 2018-2020 and 2021-2022 recorded the highest number of articles while the lowest number was recorded during 2012-2014 period (Figure 1). The high numbers in the 2018-2020 and 2021-2022 window may also be part of the general surge of literature in 2020 on alternative teaching approaches during the pandemic.

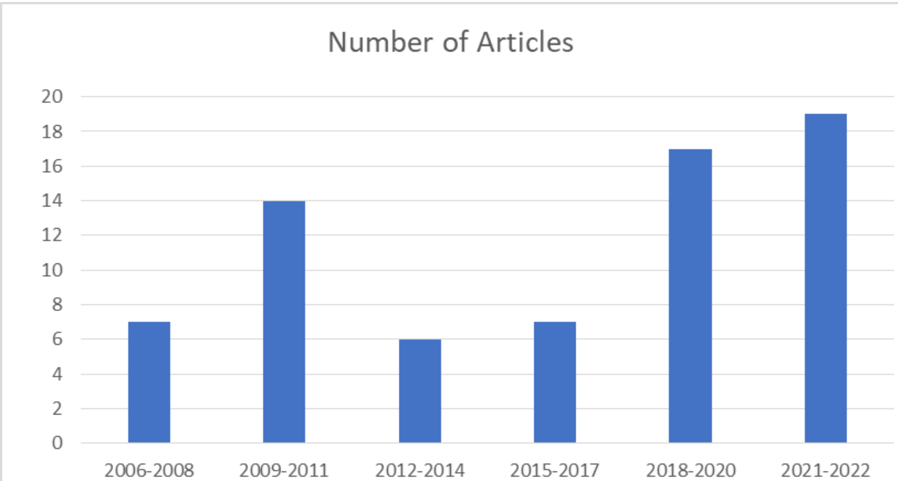

Fig. 1: Distribution by dates of publication

The articles can also be classified by the research method employed (Fig. 2): the qualitative methodology was used in the highest percentage of articles (41%), while the mixed research methods used the least (24%). A wide variety of approaches and metrics were employed (alone or in combination) by authors in studying and assessing alternative laboratory activities. This included data on student performance in the form of grades on lab reports (21%), pre/post-achievement tests (20%), lab exams (11%), instructor perception (10%), and practical assessment (6%); and, to a lesser extent, other measures such as lab report submission rate (1%), lab kit critique (1%), and eye tracking for online work (1%). However, the major methodology was to gauge student perception, where 55% explicitly reported survey and/or interview data, while the rest asserted that students were satisfied with the laboratory.

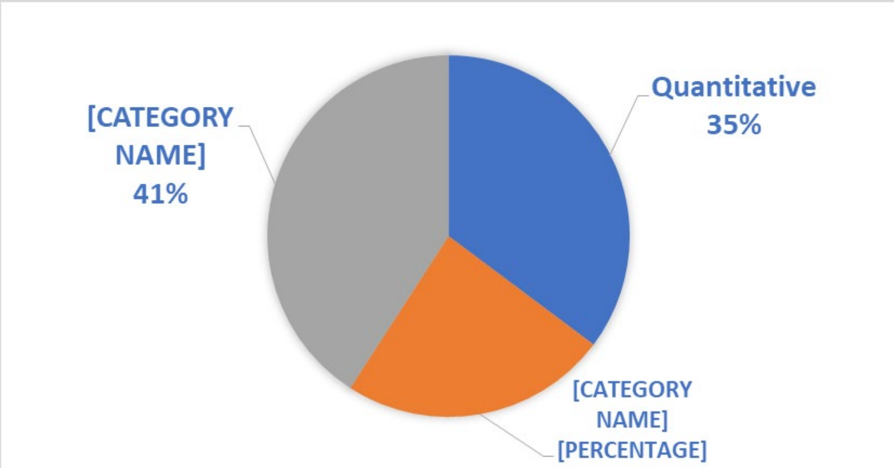

Fig. 2: Classification according to research method

Vignettes of key studies

Indeed, there was variation between studies not only by research methodology, but also by discipline, learning outcomes tracked, and delivery mode employed. It is not surprising that science educators also need to consider multiple components in their particular local context when designing and testing new learning environments. Before moving on to presenting more aggregated data and teasing out some trends between reports we provide a glimpse into a few studies that are meant to reflect the voice, passion, and creativity of individual researchers. This narrative format is not only important in gaining a deeper understanding of other educators' experiences, it also provides some needed perspective when we later consider the 51 papers collectively.

For instance, Casanova et al. (2006) compared student performance in two first-semester general chemistry courses to determine whether a distance learning model can provide a comparable learning opportunity to the conventional lecture-laboratory format. The laboratory portion of the distance learning course consisted of at-home (kitchen chemistry) experiments where distance learners demonstrated manipulation, data analysis, and data reporting skills that surpassed those of the students in the conventional course. Distance students scored 10% higher on the laboratory component and 14% higher on the final exam compared with on-campus students. However, on-campus students had a higher retention rate (90% versus 57%), which the authors attribute mostly to the non-academic personal circumstances of the distance learners. The results suggested that this distance learning model for teaching chemistry can be an effective alternative to conventional teaching methods for the types of students who typically succeed in a distance learning environment. The study also demonstrated the unique approach of using home-study experiments to help students appreciate the relevance of chemistry in their daily lives.

Lyall and Patti (2010) also reported another form of hands-on chemistry experimentation: using home experimental kits to perform the same experiments that would be performed in the physical laboratory, but arranged in a different place for the students. Noted disadvantages for the distance learner included safety, since the teacher is not available for guidance, and time spent by students in setting up the apparatus/equipment. However, the successes recorded in using home experimental kits at Monash University (Australia) and Athabasca University (Canada) were attributed to (1) keeping the experiment similar to that in the physical laboratory; (2) keeping the cost of the kits as low as possible; and (3) making sure kits are transportable and safe (with the realisation that the risk should be reduced to a minimum since the apparatus may be going to homes with children). To avoid injury from breakage, glassware was replaced with less expensive plastic that could withstand heat and corrosion. Benign chemicals were preferred and hazardous substances that could not be avoided were provided only in small quantities with strict warnings attached. Highly flammable materials were excluded because of carriage regulations. This major concern for safety and portability in these home-study kits, while still achieving university-level quality in the experiments, was expressed in an earlier study (Kennepohl, 2007), which examined both the student experience and their actual performance. The Canadian students' lab grades increased (7%) and overall course grades remained the same, while both lab (3-7%) and overall course grades (6-13%) increased for Australian home-kit users. The kits also offered the student improved access and flexibility, and increased participation in the laboratory component.

During the COVID-19 pandemic, Easdon (2020) described experiments written for students to provide alternative hands-on lab experiences in a chemistry food, flavour and fragrances course. Students took a strong interest in developing their own at-home laboratories and showed a great deal of creativity in solving problems and obtaining experimental data. The students' lab reports were supplemented with photos and videos to show their equipment and procedures. However, some problems encountered by the students included a lack of usable kitchen space, as well as difficulty getting supplies or paying for the material, recovery of the disappointingly small amounts in extraction as compared to traditional labs, and issues with getting a desired range of temperatures. These experiments allowed students to experience a level of hands-on laboratory techniques with normal record-keeping expected of science students. Also, the problem-solving nature of doing the experiments in an at-home situation was a valuable experience. As Jeschofnig (2004) had earlier emphasised, there are both positive and negative student experiences with self-contained kits. as with all the distance learning substitutes for traditional science laboratory experiences.

On the other hand, Kennepohl (2010) gave a brief review of the importance of remote-controlled science laboratories, especially in the light of increased availability of mobile alternative labs and interest in mobile learning. He emphasised that though the initial investment in setting up a quality remote lab may be high, the ability to share experiments and equipment can reduce the cost. The learner experience is not necessarily identical to the on-campus supervised laboratory but is equivalent and attractive for distance education. Students obtained real results using real materials to arrive at real conclusions, with improved laboratory skills, as they have access to science experiments in the physical laboratory.

This was also reported by Anđelković et al. (2015) on a pilot test on the use of a remote laboratory approach in a chemistry university course. According to the researchers, using VL can aid students in performing even complicated and hazardous experiments and obtain a deeper understanding of the chemical theory, while the remote laboratory approach allows working on real experiments in contact with the researcher or distant teacher. However, the feeling of real experiments with operational problems, errors, non-ideal results and ways of overcoming the problems were presented.

Corter et al. (2011) also compared learning activities and outcomes for hands-on, remotely-operated, and VL in an undergraduate engineering course. This entailed students working in small-group lab teams to perform two experiments with each team in one of three lab formats (hands-on, remotely-operated, or simulation-based), collecting data either individually or as a team. It was found that the hands-on lab format had higher learning outcomes working as a group (4.75), rather than individually collecting data sets to be combined later (4.10). For remotely operated labs, individual data collection was best (4.45 versus 3.94 for group). The pattern of time spent on various lab-related activities suggests that working with real instead of simulated data may induce higher levels of motivation. The results suggested that learning with computer-mediated technologies can be improved by careful design and coordination of group and individual activities.

At the high school level, the research report by da Cuna Gomes (2018) on taking advantage of the interest in robotics and remote digital operation gives further insight into enhancing student learning and overcoming the difficulties teachers encounter when trying to implement experiments in their classes. Such issues led to the development of the "FEUP ChemLab," an innovative system that allows high school students and teachers to access, monitor and control a real experience at a distance using common digital tools (web browser). The "FEUP ChemLab" includes a robotic manipulator and a webcam that allows students to, for example, finish an experiment they have started earlier in the class Although the remote lab is very expensive since the physical structure is still in place, the fact that the students can have access to the real and physical lab by controlling the computer gives an added advantage over the traditional.

Bilek and Skalická (2010) assessed the results of using real and VL applications for school children measuring pH. While the quality of the data collected by the students in either mode was statistically the same, most would rather conduct experiments in hands-on labs as they did not think that VLs are mediums to gain experience. This was supported by Tüysüz (2010) reporting that VL can only be an alternative to a real lab when the experiments cannot be conducted in a real lab for some reasons. The research looked into the effects of virtual chemistry labs on students' success and attitude with 341 students selected from 9th-grade high school students. It was observed that VL software positively affects the success attitudes (40% increase) and motivation of the students, and it enabled the students to recognise the learnt concepts more easily (doubling score on the knowledge scale post-test compared with the control group). Oloruntegbe and Alam (2010) also analysed the scientific VL environments in the dimensions of cognitive learning, skills and attitudes and found that virtual environments led to increased performance and higher levels of learning; students were satisfied by VL applications and think that they were attractive and enjoyable.

Harrison *et al.* (2009) examined the effects of VL software on 464 secondary school students. It was found that the students who used virtual chemistry lab software gave more correct answers (89% vs 26%) to the questions related to experimental techniques and they did tend to use this software in chemistry lesson applications. The students said with the software, they were able to focus on the experimental process and fully understood the experiment.

Most studies that compare traditional with alternative laboratories measure and compare gains in the cognitive domain. Among the few general chemistry laboratory studies that looked at affective measures, Hensen and Barbera (2019) assessed the affective differences between a virtual general chemistry experiment and a hands-on experiment. It was reported that overall, students who completed the virtual experiment scored significantly lower on emotional satisfaction (−16%), intellectual accessibility (−13%), the usefulness of the lab

(−8%), and equipment usability scales (−11%). However, it was noted that student responses in the virtual environment varied significantly according to which teaching assistant instructed the section. The result is an indication that the teaching assistant instructing the course might have been more influential on students' affective outcomes than the environment in which the experiment was performed.

Wijayanti and Ikhsan (2019) reported on the effect of using virtual chemistry laboratory-integrated hybrid learning on students' learning achievement in thermochemistry. The results showed that there is a significantly different learning achievement between classes using both chemistry virtual laboratory integrated hybrid learning (75%) and traditional hands-on laboratory (63%). The results of this study supported several research results that claimed that virtual laboratories enriched with simulations had many advantages in increasing students' chemistry learning achievement.

With the inequitable distribution of resources for laboratory-based science learning in South Africa, the Penn and Ramnarain (2019) study explored how available virtual learning resources could also be used for learning chemistry concepts. They went further to compare student achievement in chemistry content with both traditional and virtual laboratory learning resources. While the results from the tests revealed that all students obtained significantly higher achievement scores after a laboratory intervention, the virtual laboratory group had significantly higher achievement scores (79.4%) than the traditional laboratory control group (68.7%). Based on these findings, the researchers concluded that laboratory learning has a positive impact on achievement in chemistry and that virtual laboratories provide a worthy complement to traditional laboratories when learning abstract and difficult chemistry concepts.

Systematic analysis

The 70 articles were placed into three categories by type of alternative lab used in delivering the laboratory experience (One reports on both home-study and virtual labs). The categories (and number of articles) include home-study lab (21), virtual lab (simulations) (42), and remote-controlled (and mobile) lab (8). The distribution is graphically shown in Fig. 3. The far lower numbers for remote-controlled and home-study labs may not be surprising as these involve physical components that can present additional financial and logistical challenges.

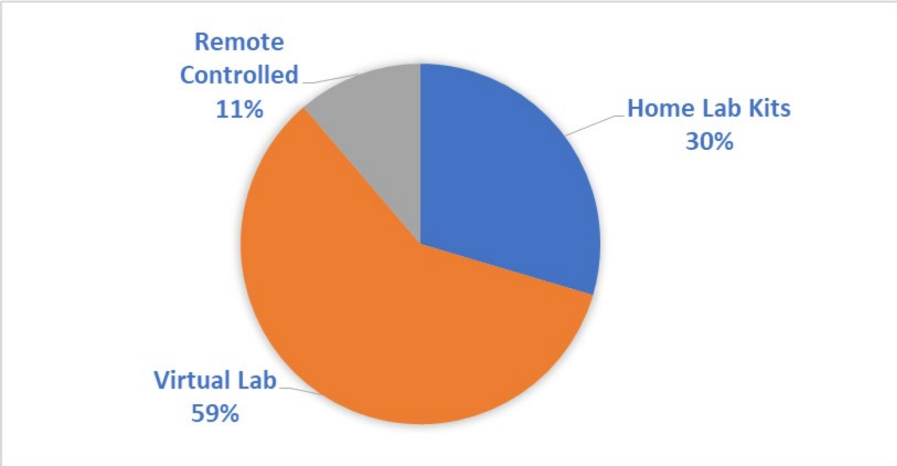

Fig. 3: Distribution of research articles by use of alternative lab

There are some common threads present in these studies. First, like traditional in-person laboratories, the alternative laboratory modes use the framework of scientific methodology as a vehicle for the learning intervention. However, unlike the in-person experience, alternative modes do not have a tangible physical presence and/or on-site supervision, because they are done at a distance. Indeed, students who do experiments outside the traditional laboratory setting often cannot acquire more sophisticated lab techniques and skills. Alternative labs also primarily rely on student-content interaction, while student-student and student-teacher interactions are much weaker or not present. Still, the studies examined generally report equivalent or greater learning gains with alternative laboratory modes compared with in-person, which is consistent with Anderson’s Equivalency Theorem (2003) on student interaction. Essentially learning can and does occur using alternative laboratories suggesting also that the transactional distance, described by Moore, is much shorter than anticipated irrespective of the physical distance (1997). Collectively the studies seem to indicate that based on learning gains alternative laboratories should be strongly preferred.

However, the analysis also reveals an important gap in the literature and a word of caution for the reader. Earlier the various metrics employed in these studies were described. In most cases, those more readily available (therefore more employed) instruments measure content knowledge, comprehension, and student perception. Yet, other outcomes important in laboratory work like physical manipulation skills, discovery skills, analytical skills, and communication were often not considered. In his study on laboratory learning outcomes, Brinson (2015) wisely lobbied for a broader and more systematic approach to include these in empirical studies of both alternative and traditional laboratory interventions.

In the introduction, it was noted the unevenness of what is being measured in terms of Bloom's Taxonomy and its three learning domains: cognitive, affective, and psychomotor. Again, when targeting measurements to specific domains, one cannot guarantee that this is necessarily a comprehensive reflection of the whole. Most articles deal with the cognitive domain when comparing in-person with alternative labs. There were no direct metrics reported for alternative labs in the psychomotor domain even though this is present in home-study labs and to some extent in remote labs. However, some studies did examine virtual labs in a pre-lab context, where those learners scored higher on physical manipulations when they were eventually there in person compared with their classmates who had no pre-lab (Burewicz & Miranowicz, 2006). Only one article addressing the affective domain, described earlier in the Hensen and Barbera (2019) vignette, was noted. Unlike the other studies examined, it reported the alternative laboratory as having some lower scores on the metrics (albeit in the affective domain) compared with in-person labs. The result illustrates the importance of both in selecting and understanding what is measured. When a science educator is reading the literature and considering an alternative laboratory experience, can a few select metrics in the cognitive domain serve as an adequate proxy to generally assess its learning utility?

Another consideration (and there are many) by science educators in creating or adopting alternative laboratories is student perception. Across the 70 articles student satisfaction was the most common metric reported. Students generally greatly preferred the flexibility and access to alternative labs to come on campus for in-person labs, with some caveats. They were critical of any additional work (whether real or perceived) such as gathering materials for home study labs, learning to operate an instrument by remote control, and dealing with non-intuitive VL programmes. Many also missed both the atmosphere of the in-person lab and, more importantly, direct human contact. Some of this can be ascribed to reducing additional work by having instructors and classmates immediately present to answer questions. However, we feel there is also a strong natural social component where a high value is placed on in-person contact. In some cases, there was also a perception that alternative labs were second-rate because they were being done at home.

The studies reviewed exploring the use of home-study labs demonstrate that, in addition to cognitive gains, the learner also develops psychomotor skills. However, the major issue is whether the home-study labs can conveniently replace the physical labs when considering safety, liability, and cost issues, as well as the assumption that a "laboratory atmosphere" cannot be replicated outside of a laboratory setting. These have been argued with the suggestion of "looking outside the box." According to researchers, physical phenomena have been around for a long time and are not confined to laboratories alone; most of the important experiments and discoveries in the early days were conducted at home using simple tools and equipment (Dalgarno et al., 2003). Finally, bringing the laboratory experience into the home can contextualise science by demonstrating that science is all around us and experiments can be done outside a formal laboratory setting.

Experimenting on the computer (virtual and remote control) can also be advantageous if cost and security reasons do not allow all students to carry out a real experiment. This is not to downplay the importance of science lab work and the acquisition of skills gained hands-on using lab equipment and tools in science, and the complaint of lack of touch, taste, smell, together with the cost and hazards associated with transporting (especially with the home-study lab). Even with one of the latest technological innovations named "haptic" which enables users to feel, touch sensation, it may still not be the same experience as in the traditional/physical labs setting (Tatli & Ayas, 2010). Indeed, some of the research literature still supports that virtual and remote lab experiences are best used when there is no physical in-person lab available.

Throughout the 70 papers we also examined the author's preference for how alternative labs might be best used: as either a straight substitution (Alternative), or not at all (in-person), or blending of alternative and in-person (Hybrid). In each case, the article distribution of alternative lab or mode employed (Remote Labs, Virtual Labs, Home-study labs is provided (Figure 4). For example, within the 43 articles examining VL some thought in-person was best (7), while others believed VL could be used effectively as a hybrid (17) or just on its own (19).

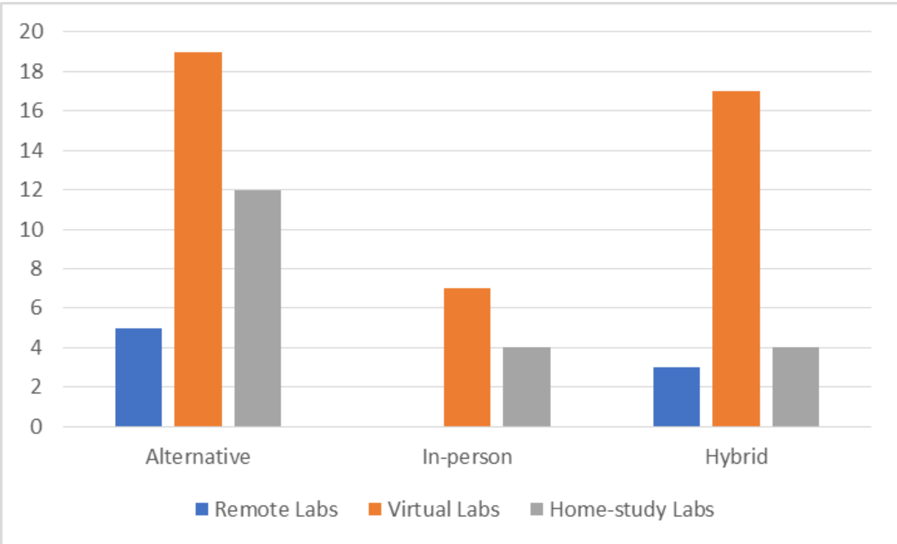

Fig. 4: Preference indicated in the use of each alternative lab

From the analysis, the highest number of the articles (50.7%) reviewed prefer the use of alternative labs followed by the hybrid approach (33.8%) and in-person labs (15.5%). However, the authors of this review were surprised that, given a choice, the preference by science educators for a hybrid approach across all alternative labs was not greater, as alternative and in-person lab experiences can bring different learning opportunities (Brinson, 2015).

To wrap up the analysis, a summary of the major reported advantages and disadvantages of each alternative lab as outlined in the articles is provided (Table 1). Advantages and disadvantages could be identified for all delivery modes, but the remote and virtual labs had more advantages and fewer disadvantages compared with the traditional and home-study labs. Still, it is interesting to note some prominent advantages of the home-study lab kits such as transportability, useability within the comfort of the learner's home, and the exposure to trial and error to build confidence. It is also worth noting with the virtual and remote labs the increased performance and understanding of science concepts, teamwork, flexible access to lab spaces and ability to repeat experiments, and confidence built up during the trial-and-error process were identified as clear advantages. Remote labs also emphasised the ability of the students to work with sophisticated equipment. All these notwithstanding, the fact that there is still no face-to-face contact, no hands-on for the students to feel, taste and smell, and no immediate help and advice when needed by the student still presents disadvantages compared with traditional in-person experiences.

Table 1: Advantages and disadvantages expressed for each lab type

Lab type	Advantages	Disadvantages
Home-study lab	• Experiments are similar to those performed in the traditional labs. • Low cost of kits and are transportable. • Innovations of replacing glassware with plastics. • Valuable unsupervised home experience that builds confidence from trial and error. • Students' experience is real.	• Not all experiments are safe in the home environment. • No face-to-face contact and immediate help and advice. • Students spend more time setting up experiments. • High cost of transportation and highly flammable substances are excluded.
Traditional lab	• Provides face to face contact and immediate help and advice available. • Real materials are used and highly flammable/toxic materials are monitored. • Promotes team and peer group work. • Students acquire hands-on skills in manipulations and observations.	• High cost of building, equipment, maintenance and provision of human resources. • Underequipped labs and some materials not available. • Constant guide provided may not allow the students to build enough self-confidence.
Remote lab	• There is contact between the teacher and learner and quite economical for practicals. • The feel of a real experiment with the operational problems and errors using sophisticated equipment.	• No face-to-face, hands-on and immediate help and advice. • Experience gathered not same as traditional.

	• Enable the students to rehearse, complete, repeat or extend their lab work by offering flexible access.	• Can be expensive since it requires the physical structure, sophisticated equipment and technicians in place. • Not easy to access skills.
Virtual lab	• Increases students' success, positive attitude, motivation and performance. • Students find it enjoyable, attractive and provide more correct answers. • It facilitates learning with a better and deeper understanding of theoretical concepts and chemical theories. • Build students' confidence in the trial and error process. • Can be repeated as often as needed with modification but without additional cost on human and material resources. • Easily transportable and students can perform complicated and hazardous experiments. • Helps in learning abstract and difficult concepts.	• Detrimental to acquiring hands-on skills in manipulation and observation. • No immediate help and advice. - Face-to-face contact or teacher interaction not available. • Absence of smell, sound, sight and touch. • Excludes care and precision necessary for experimental basis and disciplines.

Conclusion

This analysis of alternative laboratory experiences could not have come at a better time than now when many who had been sceptical have explored their use during the pandemic. Indeed, on occasion, alternative laboratories have also inspired novel approaches for in-person laboratories, For example, Hanson describes the development of experiments for school children in Ghana moving away from conventional equipment to use many of the principles (e.g., safety, transportability, ease of use, microscaling) that are common in the development of home-study lab kits (2022). Although there is still a lot to be covered in this topic to do justice to it, it is important to note that both the traditional and alternatives have their advantages and disadvantages (Table 1). Whether one views this through the lens of those modes of delivery (advantages-disadvantages) learning outcomes achieved or learning domain targeted (Bloom's Taxonomy) or even the individual contexts encountered (reflected in the vignettes), one is immediately struck by the wide scope and complexity presented to the science educator. To decide on which option to use to conduct a teaching experiment a great deal needs to be taken into account. However, we feel it is that educators who are best placed to adopt, adapt, and create solutions to get the right mix to meet local requirements. To aid in this some general recommendations are offered.

Recommendations

1. Match lab mode with student and institutional abilities and needs.
2. Use and adapt evidence-based interventions where possible.
3. Do not hesitate to explore combinations of laboratory modes.
4. Start with one change and build from there.
5. Measure and keep track of student success (satisfaction and performance) to help inform future changes.

Remarkably, our analysis revealed the preference for virtual and remote labs over traditional in-person experiences. Virtual labs do provide experiments that can be repeated safely as often as necessary from any location at no additional cost in resources or personnel. Remote control labs also offer safety, because the student is using a computer interface. However, unlike computer simulations, the capacity to repeat experiments is physically limited. Then again, that physical limitation, coupled with non-ideal results generated from real samples, has been flagged as a clear advantage for the learner. This along with evidence of meeting stated learning outcomes, has led some researchers to claim that the online experience is "about as good as the real thing." Not to be forgotten, although home-study labs are not technically online, they are still an important vehicle to consider when supporting online and off-campus science courses. They provide both a physical experience and can contextualise learning by bringing the lab to the student.

The various comparisons and analyses also revealed some weaknesses in the existing literature. For instance, though it is clear that traditional labs help in the acquisition of practical skills, nothing indicates that the alternative laboratory experiences negate student success in subsequent traditional labs. This provides an area for further research. Still, a bigger concern is that a majority of studies to date have been focused on the cognitive domain emphasising content knowledge with metrics often limited to grades and student perspectives. There is a serious need to track and measure a wider range of learning outcomes to gain a better understanding of any laboratory intervention (traditional and alternative), which will hopefully lead to more evidence-based options for the practitioner in future.

Science educators at online, distributed, and open institutions have been developing and examining alternative laboratories for many years and with some success. It comes with a strong practical and social mandate that essentially facilitates a vital pathway to STEM education. Historically, this alternate approach has provided some learners with access and flexibility that they might not otherwise find at on-campus institutions. However, the COVID pandemic has more broadly opened the world of alternative science laboratory experiences to learners who cannot take advantage of conventional on-campus settings—these alternatives have become very handy!

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Appendix A: Articles (70) in the review

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