

Virtual Laboratories in Enhancing Experimental Skills and Scientific Understanding among High School Learners

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Abstract This study examines how virtual laboratories can enhance high school students' experimental skills and understanding of science. With the growing use of technology in education, virtual labs enable students to conduct science experiments online, which can improve their engagement, critical thinking, and teamwork. The study involved 114 senior high school students from a private school in the locale of the study during the 2024-2025 school year, who are selected based on their familiarity with virtual labs. Data was collected through a survey that evaluated the accessibility and effectiveness of these virtual environments in enhancing students' skills and understanding. The findings indicate that students generally perceive virtual labs as beneficial for learning, reporting improvements in their ability to follow scientific procedures, manipulate variables, and grasp complex concepts. Additionally, virtual labs provide a safe space for experimentation, particularly when physical labs are not feasible. The study emphasizes the importance of integrating virtual labs into the curriculum to help students better understand scientific principles and prepare for future challenges in science and technology. It also suggests the need for further research to explore how different students respond to virtual labs and the long-term impacts of technology in education. Thus, this research supports the notion that virtual laboratories are valuable resources for enhancing STEM education among high school learners.

Keywords: Virtual Laboratories, Experimental Skills, Scientific Understanding, Science education

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1. Introduction

One of the most significant and popular e-learning strategies nowadays is virtual laboratory simulation. It is regarded as a 3D immersive science simulation that lets students perform science experiments remotely at any time and from any location using their own devices. By teaching the various scientific principles and techniques, making the experiment steps more understandable, and facilitating the application of the practical portion of the curriculum, virtual laboratories help both teachers and students reach their desired educational goals [1].

Multimedia Learning Theory, developed by Richard Mayer [2], suggests that people learn more effectively from words and pictures than from words alone. It

emphasizes the importance of using multiple forms of media, for example, text, images, audio, and video, to enhance learning. In virtual laboratories, multimedia elements can provide rich, interactive experiences that cater to different learning styles and help students visualize complex concepts, thereby improving comprehension and retention.

Students can investigate scientific ideas and concepts in a virtual setting by participating in simulations of experiments or other practical activities known as virtual laboratories. Students can learn and interact with the laboratory as a work environment in a flexible and convenient way by using these simulations to augment or replace traditional laboratory experiences on campus [3].

The use of virtual labs and other synthetic learning environments in STEM higher education allows students and teachers to replicate experiments that would otherwise

need to be conducted in a teaching laboratory. It also gives students an interactive experience that enables them to test hypotheses, gather data, and analyze results by manipulating virtual tools and materials [4,5]. On the other hand, Kalogiannakis and Papadakis [6], highlight the effectiveness of virtual labs in improving students' conceptual understanding and practical skills.

According to Vassiliadou [7], virtual labs offer the following benefits: unlimited time, instant feedback, experiment repetition, and safety for both students and experiment subjects. Virtual and simulated experiments give students a realistic solution, at least in an emergency, and help them get ready for their real laboratories [8]. With the help of technology, students can communicate with teachers, ask for assistance, and share their learning experiences. Additionally, students can work in groups to conduct virtual experiments, which promote social interaction and teamwork [9]. Digital traces can be produced by virtual labs to track students' progress and pinpoint their learning preferences. According to Ramadan and Irwanto [10], these records of students' interactions with virtual labs showed improvements in their capacity for problem-solving, critical thinking, laboratory skill development, and knowledge acquisition.

Virtual labs have significantly transformed STEM education in K-12 settings by enhancing student engagement through interactive simulations and gamified elements, which increase interest and participation in STEM subjects [11]. They also improve conceptual understanding by providing visual representations and hands-on virtual experiments that simplify complex scientific concepts [12]. Furthermore, virtual labs foster critical thinking skills as students engage in hypothesis formation, data analysis, and conclusion drawing, which are essential for scientific reasoning. Additionally, they prepare students for future careers by exposing them to advanced technologies and enhancing their digital literacy, while ensuring accessibility and inclusion by providing equal high-quality lab experiences regardless of school resources [11].

The use of virtual laboratories may help boost students' interest in STEM subjects, which is important for developing the next generation of STEM experts. Future research should focus on addressing student individual differences, considering sociocultural context, and investigating different kinds of virtual laboratories. Examining the long-term impacts of integrating digital technologies into STEM education is also crucial [13].

The integration of arts into STEM education, as discussed by Ampartzaki et al. [14], highlights the importance of diverse pedagogical approaches in enhancing student engagement and understanding. This perspective can be extended to the use of virtual laboratories in high school education.

Hence, the integration of virtual laboratories into high school education marks a significant step forward in improving students' experimental skills and scientific understanding. As we move through an increasingly digital world, it becomes crucial to utilize these cutting-edge resources to enhance engagement, critical thinking, and collaboration among STEM students. This study aims to highlight the potential of virtual laboratories, demonstrating their role in not just enriching the learning

experience but also equipping students to face future challenges in science and technology. Ultimately, this research aims to aid in the formulation of effective teaching strategies that can motivate the next generation of learners, ensuring that every student is afforded high-quality, immersive learning experiences that nurture their curiosity and enthusiasm for science.

2. Methodology

This study employed a descriptive-quantitative research design to document, describe, analyze, and understand the perceptions of senior high school learners regarding the use of virtual laboratories in enhancing their experimental skills and scientific understanding. According to Bradshaw et al. [15], quantitative research design is a structured approach that emphasizes the collection and analysis of numerical data to understand phenomena, test hypotheses, and establish relationships among variables. This method is widely utilized across various disciplines, including healthcare, education, and the social sciences, due to its ability to provide objective and reliable results.

The participants of this study were the Senior high school students enrolled in a private school in Santiago City, Philippines, during the academic year 2024-2025. The purposive sampling technique was used to select respondents based on their experience with virtual laboratories, focusing on STEM students. Kanaki and Kalogiannakis [16] address key challenges in educational research sample design, stressing the importance of careful selection to ensure valid and reliable data. They point out that considering diversity and context in sampling strategies improves the relevance and rigor of research findings. This method is especially useful for assessing innovative educational interventions, as it ensures that the sample accurately reflects the target population. Afterwards, 114 learners were identified as respondents. These learners were identified based on their strand, which is the Science and Technology, Engineering, and Mathematics strand, and are routinely engaged in experiments and scientific inquiry. Virtual labs directly relate to their academic and practical learning as well, and they are more likely to have experience with both traditional and virtual laboratories. This allows them to compare the effectiveness of virtual laboratories with physical laboratories. Henceforth, they are deemed to have great values and skills to identify the effectiveness of virtual laboratories in enhancing students' experimental skills and scientific understanding and can therefore produce reliable responses on the survey questionnaire.

The researchers utilized a survey questionnaire, consisting of two parts, the first part is for the respondent demographic profile which is their sex and their grade level, The next part is composed of 25 questions divided into 5 category which are Access and Usability of Virtual Laboratories; Instructional Integration of Virtual Laboratories; Enhancement of Students' Experimental Skills; Improvement of Scientific Understanding; and Perceived Effectiveness Compared to Traditional Labs on a four point Likert scale ranging from Strongly disagree to strongly agree.

To ensure the validity and reliability of the research

questionnaire, expert pooling was utilized. A panel of field experts reviewed the questionnaire items, providing feedback on clarity, relevance, and comprehensiveness. This collaborative approach facilitated the integration of diverse perspectives, thereby enhancing the instrument's quality. The insights from the expert panel were crucial in refining the questionnaire to effectively address the research questions and objectives.

The study adheres to ethical standards to ensure the protection of participants' rights and welfare. The following ethical considerations were implemented. Before participation, students and their guardians are provided with detailed information about the study's purpose, procedures, and potential risks. Written consent was obtained from both students and their parents or guardians. All data collected was treated with strict confidentiality. Participants' identities were anonymized in all reports and publications. Participation in the study was entirely voluntary, and students had the right to withdraw at any time without any consequences. As explained by Petousi and Sifaki [17], it is essential to address the ethical issues surrounding research misconduct and integrity because research misconduct harms the scientific enterprise, emphasizing the dimensions of harm that can undermine trust between science and society.

3. Results and Discussion

Table 1. Access and Usability of Virtual Laboratories

Statement	Mean	Description
The virtual lab platforms used in my school are easy to access and navigate.	3.00	Agree
I receive adequate training and support in using virtual labs.	2.90	Agree
Technical issues with virtual laboratories rarely interrupt learning activities.	2.74	Agree
The virtual lab interface is suitable for Senior high school learners.	3.24	Agree
I can independently perform tasks using the virtual lab platform.	2.95	Agree
Category Mean	2.97	Agree

Table 1 indicates that respondents generally agree on the accessibility and usability of virtual laboratories, with a category mean of 2.97. The statement "The virtual lab platforms used in my school are easy to access and navigate" received a mean score of 3.00, indicating agreement. These results suggest that students perceive the virtual lab platforms as accessible and user-friendly, which is essential for effective learning. A study by Vassiliadou [7] supports this assertion, emphasizing that user-friendly interfaces significantly enhance student engagement in virtual learning environments. The positive feedback on usability indicates that the design of virtual labs aligns well with the needs of high school learners, facilitating a more effective educational experience. However, the statement "Technical issues with virtual laboratories rarely interrupt learning activities" received a lower mean score of 2.74, suggesting that some technical challenges may still exist in using virtual laboratories.

Table 2 indicates that the mean score ranged from 2.75 to 3.08, with students agreeing that virtual labs are integrated into their lessons. The highest score was for the

alignment of virtual lab activities with science learning standards, with a mean value of 3.08. This finding shows that educators are effectively incorporating virtual labs into their instructional strategies, which can enhance learning outcomes. According to Brinson [4], the integration of technology into educational practices leads to improved student engagement and understanding. The alignment of virtual labs with established learning standards further emphasizes their relevance in the curriculum, suggesting that they are not merely supplemental but fundamental to the educational process.

Table 2. Instructional Integration of Virtual Laboratories

Statement	Mean	Description
I use virtual laboratories regularly in my science classes.	2.75	Agree
Virtual labs are integrated into my teachers' lessons as part of the learning process	3.00	Agree
I use virtual labs when physical experiments are not possible.	2.90	Agree
Virtual labs complement my textbook and lecture-based instruction effectively	2.98	Agree
My science teachers align virtual lab activities with the science learning standards.	3.08	Agree
Category Mean	2.94	Agree

Table 3. Enhancement of Students' Experimental Skills

Statement	Mean	Description
Virtual labs improve my skills in following scientific procedures.	3.19	Agree
I learn to manipulate variables and test hypotheses using virtual labs.	2.95	Agree
The platform promotes observation, measurement, and data collection skills.	3.14	Agree
I develop a stronger grasp of experimental design through virtual simulations.	2.99	Agree
Virtual labs encourage me to think like a scientist during inquiry activities.	2.60	Agree
Category Mean	2.97	Agree

Table 3 shows that students agree that virtual labs can improve their skills in following the scientific procedures with a highest mean value of 3.19. These results suggest that virtual labs are effective in enhancing students' experimental skills, which are important for scientific inquiry. The ability to manipulate variables and test hypotheses is essential to the scientific method. Research by Sharma [11] supports this finding, indicating that virtual labs foster critical thinking and problem-solving skills, essential competencies for students pursuing STEM fields.

Table 4. Improvement of Scientific Understanding

Statement	Mean	Description
Virtual lab experiences help me to understand difficult science concepts.	3.10	Agree
I retain content better after performing simulations.	3.13	Agree
Simulated experiments promote meaningful connections to real-world science.	3.20	Agree
I demonstrate improved problem-solving in assessments after using virtual labs.	3.02	Agree
Virtual labs make abstract scientific processes more concrete and visible.	3.01	Agree
Category Mean	3.09	Agree

Table 4 shows that students agree that virtual lab experiences assist them in understanding difficult science concepts and promote meaningful connections to real-world science, garnering the highest mean value of 3.20. This suggests that virtual labs effectively make abstract concepts more concrete, thereby aiding comprehension. Mentis Sci. [12] found that visual representations in virtual labs significantly enhance students' understanding of complex scientific ideas. The ability to visualize and interact with scientific concepts in a virtual environment may lead to deeper learning and retention of knowledge.

Table 5 indicates that students agree that virtual lab serves as an effective alternative to hands-on laboratories, and the combination of virtual labs and physical labs yields the best result in science teaching, with the highest mean value of 3.32. This indicates that students perceive virtual labs as valuable learning tools, particularly when physical labs are not feasible. Breakey et al. [18] noted that virtual labs provide a safe and controlled environment for experimentation, which can enhance learning outcomes. The positive perception of virtual labs suggests that they can complement traditional laboratory experiences, offering flexibility and accessibility in science education.

Table 6 presents the group mean scores and corresponding t-Test results comparing Grade 11 and Grade 12 students' perceptions of virtual laboratories across five key domains: access and usability, instructional integration, enhancement of experimental skills, improvement of scientific understanding, and perceived effectiveness compared to traditional laboratories.

Two items revealed statistically significant differences. Grade 11 students expressed stronger agreement that virtual lab activities are aligned with science learning competencies ($p = .043$), indicating a greater perceived curricular relevance. Furthermore, they reported a significantly higher perception that virtual labs enhance their ability to follow scientific procedures ($p = .010$), which may reflect a stronger sense of skill development through simulation-based activities.

In addition to these findings, the statement regarding the use of virtual labs as substitutes for physical experiments ($p = .111$), the development of a stronger grasp of experimental design ($p = .070$), and the encouragement to think like a scientist during inquiry-based tasks ($p = .053$) suggest emerging trends. These near-significant values imply that Grade 11 students may feel slightly more engaged and supported by virtual lab environments in developing critical scientific thinking and experimentation skills than their Grade 12 counterparts.

While both grade levels hold generally favorable and comparable views of virtual laboratories, the statistically significant and borderline differences point to Grade 11 students perceiving greater instructional alignment and skill-building benefits. These findings may be attributed to differences in curriculum content, instructional focus, or familiarity with virtual lab platforms. Such results align with the observations of Wu et al. [19], who noted that students' engagement with educational technology can vary based on their academic stage and technological experience.

Furthermore, the results demonstrated that students generally found virtual laboratories to be user-friendly and effective in improving their understanding of difficult

science concepts, as well as in developing their ability to follow scientific procedures and engage in inquiry-based learning.

These findings support earlier research by Brinson [20], whose meta-analysis highlighted the effectiveness of virtual laboratories in promoting student engagement, knowledge retention, and a deeper understanding of scientific principles in STEM education. Similarly, Sharma [11] emphasized that virtual labs foster critical thinking and problem-solving skills through interactive simulations that develop students' analytical capabilities—skills essential in STEM fields.

The study also examined whether perceptions of virtual labs varied by gender and grade level. While most responses showed no significant gender-based differences, female students reported feeling less supported in their use of virtual labs. This finding is consistent with Becker [21], who found that gender differences can influence students' engagement and perceptions in technology-enhanced learning environments. Becker's study suggests that additional support may be necessary to ensure equitable access and engagement for female learners.

Moreover, Grade 12 students expressed a greater perceived need for virtual labs in scenarios where physical experiments were not feasible. This trend is aligned with Wu et al. [19], who found that students' perceptions of digital learning tools can vary with their level of technological familiarity and exposure, emphasizing the need for targeted instructional support across grade levels.

The findings also echo the work of Vassiliadou [7], who discussed the benefits of virtual labs in higher education, such as unlimited experimental time and immediate feedback. Vassiliadou's research supports the idea that virtual labs provide a controlled and safe environment conducive to science learning, especially for high school students.

Moreover, the study aligns with findings from Mentis Sci. [22] and Acenas et al. [23], who underscored the role of visual representations in enhancing students' understanding of complex scientific ideas. Their work confirms that interactive and visual experiences in virtual labs contribute to deeper learning and improved knowledge retention.

Breakey et al. [18] further emphasized that virtual labs are viable alternatives during emergencies, ensuring continuity in science education when access to physical laboratories is limited. This assertion is supported by additional studies [21,24,25,26,27], which advocate for the inclusion of virtual learning platforms as part of educational contingency planning.

In addition, the results reflect the insights of Ramadan and Irwanto [10], who found that virtual labs enhance students' thinking abilities, scientific skills, and attitudes. Their research suggests that the interactive and student-centered nature of virtual labs fosters deeper engagement with scientific content.

Thus, the findings of this study contribute to the growing body of literature supporting the integration of digital tools in education. Virtual laboratories, in particular, offer substantial benefits in improving scientific understanding, procedural skills, and engagement, highlighting their relevance in preparing students for future challenges in science and technology.

Table 5. Perceived Effectiveness of Virtual Laboratories Compared to Traditional Labs

Statement	Mean	Description
Virtual labs are effective alternatives when hands-on labs are not feasible.	3.03	Agree
I believe virtual labs enhance learning outcomes similarly to physical labs.	3.01	Agree
I am more engaged in science lessons when virtual labs are used.	3.06	Agree
Virtual labs allow safer and more controlled experimentation.	3.20	Agree
The combination of virtual and physical labs yields the best results in science teaching.	3.32	Strongly Agree
Category Mean	3.12	Agree

Table 6. Comparative Analysis on the Perception of Virtual Laboratories in Enhancing Experimental Skills and Scientific Understanding

Indicators	Group Means		t-value	p- value
	Grade 11	Grade 12		
Access and Usability of Virtual Laboratories				
The virtual lab platforms used in my school are easy to access and navigate.	3.00	3.00	.000	1.00
I receive adequate training and support in using virtual labs.	2.73	3.00	-1.943	.054
Technical issues with virtual laboratories rarely interrupt learning activities.	2.78	2.77	.091	.928
The virtual lab interface is suitable for Senior high school learners.	3.29	3.21	.680	.498
I can independently perform tasks using the virtual lab platform.	3.02	2.90	.969	.335
Instructional Integration of Virtual Laboratories				
I use virtual laboratories regularly in my science classes.	2.76	2.74	.105	.917
Virtual labs are integrated into my teachers’ lessons as part of the learning process	3.05	2.97	.525	.600
I use virtual labs as a substitute when physical experiments are not possible.	3.05	2.82	1.607	.111
Virtual labs complement my textbook and lecture-based instruction effectively	3.05	2.95	.931	.354
My science teachers align virtual lab activities with the science learning competencies or standards.	3.24	2.99	2.047	.043*
Enhancement of Students’ Experimental Skills				
Virtual labs improve my skills in following scientific procedures.	3.14	3.07	2.638	.010*
I learn to manipulate variables and test hypotheses using virtual labs.	3.10	2.86	1.540	.126
The platform promotes observation, measurement, and data collection skills.	3.24	3.08	1.252	.213
I develop a stronger grasp of experimental design through virtual simulations.	3.15	2.90	1.831	.070
Virtual labs encourage me to think like a scientist during inquiry activities.	2.83	2.47	1.952	.053
Improvement of Scientific Understanding				
Virtual lab experiences help me to understand difficult science concepts.	3.24	3.01	1.604	.111
I retain content better after performing simulations.	3.22	3.08	1.048	.297
Simulated experiments promote meaningful connections to real-world science.	3.22	3.19	.231	.818
I demonstrate improved problem-solving in assessments after using virtual labs.	3.10	2.97	.926	.356
Virtual labs make abstract scientific processes more concrete and visible.	3.12	2.95	1.381	.170
Perceived Effectiveness Compared to Traditional Labs				
Virtual labs are effective alternatives when hands-on labs are not feasible.	3.10	2.99	.832	.407
I believe virtual labs enhance learning outcomes similarly to physical labs.	2.93	3.05	-.978	.331
I am more engaged in science lessons when virtual labs are used.	3.10	3.04	.400	.690
Virtual labs allow safer and more controlled experimentation.	3.27	3.16	.813	.418
The combination of virtual and physical labs yields the best results in science teaching.	3.39	3.29	.832	.407

4. Conclusion

This research highlights the positive impact of virtual laboratories on the experimental skills and scientific understanding of high school students. The findings suggest that virtual labs serve as valuable educational resources that can enhance student engagement in STEM subjects. However, the study also points to the necessity of addressing the varying needs of students, particularly in terms of support and resources. By recognizing and responding to these differences, educators can maximize the effectiveness of virtual laboratories and ensure that all students have equitable access to high-quality learning experiences in science education. As technology continues to evolve, integrating virtual laboratories into the curriculum will be essential for preparing students for future challenges in science and technology. The insights gained from this study contribute to the ongoing discourse on the role of digital tools in education, emphasizing their potential to enrich the learning experience for all students.

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