HYDROGEN
JURNAL KEPENDIDIKAN KIMIA
https://e-journal.undikma.ac.id/index.php/hydrogen/index

June 2026. 14(3)
e-ISSN: 2656-3061
p-ISSN: 2338-6487
pp. 547-556

Designing a Green Chemistry Virtual Laboratory with Project-Based Learning to Improve Acid-Base Titration Outcomes

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Article History
Received: dd-mm-2026
Revised: 13-05-2026
Published: 30-06-2026

Keywords: Virtual Laboratory; Green Chemistry; Project-Based Learning; Critical Thinking Skills; Learning Outcomes

Abstract
This study developed a Green Chemistry-oriented virtual laboratory integrated with Project-Based Learning (PjBL) for acid-base titration and evaluated its impact on students' learning outcomes and critical thinking skills. The virtual laboratory was designed using the ADDIE model and implemented as a 2D Canva-based application accessible via laptops and smartphones. The study involved 35 experimental and 36 control group students. Validation by three experts resulted in a media feasibility score of 3.30 ± 0.15. The experimental group achieved an average post-test score of 83.31 ± 5.56, significantly higher than the control group's score of 72.36 ± 4.43. Critical thinking skills also enhanced, with an average score of 88.29 ± 4.82. These findings indicate that the Green Chemistry virtual laboratory significantly improves students' learning outcomes and critical thinking skills.

How to Cite: Ardi, M., Situmorang, M., Aliyyah, N., & Malau, E. (2026). Designing a Green Chemistry Virtual Laboratory with Project-Based Learning to Improve Acid-Base Titration Outcomes. Hydrogen: Jurnal Kependidikan Kimia, 14(3), 547-556. https://doi.org/10.33394/hjkk.v14i3.20567

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INTRODUCTION

Along with the rapid development of science and technology in the 21st century, the demand for innovation in science learning processes is increasing, including in chemistry education (Liliasari et al., 2019) Educators are required to adopt more creative and adaptive approaches to improve learning effectiveness.

Laboratory practical activities play a crucial role in developing students' conceptual understanding and experimental skills (Situmorang et al., 2022). However, limited laboratory infrastructure, reagent availability, occupational safety considerations, and the potential for chemical waste generation are real challenges facing universities, particularly in developing countries (Priliyanti et al., 2021). This becomes even more complex in the realm of analytical chemistry at the university level, where learning emphasizes not only mastery of theoretical concepts but also the development of students' critical thinking, analytical, and practical skills.

One learning innovation that can be developed to address these limitations is the virtual laboratory. A virtual laboratory is an experimental simulation that allows students to explore scientific concepts and principles in a virtual environment (Kumar et al., 2021). Unlike conventional lab sessions that require physical equipment and chemicals, a virtual laboratory simulates experimental procedures in a digital environment, allowing students to perform experiments repeatedly without material limitations (Gunawan et al., 2015) The use of virtual laboratories makes learning more meaningful by helping students discover concepts, increasing activity and learning outcomes, and providing science process skills. One relevant platform is Canva, which allows the design of two-dimensional interactive simulations that can be accessed on a laptop or smartphone via a shareable link.

Studies have confirmed that virtual laboratories significantly improve chemistry students' academic achievement compared to conventional lecture methods, and the application of virtual laboratories across various science disciplines consistently receives high acceptability ratings. A quasi-experimental study on undergraduate chemistry students demonstrated that virtual laboratory implementation significantly improved academic achievement compared to conventional methods (Bazie et al., 2024). Furthermore, the use of virtual reality in chemistry laboratories has been shown to positively impact students' self-efficacy, interest, self-concept, and reduction of laboratory anxiety (Gungor et al., 2022). These combined benefits confirm the value of virtual laboratories in higher chemistry education (Sison et al., 2024).

In the process of developing virtual laboratories, integrating Green Chemistry principles into virtual laboratory design provides significant pedagogical value. Green chemistry education has gained increasing global attention as it cultivates critical and interdisciplinary thinking mindsets essential for innovation in sustainable technologies (Zuin et al., 2021). Green Chemistry, characterized by 12 principles to minimize the use of hazardous materials and waste generation, aligns well with digital simulation environments that do not consume physical reagents. Systematic literature reviews have confirmed that optimizing experimental work through green chemistry principles promotes sustainable development and active learning at all levels of education (Savec & Mlinarec, 2021). This alignment creates unique learning opportunities where students can learn environmentally responsible chemistry practices while developing practical skills through virtual experiments (Mitarlis et al., 2018). A Green Chemistry-oriented virtual laboratories provide solutions to existing limitations while fostering students' environmental awareness as part of a comprehensive scientific competency.

Virtual laboratories are used as simulation media to design and conduct experiments collaboratively and independently. In its implementation, an integrated approach is required that encourages active student involvement in the knowledge construction process. Project-Based Learning (PjBL) is one approach that emphasizes project-based learning to improve students' critical thinking skills (Abidin et al., 2020). Consistent with research by Purba & Situmorang (2015), PjBL in chemistry learning can improve students' overall competency.

The PjBL model oriented toward green analytical chemistry with virtual laboratories (PjBL-GACVL) has been shown to effectively guide students in planning and implementing contextual titrimetry projects while encouraging higher-order thinking skills (HOTS) as a scientific step towards achieving analytical chemistry competency (Situmorang et al., 2026). When integrated with virtual laboratories, PjBL encourages students to plan and implement mini-projects, analyze results, and develop critical thinking skills competencies that are increasingly needed in the modern era (Julianingsih & Situmorang, 2025).

Analytical chemistry learning, particularly on the topic of acid-base titration, requires both conceptual understanding and procedural precision. This topic is highly suitable for development in a virtual laboratory given the complexity of titration curves, the variety of indicators involved, and the potential hazards of physical reagents such as strong acids and bases. Lecturers have proposed various solutions to address the limitations of titration practicums, but the lack of direct student involvement results in passive and in-depth student understanding. Identification of students' conceptual understanding indicates that there are still difficulties in acid-base titration that need to be addressed through innovative learning media (Rumape et al., 2024).

Previous studies have shown that virtual laboratories can effectively support titration learning (Hauriyah et al., 2019), but few have combined a Green Chemistry orientation with PjBL in a comprehensive virtual laboratory design for this topic. The development of interactive learning media for acid-base titration is also continuing to develop to find the most effective format for students (Amry, 2024).

In the process of developing a virtual laboratory, it must be adapted to the needs of students, so that learning innovations are needed that can strengthen understanding while improving students' practical skills. The results of the needs analysis become the basis for developing a virtual laboratory that suits students' needs. Based on this description, this study aims to develop a Green Chemistry-oriented virtual laboratory for acid-base titration learning using the ADDIE model, determine a virtual laboratory standardization strategy based on BSNP eligibility criteria; evaluate the effect of the virtual laboratory on student learning outcomes, identify differences in learning outcomes between the experimental and control classes, and measure students' critical thinking skills developed through the use of the virtual laboratory.

METHOD

This study used a Research and Development (R&D) approach combined with a quasi-experimental design to evaluate the effectiveness of a Green Chemistry-oriented virtual laboratory. A quasi-experimental design was chosen because random assignment of participants to classes was not feasible in a naturalistic university setting; intact class groups served as both experimental and control groups, which is consistent with common practice in educational research conducted in real classroom contexts. The ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) was used for development, ensuring a systematic and structured approach to media creation. The experimental phase used a pretest-posttest control group design to evaluate the effectiveness of the developed virtual laboratory. The research was conducted at Universitas Negeri Medan with 71 students, divided into experimental (n=35) and control (n=36) groups. Data were collected through pre-tests, post-tests, and critical thinking skills assessment using a practicum report rubric. The ADDIE model was chosen because of its systematic approach to developing learning media and its proven effectiveness in various previous virtual laboratory development studies (Rusdi et al., 2023).

The ADDIE model is widely recognized as an effective and systematic instructional design framework that can be adapted to the digital learning context in higher education (Sari, 2017). This research was conducted at the Universitas Negeri Medan in the 2025/2026 academic year. The research subjects consisted of fourth semester students taking Analytical Chemistry course in the Chemistry Education Study Program, as well as lecturers who had taught the course. A total of 71 students participated in this study: 35 students in the experimental class (PSPK 24C) and 36 students in the control class (PSPK 24B). Class selection was carried out using a purposive sampling technique.

This research has three main stages that follow the ADDIE model flow as presented in Figure 1, namely the initial stage (Analysis) encompassing analysis of the Semester Learning Plan (RPS) to identify Course Learning Outcomes (CPMK) and Competency Achievement Indicators (IPK), as well as the analysis of the needs of virtual laboratory based learning media on acid-base titration material. The implementation stage which includes Design, Development, and Implementation, namely the design of a virtual laboratory framework that integrates the principles of PjBL and Green Chemistry, the creation of a virtual laboratory based on Canva 2D, feasibility testing, expert validation, and implementation in the experimental class through the collection of pre-test, and post-test, and the final stage (Evaluation) which is the stage of descriptive qualitative and quantitative data reduction to evaluate the effectiveness of the virtual laboratory on students' learning outcomes and critical thinking skills. The research instruments in the form of questionnaires and assessment rubrics used in the study have been validated and adapted from relevant previous research (Lara & Situmorang, 2024).

The instruments consisted of a needs analysis questionnaire, a practicum report assessment rubric, and learning outcome test questions. Learning outcomes were measured using a validated multiple-choice test administered as a pre-test and post-test. Critical thinking skills were assessed using a practicum report assessment rubric consisting of five aspects: Providing Explanations, Basic Skills, Summarizing, Further Explanations, and Organizing Strategies and Tactics. These five aspects of critical thinking align with indicators used in research on project-based chemistry learning (Situmorang et al., 2022).

Media validation was conducted by three expert validators using BSNP feasibility criteria, covering content feasibility, media design, and language readability, each rated on a scale of 1–4. Student responses were measured through a Likert scale questionnaire consisting of 20 items. This study employed two data analysis approaches: quantitative and qualitative descriptive analysis. Descriptive statistics were used to summarize validation scores, mean post-test scores, mean critical thinking skills, and percentage of student responses. Data normality was tested using the Kolmogorov-Smirnov and

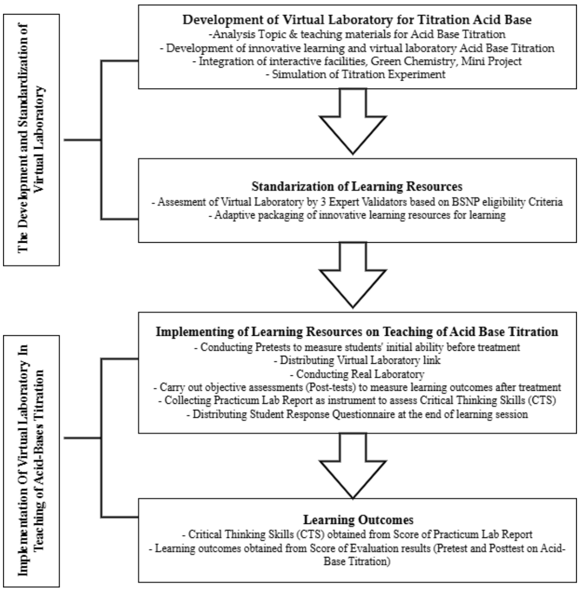

Figure 1. Development of a virtual laboratory Acid-Base Titrations

Shapiro-Wilk tests, while homogeneity was tested using the Levene test. Differences in learning outcomes between the two classes were analyzed using the Independent Samples T-Test (SPSS 26) at a significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Development of a Virtual Acid-Base Titration Laboratory

The virtual laboratory for acid-base titration was developed to support experimental learning by integrating active learning methods, including multimedia animations, instructional videos, quizzes, and simulations. The development process encompasses indicator selection, concentration determination, and titration curve analysis. A summary of the virtual laboratory learning materials is presented in Table 1.

Table 1. Description of the Acid-Base Titration Virtual Laboratory as a Teaching Tool in Acid-Base Titration Teaching

No	Sub Topic	Contents	Description	Project
1.	Virtual Acid-Base Titration Lab Focused on Green Chemistry	Introduction, Pre-Lab, Simulation	Contains information about the menus available in the virtual laboratory	Educational animations, Interactive quizzes, Hyperlinks
2.	Selecting the Right Eco-Friendly Indicators for Acid-Base Titration	Provides an explanation of how to select natural or eco-friendly indicators for acid-base titration	Through this material, students are guided in selecting the appropriate type of natural indicator so that it can be used in acid-base titration without producing waste that is harmful to the environment	Educational animations, Instructional videos, Quizzes
3.	Understanding Indicators Based on the Principles of Green Chemistry	Introductory material on natural indicators based on green chemistry	This section of the menu provides an explanation of the principles behind using natural substances as indicators according to established theory, as well as their relevance to the concept of acid-base titration.	Educational video
4.	Simulation for Analyzing Substance Concentrations and Titration Curves	Virtual acid-base titration experiment and curve plotting simulation	Students conduct a virtual titration to determine titrant volume at the equivalence point, calculate solution molarity, and correctly obtain and interpret acid-base titration curves	Questions

Learning Activities Using the Acid-Base Titration Virtual Laboratory

Learning activities using a virtual laboratory of acid-base titration were carried out at Universitas Negeri Medan in the 2025/2026 academic year using a two-dimensional virtual laboratory application as a preparation medium before students carried out direct practicums in real laboratories. In this activity, each group collaborated to simulate acid-base titration experiments starting from reading instructions together, operating the virtual laboratory according to instructions, to observing the results obtained, so that when students proceed to the real laboratory they have been equipped with adequate procedural understanding which is expected to increase the efficiency of implement-ing real practicums and significantly improve student learning outcomes, with the complete stages of experimental class activities presented in Table 2.

Table 2. Learning Activities in the Experimental Class

No	Stage	Activity
1.	Pre-Implementation Phase of the Virtual Laboratory	(1) Administer the pre-test (2) Students receive the virtual lab link via WhatsApp (3) Divide students into study groups
2.	Conducting Virtual Laboratory Activities	(1) Students open the virtual lab link (2) Students review the provided materials (3) Students take the quiz available in the app (4) Students conduct an interactive acid-base titration simulation
3.	Conducting In Person Laboratory Activities (Real Laboratory)	(1) Students conduct acid-base titration experiments in person in the laboratory (2) Students apply the procedural knowledge they have gained from the virtual laboratory (3) Students observe and record the results of the experiment
4.	Post-Practicum Phase	(1) Administer the post-test (2) Prepare a practicum report

Standardization of the Virtual Laboratory

The standardization of the acid-base titration virtual laboratory was carried out referring to the eligibility criteria set by the National Education Standards Agency (BSNP), by involving three expert lecturers from Universitas Negeri Medan as validators. The results of the standardization test of the eligibility assessment by three respondents, after statistical analysis, can be seen in Table 3. The expert validators strongly approved the quality of the acid-base titration virtual laboratory with an average overall score of 3.30 ± 0.151, which is included in the "Very Feasible" category, so that the developed media is declared feasible to be implemented as an acid-base titration learning medium.

Table 3. Results of the Virtual Laboratory Feasibility Test

Eligibility Standards	Respondents (M ± Sdv)
Content Quality Standards	3,50 ± 0,170
Presentation Quality Standards	3,29 ± 0,140
Language Quality Standards	3,14 ± 0,140
Electronic Media Quality Standards (Graphics)	3,25 ± 0,173
Average Media Quality Score	**3,30 ± 0,151**

Student Learning Outcomes

A Green Chemistry-oriented acid-base titration virtual laboratory was implemented in the experimental class, while the control class received conventional learning as a comparison. The effect of the virtual laboratory on improving learning outcomes can be seen from student achievement in the pre-test, post-test, and critical thinking skills assessment. Learning outcome data from both classes are summarized in Table 4.

Table 4. Description of Student Learning Outcomes in the Application of a Virtual Laboratory for Teaching Acid-Base Titration

No		Learning Outcomes, Score (M ± Sdv)	
		Experiment Class	Control Class
1	Pre-test	30 ± 6,109	31,8 ± 5,26
2	Post-test	83,31 ± 5.561	72,36 ± 4,43
3	**N-Gain**	**0.76 (High)**	**0.59 (Medium)**

The pre-test results showed that the initial achievement of the experimental class (M=29.97 ± 6.11) and the control class (M=31.08±5.26) was not significantly different, which proves that both classes had equivalent initial abilities before the treatment was given. During the learning process, the experimental class used a Green Chemistry-oriented virtual laboratory, while the control class underwent conventional learning. The posttest results showed that student achievement in the experimental class (M=83.31 ± 5.561) was higher than that of the control class (M=72.36 ± 4.43). Both classes had normal data distribution (Shapiro-Wilk, $p>0.05$) and homogeneous variance

(Levene's test, $p=0.122$). The Independent Samples T-Test produced a 2-tailed significance value of 0.000 ($p<0.05$), which indicated a statistically significant difference in learning outcomes between the two classes. The effectiveness of both classes was further evaluated using normalized gain (NG). The experimental class achieved NG = 0.76, categorized as high effectiveness, while the control class achieved NG = 0.59, categorized as medium effectiveness. This result confirms that the Green Chemistry-oriented virtual laboratory with PjBL integration is significantly more effective in improving student learning outcomes than conventional learning. The complete learning outcome data including N-Gain values are presented in Table 4. It was concluded that the virtual laboratory was very effective in improving student learning outcomes in acid-base titration learning.

The results of this study prove that a Green Chemistry-oriented virtual laboratory with PjBL integration is more effective in improving student learning outcomes compared to conventional learning. This improvement is related to the interactive simulation feature that allows students to dynamically visualize titration curves, the PjBL structure that encourages active problem-solving, and the Green Chemistry context that connects academic learning with real-world environmental issues. The use of virtual laboratories in chemistry learning provides students with a lasting learning experience due to active involvement in virtual experimental simulations, and is a good strategy for improving learning outcomes.

These findings are in line with Situmorang et al. (2026), who reported that the PjBL-GACVL model (Project-Based Learning oriented toward Green Analytical Chemistry with Virtual Laboratories) produced significantly higher posttest scores in the experimental group ($M=84.35 \pm 5.67$) compared to the control group ($M=69.05 \pm 10.75$), with a normalized gain of NG=0.79 versus NG=0.59 for direct instruction, confirming the effectiveness of combining PjBL with green chemistry principles and virtual laboratories for improving analytical chemistry learning outcomes. Furthermore, Situmorang et al.,(2026) demonstrated that higher order thinking skills (HOTS) achievement was strongly and positively correlated with improved learning outcomes ($R^2=0.8523$), suggesting that virtual laboratory-integrated active learning models consistently promote both thinking skills and knowledge mastery in chemistry education.

This finding strengthens evidence from (Hauriyah et al., 2019) which shows that the use of virtual laboratories in acid-base titration practicums significantly improves students' laboratory skills. In line with this, Lara & Situmorang (2024) reported that the implementation of an innovative web-based virtual laboratory for acid-base titration resulted in post-test scores for the experimental class ($M=83.00 \pm 4.95$) that were significantly higher than those for the control class ($M=65.40 \pm 7.02$), with a t-count of 10.244 > t-critical of 1.677 a pattern highly consistent with the findings of this study. Furthermore, the low understanding of titration concepts in conventional learning (Rumape et al., 2024) further underscores the need for media innovations such as those developed in this study. Virtual laboratories are highly appropriate for implementation in chemistry learning that demands simultaneous improvement of skills and knowledge. This conclusion is grounded in several established learning theories.

Constructivist learning theory emphasizes that knowledge is actively constructed through hands-on engagement, inquiry, and problem-solving. Virtual laboratories align with this principle by enabling students to directly interact with simulated experimental environment, encouraging active participation and deeper conceptual understanding. Furthermore, experiential learning theory highlights the importance of concrete experience and reflective observation in knowledge formation virtual laboratories operationalize this by providing iterative simulation activities that support reflection and bridge the gap between theory and practice. Cognitive load theory further supports the use of virtual laboratories by noting that well-designed digital simulations manage unnecessary cognitive demands, freeing up cognitive capacity for meaningful learning (Bazie et al., 2024). The simultaneous improvement in practical skills and declarative knowledge observed in this study is therefore theoretically consistent with these frameworks.

Comparable findings have been reported in various previous studies. Kolil & Achuthan (2024) demonstrated that virtual laboratories in chemistry education significantly enhanced both laboratory consciouness and practical skills among university student, emphasizing that digital simulation environments promotes intrinsic motivation and procedural competence simultaneously. Similarly, a meta-analysis by Castro (2025) confirmed that chemistry virtual laboratories produced significant academic achievement gains at the secondary and tertiary levels, with particularly pronounced effects when the virtual modality is combined with active learning strategies. Reyes et al. (2024) further documented that virtual laboratories enhanced experiential science learning by strengthening both conceptual knowledge and science process skills when implementation was supported by structured scaffolding. Collectively, these findings reinforce that the effectiveness of virtual laboratories in this study is not an isolated result but reflects a robust and theoretically coherent pattern documented across diverse educational contexts.

Critical Thinking Skills

Students' critical thinking skills were assessed using acid-base titration practicum reports carried out through a combination of virtual and face-to-face laboratories, covering five assessment aspects, namely providing simple explanations, basic skills, concluding, providing further explanations, and developing strategies and tactics. Based on Table 5, the average overall score of students' critical thinking skills was 88.29 ± 4.82, which indicates that the application of virtual laboratories in acid-base titration learning effectively supports the development of students' critical thinking skills at a high level.

Table 5. Students' Critical Thinking Skills After Implementing Instruction Using a Virtual Laboratory for Acid-Base Titration

No	Critical Thinking Skills	Description of Critical Thinking Skills	Score
1	Providing Simple Explanations	Be able to clearly formulate scientific problems and questions and provide preliminary explanations based on the concept of acid-base titration in a logical, coherent, and systematic manner in a report.	86,43 ± 16,43
2	Basic Skills	Be able to present data, calculations, and data processing related to acid-base titration in a comprehensive, accurate, and report-writing guideline-compliant manner, free of conceptual errors.	86,43 ± 14,02
3	Summarizing	Be able to interpret the results of data analysis and draw conclusions that are accurate, logical, and fully aligned with the objectives of the laboratory exercise.	88,57 ± 15,27
4	Further Explanations	Be able to formulate hypotheses or further explanations based on the results of data analysis in a logical manner, supported by relevant theories and the principles of green chemistry.	87,86 ± 15,31
5	Developing Strategies and Tactics	The report is organized in a systematic and coherent manner; all sections are logically interconnected; references are strategically used to support the arguments; and the line of reasoning from the problem to the conclusion is very clear.	90,71 ± 12,26
		Average	**88,29 ± 4,82**

Student Responses to the Virtual Acid-Base Titration Laboratory

Student responses to the Green Chemistry-oriented acid-base titration virtual laboratory yielded an overall score of 82.89%, categorized as "Good." Student responses focused on several assessment aspects. The highest-rated items related to the quality of the virtual laboratory's visual design and animation (87.1%), ease of use (87.1%), and the application's effectiveness in supporting independent learning (85.7%). The lowest-rated item was the clarity of language in certain sections (78.5%), which was also noted by the validators and addressed in the final product revision.

Positive student responses confirmed that the Canva-based virtual laboratory was highly engaging and a novel approach that motivated students to learn optimally. The Canva-based delivery format was easily accessible and engaging for students already familiar with digital platforms. The mini project assignments were very well received, with 80.0% of students providing positive feedback, indicating that the PjBL assignments enhanced the relevance and meaningfulness of the learning experience. The use of virtual laboratories in chemistry learning is highly beneficial because students can learn at any time according to their convenience without the constraints of a physical classroom or laboratory.

This aligns with the findings of (Kumar et al., 2021), found that virtual laboratories as an interactive e-learning resource received a positive response from students due to their flexible accessibility and ease of use, as well as their support for independent learning that is not limited by time and place. Transformation in chemistry education through innovations such as this is an inevitable necessity in the 21st century. A needs analysis conducted byJulianingsih & Situmorang (2025) also confirmed that chemistry students showed high approval of the development of virtual laboratories (75.17%), particularly regarding the visualization and simulation aspects (85%), confirming that the virtual laboratory-based learning format aligns with the needs and expectations of science students in higher education. Furthermore, remote and virtual laboratories have been shown to increase student engagement and support active learning pedagogy when implemented in higher education contexts (Simatupang et al., 2025).

This positive reception can be understood through the lens of constructivist learning theory, which states that students achieve deeper understanding when they actively engage with meaningful, problem-based tasks rather than passively receiving information (Situmorang et al., 2022). The PjBL mini project assignments embedded in virtual laboratories provided this type of active, student-centered engagement, explaining the strong positive response rate of 80.0%. These findings are further corroborated by Bazie et al. (2024), who conducted a quasi-experimental study of undergraduate chemistry students and showed that the implementation of virtual laboratories was positively received by students and significantly improved their academic performance compared to conventional methods.

Similarly, a meta-analysis by Castro (2025) that synthesized results from multiple studies confirmed that virtual laboratory-based learning consistently produces positive responses and outcomes from students across various science disciplines, with student motivation and engagement identified as key mediating factors. The high acceptance of virtual laboratories in this study is also consistent with the findings of Sison et al. (2024), who reported high levels of student acceptance for virtual laboratory applications across a variety of science disciplines in higher education. Collectively, these theoretical and empirical alignment confirms that the positive student responses observed in this study are not isolated outcomes, but rather reflect a broader, well-established pattern, virtual laboratories that integrate active learning strategies, real-world relevance, and accessible digital platforms consistently receive strong student support and foster meaningful learning in 21st-century chemistry education.

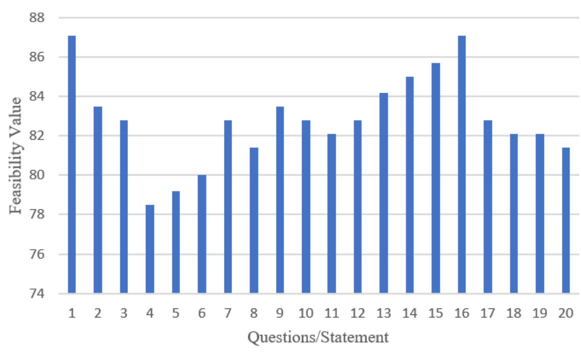

Figure 2. Graph of Student Responses to Acid Base Titration Virtual Laboratories

CONCLUSION

This research successfully developed and implemented a Green Chemistry-oriented virtual laboratory integrated with Project-Based Learning for acid-base titration learning in higher education. The development process followed the ADDIE model and resulted in a two-dimensional Canva-based application that has been validated by experts and declared suitable for use as a learning medium. The implementation of this virtual laboratory significantly improved student learning outcomes, with the experimental class outperforming the control class, while students' critical thinking skills also developed through structured Project-Based Learning (PjBL) activities within the virtual laboratory. Consistently positive student responses further confirm that this learning medium is not only effective and engaging, but also environmentally friendly, reflecting the core principles of Green Chemistry. These findings overall demonstrate that the integration of virtual laboratory technology with active learning approaches such as Project-Based Learning (PjBL) offers a meaningful and innovative solution to the challenges of laboratory-based chemistry learning in higher education. Future research is recommended to explore the application and further development of this model to other analytical chemistry topics, such as potentiometric and complexometric titrations, to broaden its applicability and strengthen the empirical foundation of virtual laboratory-based learning in chemistry education.

RECOMMENDATION

Future research should expand the scope of the virtual laboratory to include other analytical chemistry topics, such as potentiometric titration and complexometry, to broaden its applicability across analytical chemistry curricula. Furthermore, increasing the number of expert validators and incorporating peer review from chemistry faculty at other universities would strengthen the generalizability and robustness of the findings beyond a single institutional context. Furthermore, developing a fully interactive web application with automated feedback features could further enhance the learning experience by providing real-time, personalized guidance to students during their simulation activities.

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