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Virtual Laboratories in Science Education: A Systematic Review of Effectiveness on Conceptual Understanding and Learning Outcomes

Devi Apriana Meronda, Hayuni Retno Widarti*, & Yahmin
Department of Chemistry, Universitas Negeri Malang, Indonesia

Abstract: Virtual laboratories (VLs) have emerged as a significant innovation in science education, enriching learning experiences, deepening conceptual understanding, and providing more flexible and safer access to experiments. Nevertheless, the implementation of VLs still faces challenges, particularly in developing practical skills and ensuring integration with physical laboratories. This study aims to present a comprehensive review of the impacts, potentials, and limitations of VLs through a systematic literature review. The method employed follows the PRISMA protocol, with Scopus as the primary database. Out of 489 initial articles, only 21 articles met the inclusion and exclusion criteria after the screening process. The analysis was directed toward two main research questions: (1) to what extent does the use of interactive simulation–based virtual laboratories enhance conceptual understanding, and (2) how do students' learning outcomes compare with those of traditional laboratory practices? The findings revealed that the development of VLs is typically grounded in constructivist approaches and instructional design models that emphasize the creation of interactive experiences that resemble real experiments. Furthermore, the results suggested that students taught using VLs achieve better learning outcomes compared to those taught through traditional methods. VLs have been shown to support improvements in conceptual understanding, laboratory skills, scientific literacy, questioning ability, analytical thinking, and cognitive performance, all of which contribute to strengthening critical thinking skills. Thus, VLs not only serve as a solution to the limitations of physical facilities but also play a crucial role in fostering critical thinking as one of the key competencies of the 21st century.

Keywords: virtual laboratory, science education, and learning outcomes.

▪ INTRODUCTION

Laboratories play a crucial role in education by enhancing learning experiences, strengthening students' conceptual understanding, and addressing the limitations of traditional labs, such as scarce equipment, safety hazards, and high operational costs. The development of interactive platforms enables learners to engage with complex subjects without being restricted by these conventional barriers, including resource constraints and safety issues (Potkonjak et al., 2016; Xu et al., 2017). Virtual Laboratories (VLs) are particularly valuable because they can overcome physical and geographical limitations, promoting more equitable access to science and technology education (Potkonjak et al., 2016). For example, digital 3D anatomy learning systems have been shown to effectively replace physical dissections in anatomy courses, increasing student engagement and supporting independent learning (Zhang et al., 2019). Similarly, virtual laboratories applied in electrophoresis separation experiments illustrate their versatility as innovative tools for practical learning (Situmorang et al., 2024). By simulating real experimental conditions, these platforms enable learners to gain a deeper understanding while facilitating a broader exploration of scientific concepts (Liu et al., 2023).

Several studies have demonstrated that virtual experiments can positively influence students' learning outcomes. (Quiroga and Choate, 2019) highlighted that virtual

Hayuni Retno Widarti
*Email: hayuni.retno.fmipa@um.ac.id
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experiences help deepen students' understanding of physiological processes, thereby enhancing the effectiveness of inquiry-based learning. Similarly, Xu et al. (2017) found that virtual platforms increase student engagement by allowing repeated experimentation without the physical constraints typically found in traditional laboratories. This flexibility is key in developing critical thinking and research skills, which are vital competencies in contemporary education. From a historical perspective, Raman et al. (2022) noted that virtual laboratory designs have evolved significantly to accommodate diverse educational contexts, positioning them as effective solutions to modern learning challenges. In addition, Chen and Wang (2023) emphasized that integrating theoretical knowledge with practical simulations through virtual laboratories not only enriches the learning experience but also fosters motivation, enthusiasm, and creativity among students.

The implementation of traditional laboratory practices has faced increasingly complex challenges, particularly following the onset of the COVID-19 pandemic. The abrupt transition to online learning forced many physics education institutions to grapple with various constraints, including insufficient laboratory infrastructure, limited equipment, and a shortage of experimental materials. These challenges have directly impacted both learning effectiveness and students' academic performance (Alsaleh et al., 2022; Aththibby et al., 2021). Moreover, such limitations often led to a sense of detachment among students, despite the importance of active participation in laboratory activities for understanding abstract and complex physics concepts (Kelley, 2021; Destino & Gross, 2022). While hands-on experimentation remains a crucial element for mastering concepts (Kapıcı et al., 2019), virtual laboratories and other remote learning tools cannot entirely replace in-person lab experiences. The absence of direct interaction with experimental equipment not only restricts students' comprehension but also hampers the development of essential practical skills (Dukes, 2020; Ramadhani & Titisari, 2019).

Management factors and time constraints also pose challenges in physics learning. Many students reported experiencing an increased workload and additional pressure when adapting to online learning through video-based or interactive media, which ultimately reduced the effectiveness of laboratory practice. Although distance learning methods continue to advance, most learners still prefer direct laboratory experiences, as they provide tangible validation of the concepts being studied (Aththibby et al., 2021; Destino & Gross, 2022). This condition indicates that despite the rapid development of educational technology, the role of physical laboratories remains important and cannot be overlooked. Therefore, the integration of physical and virtual practices through active learning strategies supported by technology is considered a strategic step to overcome the limitations of traditional laboratories while deepening students' conceptual understandings (Maynard et al., 2021; Muliandi et al., 2024). Given the various challenges faced by conventional laboratories, innovation in teaching methods, technology integration, and more effective resource management is required to improve the quality of laboratory learning. One rapidly growing solution is the virtual laboratory, which has emerged as an alternative to address the limitations of traditional practice. Alongside technological advancements, the use of virtual laboratories has become increasingly widespread, particularly during the COVID-19 pandemic, when education systems transitioned entirely to online learning. A study by Hapsari et al. (2021) found that the use of virtual laboratories significantly enhanced student engagement and had a positive impact on academic achievement.

The effectiveness of virtual laboratories has been demonstrated not only in physics but also across various disciplines, including accounting and electrochemistry. The study by Widarti et al. (2024) emphasized the importance of developing small-scale learning media that integrate ethno-electrochemistry with a content creator approach. As a result, many students perceive that digital platforms, such as YouTube, TikTok, and Instagram, play a significant role in enhancing motivation, learning outcomes, digital literacy, and engagement in science. In terms of feasibility, several studies have also reported high validity of these media. The findings stated that internet-based virtual laboratories using a multirepresentational approach were considered highly feasible, with media validation at 87.8%, material validation at 82.7%, teacher readability at 91.1%, and student readability at 92.3%. The integration of macroscopic, submicroscopic, and symbolic representations enabled students to better understand abstract chemical concepts, complementing the limitations of real practices while also fostering learning motivation (Widarti & Anggraini et al., 2022). Similar findings were reported by Muchson et al. (2018), who showed that an Android-based virtual laboratory for acid–base topics was rated highly feasible, with strong scores in functionality (85.44%), conceptual accuracy (84.67%), and student perception (89.27%). Coupled with features such as pretest–posttest assessments, particle visualization, flexibility in usage, and resource efficiency, virtual laboratories have proven increasingly effective in enhancing students' understanding, skills, and overall learning outcomes.

Although many studies have demonstrated that virtual laboratories are effective and efficient in enhancing learning quality, several fundamental questions remain unanswered. One of these concerns is whether interactive simulation–based virtual laboratories can truly improve students' conceptual understanding and learning outcomes more effectively than conventional laboratories. Another important question is the extent to which significant differences arise between the use of virtual laboratories and the practical aspects of real laboratories. This uncertainty highlights the need for further research on comparative effectiveness to determine whether virtual laboratories serve primarily as a complement, support, or even a potential replacement for traditional practices in modern science education.

Most studies indeed report improvements in conceptual understanding and student learning outcomes with virtual laboratories; however, not all demonstrate significant advantages when directly compared to physical laboratories. For instance, Al-Duhani and Abdullah (2023) found that the group using virtual laboratories achieved higher results, with average scores increasing from 19.10 to 32.40, whereas the control group only rose from 18.75 to 23.50. Improvements in knowledge, application, and reasoning have been observed with virtual laboratories; however, Shana and Abulibdeh (2020) noted that traditional labs often yield higher learning outcomes, engagement, motivation, and conceptual understanding in subjects like biology and chemistry. While virtual labs offer advantages in terms of time and cost efficiency, the value of hands-on experience remains critical, underscoring the need for a thorough systematic review to compare their relative effectiveness.

To address this gap, the current study undertakes a Systematic Literature Review (SLR) that specifically examines the effectiveness of virtual laboratories in science education, with a focus on direct comparisons with traditional laboratory practices and the strategies used for their implementation. This review stands out due to its comprehensive scope, as it not only consolidates the latest research findings but also serves as a foundation for improving pedagogical approaches and advancing current scientific knowledge. The research questions (RQs) previously established are expected to be thoroughly addressed through this in-depth scholarly analysis.

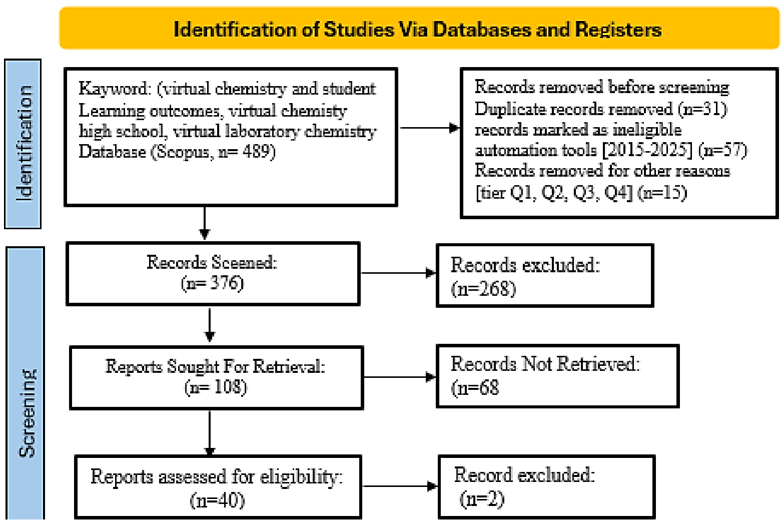
1. Does the use of interactive simulation–based virtual laboratories in learning improve students' conceptual understanding and learning outcomes compared to traditional laboratory practices?
2. Are there differences between the application of virtual laboratory media and direct traditional laboratory practices?

▪ METHOD

This study employs a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize findings from previous research. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, a reporting guideline designed to enhance transparency, consistency, and quality in systematic reviews and meta-analyses (Moher et al., 2009). Within the context of virtual laboratories, PRISMA provides a structured framework for consolidating evidence and presenting research outcomes. Virtual laboratories themselves are interactive, simulation-based environments that are increasingly used in education, particularly in the fields of science, technology, and engineering. Numerous studies have shown that the use of virtual laboratories has a positive impact on learning outcomes, making them a promising alternative to physical laboratories.

Research Design

This study employs a Systematic Literature Review (SLR) methodology following the PRISMA guidelines. The review was conducted in a structured manner, starting with the identification of relevant studies, followed by screening, assessment of eligibility, and the final selection of articles for inclusion. The flow diagram in Figure 1 presents the number of articles retrieved from databases, the studies excluded at each step, and the total number of studies that satisfied the inclusion criteria. The selected articles were then examined using a thematic analysis to identify recurring patterns, similarities, and differences concerning the use of virtual chemistry laboratories and their effects on student learning outcomes.



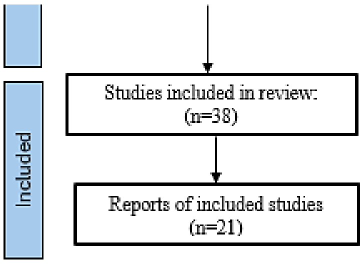


Figure 1. PRISMA flowchart

Search Strategy

For this study, articles were retrieved from the Scopus database using a targeted search string focused on virtual chemistry laboratories and their impact on student learning outcomes. Scopus was selected for its comprehensive coverage, high-quality publications, and international recognition in the fields of science, technology, and education. To ensure relevance, only indexed journals published between 2015 and March 2025 were included. The search was refined using Boolean operators (AND, OR, NOT) to filter results, applying the following string: ("virtual chemistry laboratory" OR "laboratorium kimia virtual") and ("learning outcomes" OR "student achievement" OR "academic performance" OR "hasil belajar siswa") AND ("secondary school" OR "science education" OR "sekolah menengah") NOT ("medical laboratory" OR "clinical laboratory"). The search string was structured to capture terms related to virtual chemistry laboratories, learning outcomes, and secondary science education, while excluding studies on medical or clinical laboratories. A publication filter from 2015 to 2025 ensured the inclusion of recent studies. The initial search in Scopus retrieved 489 articles. After removing duplicates and irrelevant records, 386 articles remained for title and abstract screening, of which 268 were excluded. A full-text review was conducted on 108 articles; however, 68 were inaccessible, and two were excluded after in-depth assessment, leaving 38 studies for qualitative analysis. From these, 21 articles met the inclusion criteria for quantitative synthesis. The entire selection process is summarized in the PRISMA flow diagram (Figure 1), forming the basis of this review.

Inclusion and Exclusion

Screening Stage

During the screening process, inclusion and exclusion criteria were applied to ensure that only studies relevant to the research objectives were considered. Inclusion criteria guided the selection of articles aligned with the study's focus, while exclusion criteria filtered out irrelevant studies. This approach made the selection process systematic, transparent, and focused, reducing potential bias in the literature review. The inclusion criteria were established to ensure that the selected articles were fully aligned with the objectives of this study: (1) The articles had to focus on virtual laboratories or virtual reality in the educational context, whether as a medium, method, or learning environment, thereby ensuring relevance to technological innovation in education. (2) The articles had to be published in reputable journals indexed by Scopus to guarantee scientific quality, credibility, and validity of research findings. (3) The articles had to be related to science education, particularly in the field of chemistry, since this study aimed to identify the effectiveness of virtual laboratories in supporting chemistry learning. (4)

The selected articles had to explicitly present research findings on the effectiveness of virtual laboratories, whether in improving learning outcomes, conceptual understanding, or students' practical skills. (5) Only publications released between January 2015 and January 2025 were considered, ensuring that the analyzed literature remained up-to-date and relevant to recent developments in virtual laboratory technology.

To obtain articles that align with the research objectives, inclusion and exclusion criteria were applied as the basis for screening. The details of these criteria are presented in Table 1.

Table 1. Inclusion and exclusion criteria in the screening stage

Criteria	Inclusion	Exclusion
Study Focus	This article discusses virtual laboratories or virtual reality in an educational context (media, methods, or learning environments).	This article covers additional topics beyond virtual laboratories and virtual reality.
Publication Quality	The article was published in a leading journal indexed by Scopus.	The article is not published in a reputable journal (not indexed by Scopus).
Publication Quality	Pre–post test to assess understanding of the DNA/gel electrophoresis	This article is not related to science education or discusses non-science fields.
Research result	This article presents the results of research that discusses the effectiveness of using virtual laboratory media (learning outcomes, conceptual understanding, and practical skills).	This article does not present research results related to the effectiveness of virtual laboratories.
Publication Year	Articles published between January 2015 and January 2025	Articles published before January 2015 or after January 2025.

Feasibility Stage

At the eligibility stage, the initially retrieved articles were further screened to ensure their alignment with the research criteria. From the initial search, 489 articles were identified and then examined in depth to assess content relevance, so that only literature fully aligned with the focus of this review proceeded to the next stage of analysis. This eligibility process was used to exclude articles that did not meet several criteria, including relevance to the research topic, publication quality (published in reputable international journals), suitability of the field of study (particularly science education with a focus on chemistry), publication period, and availability of full text. Articles failing to meet any of these aspects were excluded from the analysis. From the 489 identified articles, following screening and eligibility assessment, two articles were eliminated because they did not specifically address the use of virtual chemistry laboratories and were therefore considered outside the scope of this review. The detailed inclusion and exclusion criteria are presented in Table 2.

Table 2. Inclusion and exclusion criteria at the eligibility stage

Criteria	Inclusion	Exclusive
Title & keywords	The title and keywords clearly reflect the topic of virtual	Ambiguous and irrelevant titles/keywords, or those that only

	laboratories/virtual reality in education.	mention general terms without focusing on the virtual laboratory.
Research Focus	This article examines the effectiveness of the implementation of virtual laboratories in science education (specifically chemistry).	This article only discusses general theories, opinions, or topics that are not related to the research questions.
Field of study	This article falls within the field of science education, specifically in the area of chemistry.	The article is from a non-science field or is not relevant to education.
Full text availability	This article is available in full text and is accessible for analysis.	This article is an abstract only, and the full text is not available.

In this review, the 21 articles that met the inclusion criteria were further assessed for quality using the fundamental principles of the JBI Critical Appraisal Tools, adapted to the characteristics of each study. The assessment considered several key aspects, including the clarity of research objectives, the appropriateness of the design and methods in relation to the research questions, the completeness of data reporting, and the alignment of findings with the focus of the study. Articles demonstrating strong methodological validity and high relevance were retained for synthesis. Although some studies did not provide detailed explanations regarding ethical procedures or research limitations, they were still included due to their robust design and valuable contribution to the topic. Through this process, 21 credible empirical studies were identified the basis for as analysis and synthesis regarding the effectiveness of virtual laboratories in chemistry education.

Data Analysis

Data extraction and analysis were conducted qualitatively using a descriptive approach, synthesizing findings from the selected studies. Each article was reviewed based on research objectives, design, sample characteristics, type of virtual laboratory, learning outcome indicators, and main results. A comparative analysis was also conducted to examine the similarities and differences, particularly in terms of the effectiveness of virtual versus physical laboratories. The analysis was presented in a systematic narrative, accompanied by tables and diagrams that illustrated patterns and highlighted research gaps. All data were processed manually, using a structured extraction form that covered study metadata, characteristics, and their relevance to the research questions. The findings were mapped to two main RQs: (1) Does the use of interactive simulation–based virtual laboratories in learning improve students' conceptual understanding and learning outcomes compared to traditional laboratory practices? (2) Are there differences between the application of virtual laboratory media and direct traditional laboratory practices? Results were further grouped into two dimensions: student outcomes (conceptual understanding, cognitive skills, and motivation) and practical aspects (resources, pedagogy, and user experience). This method enabled a structured synthesis, identification of trends, and recognition of inconsistencies across studies, as detailed in the mapping tables forming the basis of the results section.

Table 3. List of reviewed articles

No	Author & Year	Country	Study Design	Sample Size & Level	Virtual Lab Tipe	Outcome Measures	Kay Quantitative Findings
1	Toth, 2016	USA	Quasi-experimental	31 students	MyDNA (2003)	Outcome measures include a pre–posttest for understanding the DNA/gel-electrophoresis concept and an error survey for anomalous data analysis.	Students showed significant increases in knowledge of gel electrophoresis concepts after using VRL, with large effect sizes (r = 0.85 and r = 0.63) in both studies.
2	Saifan et al., 2020	Slandia Baru	mixed-methods dengan pendekatan quasi-experimental	17 undergraduate students majoring in chemical engineering	open-source bioprocess engineering simulation software	Outcome measures included a virtual lab survey (20 items) to assess understanding of safety, fermentation, data analysis, and learning experiences, as well as a hands-on lab survey (9 items) to assess effectiveness, confidence, and practical skills.	Over 95% of students agreed that the virtual laboratory helped them understand the effect of aeration on bacterial growth, and 88% of students felt they had a better understanding of how changing parameters affected fermentation results after using the virtual laboratory.
3	Mistry dan Shahid, 2021	USA	descriptive study or evaluation study.	79 chemistry program students	Interactive web-based virtual guided-inquiry simulations using Google Sites	Students' ability to connect theory with data & virtual experimental observations.	This virtual, inquiry-based organic chemistry simulation was deemed effective because it yielded consistently good average scores.
4	Dunnagan et al., 2020	USA	quasi-experimental comparative design	75 students	Immersive Virtual Reality (VR) lab	The measured results include short-term and long-term test results, as well as user satisfaction.	The difference effect was very small (Cohen’s d = 0.12; r = 0.06), indicating nearly identical learning outcomes between VR and traditional labs.
5	Tatenov et al., 2023	kazakstan	quasi-experimental design with mixed methods.	50 students	Virtual interactive inorganic chemistry lab berbasis JavaScript.	Outcome measures include conceptual understanding, laboratory skills, logic, creativity, and motivation.	The results of the report analysis showed that the experimental group was significantly superior to the control group in 7 of the 10 assessment criteria ($p < 0.05$).
6	Hassan et al., 2022	Australia	case study analysis.	case analysis and implementation experience	commercial MindTap forensic lab dan custom-built IBM Cloud IoT lab.	The results of this study were measured in terms of engagement, completion, satisfaction, and success rate.	The use of VLab increased engagement, enabling COIT20267 to achieve a 100% graduation rate and improving student satisfaction: COIT12201 (3.5→4.5), COIT20267 (4.3→4.7), and custom-built VLab (4.0→4.9).

7	Atta et al., 2022	Swiss	quasi-experimental comparative design	180 students	Virtual Reality (VR) immersive lab berbasis gamifikasi.	Student satisfaction questionnaire to measure ease of understanding, content appeal, experience using VR, and motivation to repeat the experience	The VR experience increased knowledge by 50% in 30 students and 60–100% in 80 students. 90% of students gained new knowledge, 85% expressed a desire to repeat the course, and 67–80% found the VR learning experience significantly more effective than a traditional theoretical lecture.
8	Antonelli et al., 2023	Swiss	educational experimental intervention with blended learning (BL).	119 students A total of 107 participants completed the initial survey, 102 took the pre-test, and 82 completed the post-test.	Virtual Reality digital twin robotics laboratory, Desktop type VR (access via browser)	Outcome measures include knowledge tests (pre- and post–quiz), self-assessment quizzes in VR (Pick & Place, Palletizing, Welding), and student perception questionnaires using a Likert scale.	Students gave positive perceptions towards the use of VRL (rating it as fun, helpful, and motivating), although there was no significant increase in knowledge outcomes.
9	Jagodzinski dan wolkes, 2015	Polandia	Quasi-experimental designs	A 200-student senior high school.	Virtual chemical laboratory berbasis NUI (Kinect sensor**)**.	Outcome measures included knowledge tests (pre-, post-, and delayed) based on Bloom's taxonomy, as well as a 10-item Likert survey assessing engagement, efficiency, motivation, confidence, and interest in real experiments.	Perception surveys revealed that 75% of students believed VR enhanced their commitment to the real lab, approximately 70% were more motivated to conduct experiments, and 80% felt more efficient and confident in their laboratory skills.
10	Devenport et al., 2023	USA	quasi-experimental with pretest–posttest.	1473 students from 12 senior high schools	ChemVLab+ (virtual chemistry lab berbasis web).	Measurements included pre–post knowledge tests for the stoichiometry (26 points) and equilibrium/thermodynamics (34 points) modules, computer log analysis of the number of attempts and successes on paired tasks,	The use of VL improves students' learning scores and work efficiency, especially when used as a review and in individual learning mode, making it more effective than as a substitute for or supplement to instruction or paired learning.
11	Chang et al., 2023	Taiwan	quasi-experimental design	404 student junior high school.	Virtual labs berbasis CoSci platform	Outcome measures included an OECD/PISA-based scientific literacy test, a pre-test for heat capacity and fluid pressure, and data analysis using ANCOVA, t-test, and Cohen's d.	Learning with virtual labs has a significant impact: Buoyancy increases the scores of low-skilled students ($d = 1.47$. $p < .05$), Heat capacity is effective for low- to medium-skilled students ($d = 0.95$–

							1.03. p < .01), and Pressure in a liquid is also significant (F = 27.54, p < .001).
12	Tarng et al., 2021	Taiwan	quasi-experimental design	50 students junior high school.	Virtual lab berbasis Augmented Reality (AR) dan Virtual Reality (VR),.	Outcome measures included achievement tests (pre- and post–tests, 25 questions) and questionnaires (content, interface, reality, motivation, and practicality), which were analyzed using the Mann–Whitney U test and ANCOVA.	The virtual experiment was more effective, with significantly higher post-test scores than the control (M = 41.60 vs. 27.67; p = 0.003). Furthermore, the questionnaire recorded a high level of satisfaction (average 3.98/5), particularly regarding the interface and practicality.
13	Tarng et al., 2022	Taiwan	quasi-experimental design	100 student junior high school.	Augmented Reality (AR) system berbasis AR cards	Outcome measures include achievement tests, learning motivation, cognitive load, and technology acceptance, analyzed using a t-test.	The AR group showed higher learning outcomes than the control group (p = 0.005), was effective in high-performing students (p = 0.033), and demonstrated stronger results in low-performing students (p = 0.002).
14	Ernawati2021	Indonesia	Research & Development (R&D) with ADDIE model	102 student senior high school	Virtual Reality Laboratory (VRL) berbasis Android (.apk)	Outcome measures include post-learning cognitive tests with ANOVA analysis, as well as VRL quality assessment.	ANOVA analysis confirmed significant differences between groups (F = 11.445. p < 0.001), with students in the experimental class achieving better cognitive outcomes than those in the control group.
15	Manyilizu et al., 2022	Tanzania	quasi-experimental design	79 student senior high school	A virtual chemistry lab was developed using the ADDIE model with animation and computer simulation.	Outcome measures: Pre-test & post-test, Real practical performance test, and Data analysis using descriptive statistics, boxplot, and difference test	The results showed that students who started with virtual labs performed better on real-world labs, with the most effective order being virtual lab → paper-based → real lab (median 65–70%, up to 78%).
16	Hu-Au at al., 2021	USA	mixed-method design with a quasi-experimental approach,	74 undergraduate chemistry students	Virtual lab: PhET Interactive Simulations	Behavioral observation achievement tests are conducted through video recordings of interactions, as well as perception surveys, with analysis using ANCOVA, interaction coding,	Both groups showed significant improvement (p < 0.001), with no difference in final scores (p = 0.67). The virtual lab focused more on concepts, while the physical lab focused on procedures, and both were rated as equally useful.

						and descriptive statistics.	
17	Tobarra et al., 2020	Spanyol	deskriptive-experimental	233 chemistry students	Virtual Reality Learning Environment (VRLE) berbasis Unity	The study used the TAM questionnaire, VRLE activity tracking data, and PLS-SEM analysis.	The results show that usefulness and ease of use have a significant impact on attitudes and intentions to use ($p < 0.01$). The majority of students received positive feedback (score > 5/7), and tracking data confirm high exploration activity according to the level of acceptance.
18	Altarawneh, 2023	Arab saudi	development and demonstration of learning cases	undergraduate chemical engineering students	Virtual lab based on DFT (Density Functional Theory) computation	Assess students' ability to calculate chemical parameters, compare DFT results with experiments, and improve conceptual understanding and simulation-based analysis skills.	The results demonstrate that the DFT-based virtual lab is capable of accurately replicating experiments and effectively enhancing students' conceptual understanding and analytical skills.
19	Ullah et al., 2016	Pakistan	quasi-experiment with three groups.	57 senior high school students	3D Multimodal Virtual Chemistry Laboratory (MMVCL)	Outcome measures include experiment completion time, number of errors, student perceptions (ease, clarity, satisfaction, and confidence),	The use of procedural guidance in virtual chemistry labs has been shown to improve performance and learning. siswa.
20	Wang et al., 2015	Taiwan	quasi-experimental pretest–posttest control group design.	60 senior high school students	Virtual Chemistry Laboratory (VCL) interaktif.	Outcome measures include the Chemistry Achievement Test (CAT), a 20-question multiple-choice test to measure learning achievement, and the Students' Attitude Towards Chemistry Questionnaire (SATCQ).	The results of the study showed that the achievement scores of the experimental group ($M = 11.23$) were significantly higher than those of the control group ($M = 7.87$. $t = 5.13$. $p < 0.05$).
21	Saluga et al., 2022	USA	mixed-method	137 students	Virtual organic chemistry lab berbasis Twine (choose-your-own-adventure style).	Student survey with a Likert scale to assess effectiveness, engagement, and perception of learning, and open comments	Over 70% of students reported that Twine increased their readiness, engagement, motivation, and supported critical thinking and decision-making skills.

▪ RESULT AND DISSCUSSION

From the 489 studies collected, this section presents a synthesis of the 21 articles selected and analyzed systematically. To provide a more structured overview, the discussion is organized according to the main themes that emerged from the data analysis. This approach enables the identification of patterns, similarities, and differences across studies, while also offering a deeper understanding of the contributions of virtual laboratories to student learning outcomes. The main themes discussed include:

RQ1. Does the Use of Interactive Simulation–Based Virtual Laboratories in Learning Improve Students' Conceptual Understanding and Learning Outcomes Compared to Traditional Laboratory Practices?

Most studies confirm that interactive simulation-based virtual laboratories can enhance students' conceptual understanding, analytical skills, and learning motivation compared to traditional approaches. Significant improvements have been observed across various topics, such as DNA and electrophoresis (Toth, 2016), fermentation (Saifan et al., 2020), and inquiry-based chemistry learning (Mistry & Shahid, 2021). The advantages of virtual laboratories have also been reported across multiple aspects of learning (Tatenov et al., 2023), with studies noting an increase in understanding of up to 84% (Jagodzinski & Wolkes, 2015). Furthermore, virtual laboratories are effective as a review tool (Davenport et al., 2023), in improving science literacy (Chang et al., 2023), and consistently yield higher post-test scores and cognitive achievements compared to control groups (Tarng et al., 2021; Tarng et al., 2022; Ernawati, 2021; Wang et al., 2020). Several studies also indicate that experience with virtual laboratories helps students perform better in real-life practical sessions (Manyilizu et al., 2022), strengthens analytical skills (Altarawneh, 2023), and provides procedural guidance that positively impacts performance (Ullah et al., 2016). From an affective perspective, more than 70% of students reported that virtual laboratories increased their preparedness, engagement, motivation, and critical thinking skills (Saluga et al., 2021). Overall, these findings suggest that virtual laboratories are not only comparable to physical laboratories but, in many cases, superior in supporting comprehensive science learning.

The study conducted by Melville et al. (2024) demonstrated that the use of Minecraft as a virtual laboratory in engineering courses resulted in significantly higher exam scores. These findings indicate that virtual laboratories are not only as effective as traditional methods but are often superior in enhancing students' conceptual understanding, analytical skills, and learning outcomes.

Theme 1: Impact on the Cognitive Domain (Conceptual Understanding, Analytical Skills)

A growing body of research demonstrates that virtual laboratories can substantially improve students' conceptual understanding. For instance, Toth (2016) observed notable progress in learning DNA and gel electrophoresis concepts, while Saifan et al. (2020) reported that more than 95% of students successfully grasped fermentation parameters and aeration effects through virtual labs. Beyond conceptual gains, virtual platforms also enhance higher-order analytical skills, as demonstrated in Altarawneh's (2023) study, which utilized Density Functional Theory (DFT). Quantitative evidence supports these outcomes, with Atta et al. (2022) documenting knowledge gains of 50–100% in VR-based learning and Davenport et al. (2023) showing improved performance when virtual laboratories were used for review. Consistently, experimental groups using virtual labs outperform controls in both achievement and cognitive outcomes (Wang et al., 2020; Tarng et al., 2021; Ernawati, 2021), including marked increases in scientific literacy with large effect sizes ($d = 0.95–1.47$) (Chang et al., 2023). Complementing these findings, Penn and Mavuru (2020) highlighted that virtual laboratories not only strengthen conceptual and procedural knowledge but also cultivate positive student attitudes. However, they still cannot fully substitute for hands-on laboratory experiences.

Theme 2: Impact on the Affective Domain (Motivation, Self-Efficacy)

The use of virtual laboratories (VLs) has been consistently shown to have a positive impact on students' affective domain, particularly in terms of motivation, engagement, and self-efficacy. Hassan et al. (2022) reported that VLs increased student engagement, satisfaction, and graduation rates, while Atta et al. (2022) found that 85% of students were eager to repeat the VR experience. In terms of motivation, Jagodzinski & Wolkes (2015) observed that 70% of students felt more motivated and 75% more committed after using VLs. In contrast, Saluga et al. (2021) found that over 70% of students indicated that VLs enhanced their preparedness, engagement, motivation, and critical thinking skills. Self-efficacy also improved, with 80% of students reporting increased confidence. The use of procedural guides further strengthened their confidence in conducting experiments in real laboratories (Ullah et al., 2016). Overall, student acceptance of VLs was highly positive, as indicated by average satisfaction scores of 5 or higher out of 7 (Tobarra et al., 2020). Findings by Alhashem & Alfailakawi (2023) confirmed that VLs were effective in understanding complex concepts, providing flexibility, accessibility, and fostering independent learning experiences, with outcomes comparable to or even surpassing those of physical laboratories.

Theme 3: The Role of Virtual Laboratories for Students with Different Abilities

The use of VLs is highly effective in improving learning outcomes, particularly for students with low to moderate academic achievement. Several studies indicate that this group benefits more from VLs compared to high-achieving students. Chang et al. (2023) reported a significant effect with a large effect size ($d = 0.95$–1.47), while Tarng et al. (2021) found that VLs outperformed traditional methods for low-achieving students. These findings are further supported by Tarng et al. (2022), who demonstrated that the positive impact of VLs remained significant among high-achieving students ($p = 0.033$) and was even stronger in the low-achieving group ($p = 0.002$). Consistent with these results, Chen et al. (2025) emphasized that VLs help low-performing students understand abstract concepts, follow experimental procedures systematically, and overcome challenges that typically arise in real laboratories.

Theme 4: Comparative Analysis: When and Why Virtual Laboratories Excel

VLs have proven effective in supporting learning, though their advantages do not always surpass those of traditional laboratories outright. Some studies indicate that students' academic achievement with VLs and physical laboratories is often comparable, with differences being statistically insignificant (small effect size, $d = 0.12$). Antonelli et al. (2023) found that, although students had positive perceptions of using VLs, the knowledge outcomes achieved were equivalent to those achieved with conventional methods. Further reviews emphasize that each method has strengths in different domains. For instance, Hu-Au et al. (2021) reported that VLs are superior in supporting conceptual understanding, whereas physical laboratories are more effective for training procedural skills. The effectiveness of VLs is also highly dependent on their implementation strategy. Davenport et al. (2023) revealed that VLs yield the best results when used as a tool for review and independent learning rather than as a primary substitute for face-to-face instruction. Additionally, the sequence of learning activities significantly influences outcomes, with the most effective combination beginning with VLs, followed by paper-based exercises, and concluding with hands-on laboratory practice. Research by Arista & Kuswanto (2018) further supports these findings, demonstrating that the Android-based ViPhyLab application effectively addresses common limitations of traditional laboratory practices, such as time constraints, procedural complexity, and equipment availability.

RQ2. Is There a Difference Between the Implementation of Virtual Laboratory Media and Traditional Hands-On Laboratory Practices?

Several studies suggest that VLs yield learning outcomes comparable to those of traditional laboratories. (Dunnagan et al., 2020) It was reported that learning achievements between the VR groups and the physical laboratory groups showed no significant differences, with only minimal variation. Similarly, Antonelli et al. (2023) found that although students held positive perceptions of VLs, the knowledge gains achieved were equivalent to those achieved through conventional practice. Comparable results were reported by Hu-Au et al. (2021), who found that both groups experienced significant improvements, with relatively similar final scores, despite differences in their approaches. VLs emphasized conceptual understanding, whereas physical laboratories focused more on procedural skills. Additional support comes from Alqadri (2018), who observed significant learning gains in chemistry using VLs, with average pre-test scores increasing from 42.5 to 81.33 on the post-test; 83.33% of students achieved classical mastery, and an N-gain of 0.69 was observed in the moderate category. Overall, these findings confirm that VLs are as effective as traditional laboratories and, under certain conditions, can serve as a more practical and efficient alternative.

Theme 1: Impact on the Cognitive Domain (Conceptual Understanding, Analytical Skills)

Several studies highlight that the differences between virtual laboratories (VLs) and conventional laboratories are most evident in the cognitive domain. Dunnagan et al. (2020) reported that learning scores for the VR group were slightly higher than those of the face-to-face group (54 versus 51.2), although the difference was not statistically significant. Furthermore, Manyilizu (2023) demonstrated that VLs can enhance the effectiveness of laboratory practice, as students who train with virtual simulations exhibit better conceptual understanding and are more prepared to apply analytical skills when transitioning to real laboratories. Similar findings were reported by Asare et al. (2023), who noted that learning outcomes in virtual laboratories are comparable to those in traditional laboratories, with VLs being perceived as more interactive and engaging in reinforcing conceptual understanding. Collectively, these findings suggest that virtual laboratories can positively contribute to cognitive aspects, particularly in enhancing students' conceptual understanding and analytical skills.

Theme 2: Impact on the Affective Domain (Motivation, Self-Efficacy)

The primary difference between VLs and traditional laboratories in the affective domain lies in the positive experiences and attitudes they foster among students. Although cognitive learning outcomes are comparable to traditional methods, Antonelli et al.

(2023) found that students held highly positive perceptions of VR, considering it an enjoyable, functional, and user-friendly medium. This positive attitude is further supported by Alqadri (2018), who reported that VLs promote favorable student dispositions because it is perceived as safer, more practical, and facilitate conceptual understanding, in addition to being effective in enhancing academic performance. Collectively, these findings suggest that the advantages of virtual laboratories extend beyond cognitive outcomes, highlighting their ability to create a more engaging learning environment, which in turn has strong potential to enhance students' motivation and self-efficacy.

Theme 3: The Role of Virtual Laboratories for Students with Different Abilities

The literature review on the third theme highlights the impact of VLs on students with varying academic abilities (high, moderate, and low). However, the systematic article selection did not identify studies that explicitly investigate the comparative effects of VLs across different ability groups. This lack of evidence indicates a significant research gap. Understanding the differential effects of VLs is crucial to ensure their implementation is equitable and inclusive, preventing the widening of achievement gaps among students. Therefore, further research is needed to evaluate the effectiveness of VLs for students with diverse initial abilities, providing educators with more precise guidance for integrating this technology into teaching and learning.

Theme 4: Comparative Analysis: When and Why Virtual Labs Are Superior

Research under this theme examines conditions in which VLs provide advantages over traditional laboratories. (Hu-Au et al., 2022) found that students who began learning with VR demonstrated better performance when transitioning to physical laboratories, indicating that VR functions effectively as a preparatory tool. Similar results were reported by Au et al. (2021), who found that students who first used VR achieved higher performance compared to those who proceeded directly to the physical laboratory, highlighting the significant influence of usage sequence on the effectiveness of VLs. In line with this, Penn and Ramnarain (2019) showed that pre-service science teachers who learned using virtual laboratories achieved significantly higher post-test scores (M = 79.36) compared to the traditional laboratory group (M = 68.72), with a large effect size (Cohen's d = 1.22). These findings underscore that virtual laboratories can excel, particularly when used to understand abstract chemistry concepts, serving both as an effective alternative and a complementary tool to physical laboratories.

The synthesis of research findings indicates that VLs are not inherently superior to physical laboratories; rather, their effectiveness is highly dependent on the context of use. In general, VLs are most beneficial when employed as a pre-laboratory (pre-lab) tool that prepares students before engaging in hands-on practice. This approach allows students to develop an initial understanding, enabling physical laboratory sessions to focus on application and verification rather than on initial experiments that may lead to misconceptions. (Tarng, Lin, & Ou., 2021) reported that low-achieving students who first practiced using a Daniell cell simulation achieved higher post-test scores (41.60) compared to the control group (27.67). Additionally, VLs are particularly effective for abstract or submicroscopic topics, such as ion movement, dynamic equilibrium, and electrochemical reactions, because 3D visualizations support the formation of more accurate mental models. This aligns with the findings of Tseng & Ou (2022), who demonstrated that AR-based interactive card applications for material structure and chemical equilibrium content can reduce cognitive load while enhancing learning outcomes, particularly for students with lower academic abilities.

Co-occurrence Map

The co-occurrence analysis of keywords related to virtual laboratories in science education identified five main clusters, with connections displayed when keywords appeared together at least twice. In the first cluster (green), the term "Virtual Labs" serves as the central node, closely linked to the concept of "e-learning." This keyword is further connected in the second cluster (red) with terms such as "education and training," "3D imaging," and "innovation." The third cluster (yellow) is dominated by the term "Virtual Laboratory," which appeared 12 times and shows strong correlations with the development of "practical skills" and "analysis." Meanwhile, the fourth cluster (blue) connects "Virtual Laboratory" with the implementation of "hands-on practical" activities in "chemistry," both appearing four times. The fifth cluster places "Chemistry" at the center, also with four occurrences. The map indicates that "Virtual Laboratory" is the most dominant concept in the research, as evidenced by the largest node size. Other frequently used keywords include "Chemistry" and "Virtual Reality" (each with four occurrences), as well as "Physics" (3 occurrences). This pattern indicates that research in this field primarily focuses on three main aspects: the conceptual design of virtual laboratories, their application in specific disciplines such as chemistry and physics, and the utilization of supporting technologies, including VR and 3D imaging.

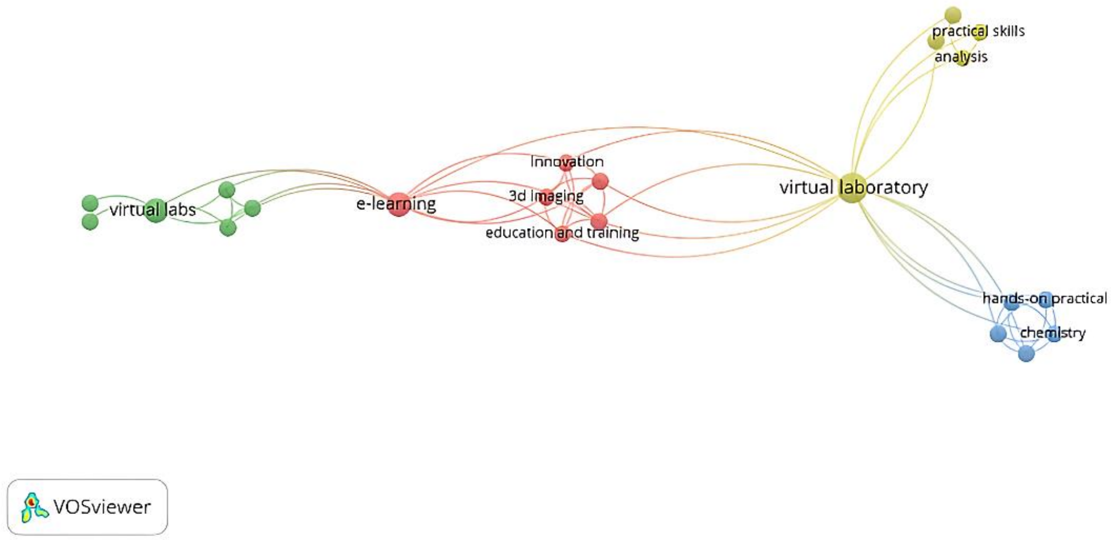


Figure 2. VOSviewer cluster graph of keyword results

Citation Network Map

To determine the citation count of the related journals, the researchers used Google Scholar. The total number of citations across the 21 articles reviewed in this study amounted to 1,197, with the citation distribution for articles published between 2015 and 2025 illustrated in the figure below.

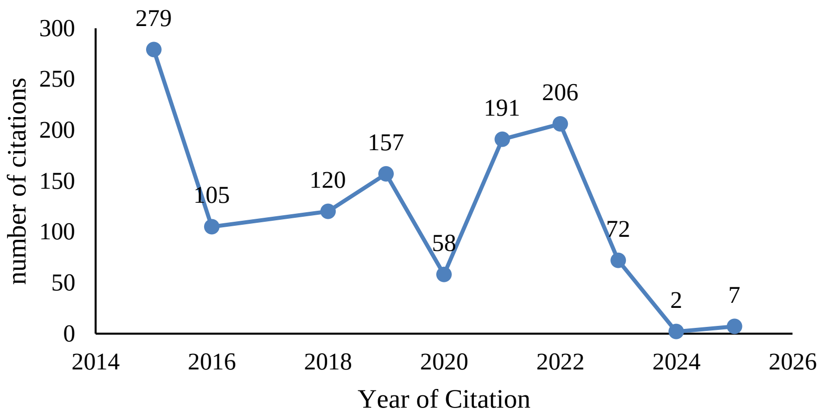


Figure 2. Citation trends based on the publication year of related articles

Map of Inter-Country Collaboration

Analysis of the international collaboration map and publication counts reveals that the global research on this topic is primarily led by the United States (6 articles) and Taiwan (4 articles), marking them as the largest contributors. Other countries contribute to a lesser extent, with Switzerland producing two articles, and New Zealand, Kazakhstan, Australia, Poland, Indonesia, Tanzania, Spain, Saudi Arabia, and Pakistan each contributing one article. This distribution indicates that research on virtual laboratories is not confined to developed nations but also involves emerging countries such as Indonesia, Tanzania, Pakistan, and Saudi Arabia. Overall, these findings underscore the global nature of collaboration in this field, despite the main research hubs remaining concentrated in North America, Europe, and East Asia.

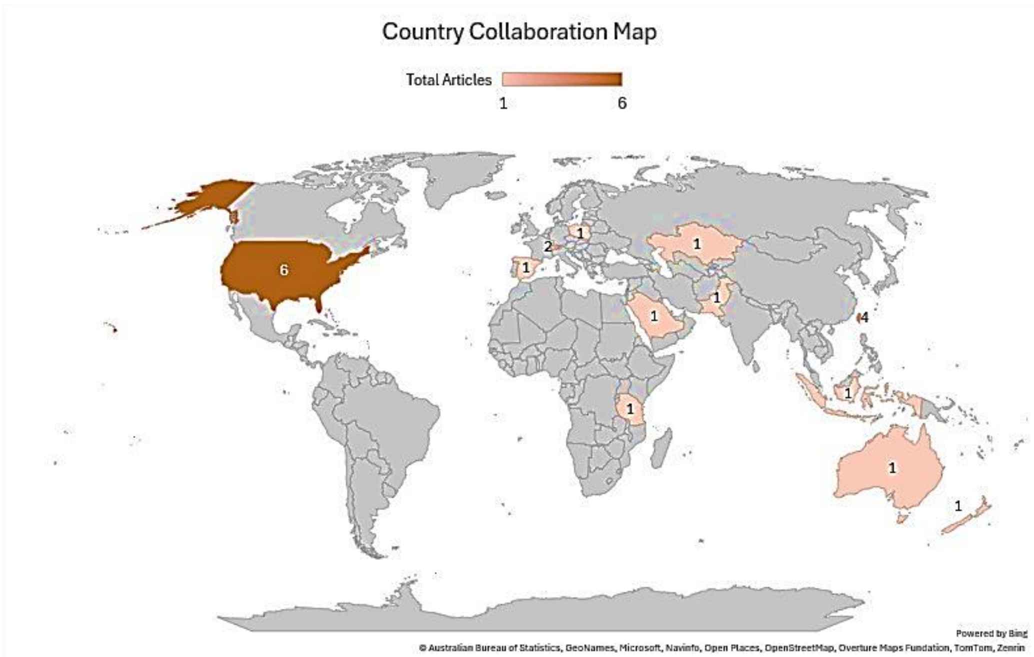


Figure 3. Country collaboration map

Bar Graph

The comparative analysis of 21 studies evaluating the effectiveness of virtual laboratories versus traditional laboratories revealed that 18 out of 21 studies concluded that virtual laboratories were superior in enhancing student learning outcomes. Additionally, three studies found that the effectiveness of both approaches was equivalent, indicating no significant difference between the two methods. It is noteworthy that none of the studies (0 studies) in this review reported virtual laboratories as being less effective than traditional methods. These findings strongly suggest that the current research literature overwhelmingly supports the advantage of virtual laboratories as an effective learning tool, or at least on par with

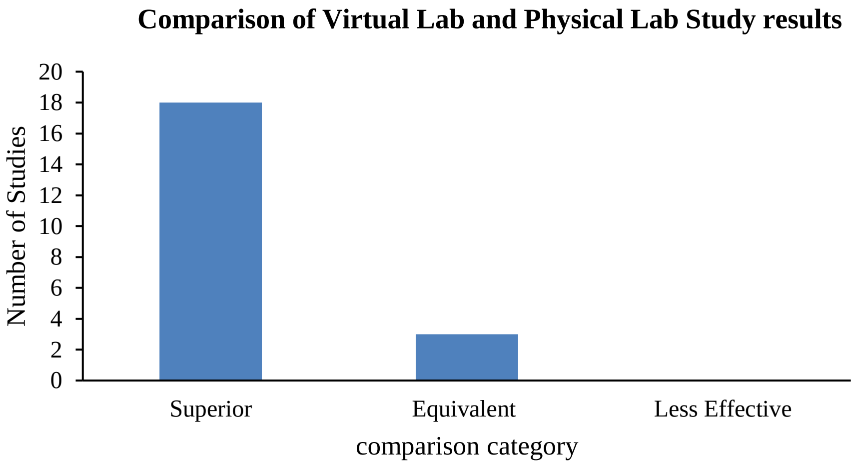


Figure 4. Comparison graph of the effectiveness of virtual labs and physical labs

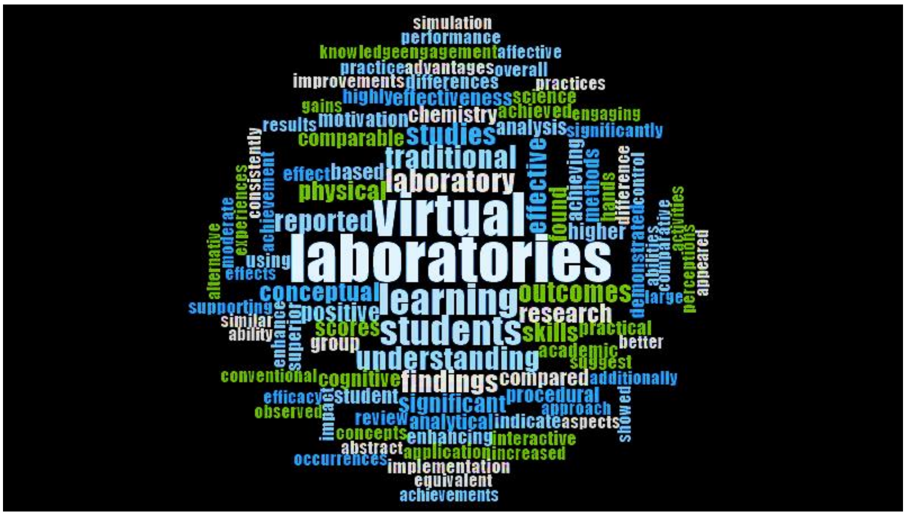


Figure 5. Word cloud

Word Cloud or Concept Map

Keyword analysis shows that this study focuses on virtual laboratories as a learning tool, highlighting their effectiveness, implementation, and impact on student outcomes.

Terms like learning outcomes, conceptual, cognitive, and skills indicate that virtual laboratories enhance conceptual understanding, critical thinking, and academic performance. Several studies also compare virtual and traditional laboratories, showing that student outcomes are often similar or superior in virtual labs, particularly in terms of conceptual mastery and readiness for hands-on experiments. The effectiveness of virtual laboratories depends on their implementation and interactivity, and they are most beneficial when used as pre-lab exercises or review tools, rather than as direct replacements for physical labs.

▪ CONCLUSION

An analysis of 21 studies examining the impact of virtual laboratories versus traditional physical laboratories on student learning outcomes reveals that both methods have a positive contribution to academic achievement. Nevertheless, virtual laboratories offer distinct benefits, particularly in fostering conceptual comprehension, critical thinking, creativity, scientific process skills, and student engagement. They appear especially advantageous for lower-achieving students, as they enable independent learning through submicroscopic visualizations and pressure-free experimentation. In general, virtual laboratories have proven to be as effective as, or in some cases more effective than, physical laboratories in supporting various learning outcomes, positioning them as a practical and efficient alternative in a wide range of educational settings.

In light of these results, educators and institutions should incorporate virtual laboratories alongside physical laboratories within a blended learning model. One effective approach is a "virtual pre-lab followed by physical lab" sequence, where students initially interact with a virtual environment to grasp key concepts, explore submicroscopic phenomena, and practice experimental procedures. This initial phase acts as a cognitive support, helping to reduce intrinsic cognitive load and build more accurate mental representations. Physical lab sessions can then concentrate on applying knowledge, validating results, and developing procedural and motor skills that cannot be fully simulated virtually. This approach enables lower-achieving students to prepare independently while providing higher-achieving students with opportunities to apply their knowledge in practice. It is particularly valuable in remote learning contexts or schools with limited lab facilities, where virtual labs can serve as temporary substitutes for physical labs, which are reserved for experiments requiring direct interaction. Future efforts should emphasize integrating both methods, utilizing virtual laboratoriess to enhance conceptual understanding and physical labs to develop procedural skills, thereby addressing the diverse needs of students across different achievement levels.

Looking ahead, science education is likely to move toward stronger integration between physical laboratories and emerging technologies such as augmented reality (AR), virtual reality (VR), and artificial intelligence (AI). The combination of these tools has the potential to expand access across diverse learning environments while providing more adaptive, personalized, and realistic learning experiences. Upcoming laboratory models may enable students to explore scientific phenomena that cannot be replicated in traditional settings, while simultaneously providing intelligent, individualized feedback. As a result, the direction of laboratory-based learning is shifting toward an innovative hybrid system that supports not only the mastery of practical and conceptual skills but also nurtures creativity, digital competence, and opportunities for global collaboration among future learners.

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