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Development of Green Chemistry Oriented Virtual Laboratory with Project to Improve Redox Titration Learning Outcomes

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Abstract: Development of a Green Chemistry-Oriented Virtual Laboratory with Projects to Improve Redox Titration Learning Outcomes. This study aims to develop a green chemistry-oriented virtual laboratory integrated with Project-Based Learning (PjBL) and evaluate its effectiveness in improving student learning outcomes in redox titration. This study used a Research and Development (R&D) approach with the ADDIE model and a quasi-experimental two-group pre-test-post-test design. The sample consisted of 72 Chemistry Education students at Medan State University who were divided into experimental and control classes. Expert validation categorized the media as highly feasible with an average BSNP score of 3.42 across all aspects of content, language, presentation, and graphics. The experimental class achieved significantly higher post-test scores than the control class, and the Wilcoxon Signed Rank Test confirmed a statistically significant improvement in learning outcomes in the experimental class ($p = 0.000$), indicating that the use of the virtual laboratory significantly improved students' understanding of the redox titration concept. Furthermore, the experimental class obtained a higher N-Gain score (0.61) compared to the control class (0.49), and an independent sample t-test revealed a significant difference in learning effectiveness between the two groups ($p = 0.003$). These findings indicate that the green chemistry-oriented virtual laboratory integrated with project-based activities is effective in improving students' understanding and learning outcomes in redox titration.

Keywords: green chemistry; learning outcomes; project-based learning; redox titration; virtual laboratory.

Abstrak: *Pengembangan Laboratorium Virtual Berorientasi Kimia Hijau dengan Proyek untuk Meningkatkan Hasil Belajar Titrasi Redoks. Studi ini bertujuan untuk mengembangkan laboratorium virtual berorientasi kimia hijau yang terintegrasi dengan Pembelajaran Berbasis Proyek (PjBL) dan mengevaluasi efektivitasnya dalam meningkatkan hasil belajar mahasiswa dalam titrasi redoks. Studi ini menggunakan pendekatan Penelitian dan Pengembangan (R&D) dengan model ADDIE dan desain pra-uji-pasca-uji dua kelompok kuasi-eksperimental. Sampel terdiri dari 72 mahasiswa Pendidikan Kimia di Universitas Negeri Medan yang dibagi menjadi kelas eksperimen dan kontrol. Validasi ahli mengkategorikan media tersebut sebagai sangat layak dengan skor BSNP rata-rata 3,42 di semua aspek konten, bahasa, presentasi, dan grafik. Kelas eksperimen mencapai skor pasca-uji yang secara signifikan lebih tinggi daripada kelas kontrol, dan Uji Peringkat Bertanda Wilcoxon mengkonfirmasi peningkatan hasil belajar yang signifikan secara statistik dalam kelas eksperimen (p = 0,000), menunjukkan bahwa penggunaan laboratorium virtual secara bermakna meningkatkan pemahaman mahasiswa tentang konsep titrasi redoks. Selanjutnya, kelas eksperimen memperoleh skor N-Gain yang lebih tinggi (0,61) dibandingkan dengan kelas kontrol (0,49), dan uji t sampel independen mengungkapkan perbedaan signifikan dalam efektivitas pembelajaran antara kedua kelompok (p = 0,003). Temuan ini menunjukkan bahwa laboratorium virtual berorientasi kimia hijau yang terintegrasi* *dengan aktivitas berbasis proyek efektif dalam meningkatkan pemahaman dan hasil belajar siswa dalam titrasi redoks.*

Kata kunci: *Kimia hijau; hasil pembelajaran; pembelajaran berbasis proyek; titrasi redoks; laboratorium virtual.*

INTRODUCTION

Analytical chemistry is a branch of chemistry that plays a crucial role in determining the qualitative and quantitative composition of substances and supports various sectors, such as industry, health, the environment, and scientific research (Mustapa & Si, 2025). In higher education, analytical chemistry plays a strategic role in developing students' scientific competencies because it emphasizes not only theoretical understanding but also laboratory skills, data analysis, and the interpretation of experimental results (Mutiah, 2021). Furthermore, the study of analytical chemistry contributes to developing students' critical thinking skills the ability to analyze, evaluate, and draw conclusions based on valid scientific evidence (Reni Andriani & Zulkarnain Gazali, 2024).

Despite its importance, students often encounter significant difficulties in learning analytical chemistry, particularly when laboratory practice is not incorporated into instruction. The absence of hands-on experience tends to impede the development of both conceptual knowledge and practical skills in the analytical field. Such difficulties are frequently rooted in unsystematic teaching approaches that hinder students' comprehension of core analytical concepts. Moreover, when subject matter is not presented in a contextual and meaningful way, students are more likely to develop inaccurate chemical understandings. These misconceptions, in turn, further compound the challenges inherent in learning analytical chemistry (Batubara & Situmorang, 2025)

However, the teaching of analytical chemistry, particularly regarding redox titration, still faces various challenges. Redox titration is considered a difficult topic because it is abstract and requires an understanding of various levels of chemical representation namely, macroscopic, microscopic, and symbolic (Salame et al., 2022). In practice, many students tend to memorize procedures without understanding basic concepts such as electron transfer mechanisms and oxidation-reduction processes, resulting in a procedural and superficial understanding. Furthermore, the implementation of conventional laboratory experiments is often hindered by limitations in facilities, time, and safety risks due to the use of hazardous chemicals such as potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$) (Susanti et al., 2025; Wahyuningsih et al., 2018).

A needs analysis of students enrolled in analytical chemistry courses clearly showed that 90% were eager to learn redox titration and actively sought out additional learning materials. However, they still faced several challenges during laboratory sessions, including insufficient laboratory time, lack of supplies and equipment, suboptimal laboratory instructions, and the use of toxic materials. Furthermore, they had limited experience with virtual laboratories and had not effectively utilized technology-based learning resources. Because Green Chemistry-based virtual laboratories were perceived to enhance conceptual understanding, improve safety, and strengthen environmental awareness, all students expressed a need for more interactive alternative learning materials, particularly virtual laboratories.

Laboratory activities are essential in chemistry education, as they allow students to actively interact with scientific concepts through hands-on experimentation and direct observation (Bretz, 2019). Students may test, examine, and assess chemical phenomena through laboratory activity, which promotes deeper conceptual comprehension and the growth of higher-order cognitive abilities (Wiratma & Subagia, 2014). However, laboratory environments also present inherent risks related to hazardous substances, improper use of equipment, and inadequate management practices, which may threaten the safety and health of students if not properly addressed. Previous studies have shown that laboratory accidents are often unintentional and largely caused by human factors, particularly unsafe behavior and limited safety awareness (Lasia et al., 2014). The majority of occupational accidents are linked to risky behavior and human mistake, according to reports from the National Safety Council (2011). These results emphasize how crucial it is to incorporate occupational safety and health awareness into laboratory-based learning, particularly for students who are still honing their basic laboratory abilities. (Saraswati et al., 2026).

In this context, the implementation of sustainable analytical chemistry practices is becoming increasingly important to support safe, healthy, and efficient laboratory operations. Students may learn how to practice chemistry in a more ecologically responsible way by including green chemistry concepts into the curriculum, such as reducing the use of hazardous materials, minimizing waste, and improving energy efficiency (Situmorang et al., 2026). Furthermore, This approach can also promote active student participation while enhancing critical thinking skills, ultimately leading to a more profound understanding of chemical processes. The application of green chemistry in education also contributes to creating a safer and more comfortable learning environment, both in the classroom and in the laboratory (Situmorang et al., 2026). Therefore, the concepts and skills of green chemistry need to be consciously incorporated into educational activities, particularly regarding the handling of chemicals and the operation of laboratory equipment that carry potential hazards. Chemistry laboratories, as learning facilities, must be managed optimally to prevent potential workplace accidents while supporting operational cost efficiency through the use of safer and more sustainable materials.

Various studies have been conducted to address challenges in teaching analytical chemistry through instructional innovations. The integration of technology into chemistry education, particularly through digital media, has been shown to enhance efficiency and interactivity in laboratory activities (Nainggolan et al., 2020). By involving students in projects based on real-world issues, the Project-Based Learning (PjBL) paradigm has been widely used to increase student engagement, develop critical thinking skills, and enhance learning results (Puspita Sari et al., 2020). Research conducted by (Pakpahan et al., 2021)demonstrated that the implementation of the Project-Based Learning (PjBL) model in chemistry practicum activities was effective in improving students' learning outcomes and analytical skills. Along with the advancement of digital technology, the use of virtual laboratories as supportive learning media has continued to develop. Virtual laboratories enable students to simulate practicum activities through realistic visualizations without requiring direct use of chemicals or laboratory equipment. Their implementation in chemistry learning has also been shown to positively influence student engagement and learning outcomes. Furthermore, virtual laboratories have been developed as an alternative to address the limitations of conventional laboratories by providing realistic experimental simulations, consequently improving pupils' willingness to study and conceptual comprehension (Dwiningsih et al., 2018).

As a student-centered instructional approach, PjBL promotes active participation through collaborative work and problem-solving, enabling students to develop a deeper understanding of core subject matter. Within this framework, students are guided through the completion of a defined project or task, which trains them to identify problems, conduct investigations, gather and interpret data, and critically evaluate findings throughout the learning process all of which are directly relevant to the competencies expected in analytical chemistry learning (Fadillah & Sutiani, 2025)

Despite the fact that several studies have looked at project-based learning, virtual laboratories, and green chemistry concepts in chemistry education, most still treat these approaches separately and have not yet conceptually integrated them into a cohesive instructional design. This situation results in instruction that tends to emphasize only one aspect whether the use of technology, the development of higher-order thinking skills, or environmental sustainability awareness without optimizing the interconnections among all three.

Studies specifically integrating green chemistry-based virtual laboratories with mini-project activities in redox titration learning are still scarce, as most existing virtual laboratories only focus on procedural simulations or conceptual visualizations without simultaneously embedding green chemistry principles and project-based problem-solving. To address this gap, the virtual laboratory developed in this study combines three distinguishing features: applying green chemistry principles through the use of safer reagents in smaller quantities; integrating mini-project activities that engage students in contextual problem-solving beyond simulation; and serving as a pre-laboratory medium that allows students to practice experimental procedures independently before the actual lab work, thereby improving conceptual readiness, reducing errors, and promoting safer and more environmentally responsible laboratory practices.

In the context of teaching complex and potentially hazardous redox titrations, the need for an approach capable of addressing all three of these aspects has become increasingly relevant. The integration of virtual laboratories which enable safe and flexible experimental simulations with a Project-Based Learning approach that encourages students' active engagement in problem-solving, and the application of green chemistry principles that emphasize safety and sustainability, has the capacity to produce a more thorough educational experience. This approach not only promotes a more in-depth understanding of concepts but also enhances critical thinking abilities and fosters awareness of responsible practices in chemistry.

The novelty of this study lies in the integration of three instructional dimensions simultaneously: (1) green chemistry principles through the use of safer reagents in smaller quantities, (2) project-based mini-project activities that encourage contextual problem solving, and (3) the use of a virtual laboratory as a pre-laboratory learning medium that enables students to practice procedures independently before real practicum activities. This integrated approach is expected to improve conceptual readiness, reduce procedural errors, and promote safer and more environmentally responsible laboratory practices in redox titration learning.

Based on this background, the research question of this study is: How can a Green Chemistry-based virtual laboratory integrated with project activities be developed and implemented in redox titration learning? How effective is the developed virtual laboratory in improving students' learning outcomes?

METHOD

Research Design

The ADDIE paradigm, which has five stages; analysis, design, development, implementation, and evaluation is used in this study's research and development (R&D) methodology (Fadhilah et al., 2025). In the Analysis stage, learning needs and existing challenges are identified. The Design stage involves planning the instructional framework, content structure, and media features. The Development stage encompasses the actual creation and expert validation of the learning media. The Implementation stage involves deploying the media in real learning settings, and the Evaluation stage assesses the effectiveness of the developed product. This particular model was used to systematically develop a green chemistry-based virtual laboratory integrated with Project-Based Learning for redox titration material.

This study also used a quasi-experimental methodology using a two-group pretest–posttest design to evaluate the efficacy of the created product. In the design, students' abilities were measured before (pretest) and after (posttest) learning. While the control group employed traditional teaching techniques, the experimental group was instructed utilizing the created project-based virtual laboratory. Table 1 displays the design of the methodology employed in this investigation.

Table 1. Research Design of Learning Outcomes

Class	Pretest	Treatment	Posttest
Control	Q_1	X	Q_2
Experimental	Q_1	Y	Q_2

Notes :
Q1 = Pretest (Before being treated)
Q2= Posttest (After treatment)
X = Classes that are not given lab virtual development
Y = Classes given virtual lab development

Population and Sample

All students enrolled in Medan State University's Chemistry Education Study Program, class of 2024, encompassing five classes, made up the study's population. The sample included 72 students from two classes who were enrolled in the Qualitative and Quantitative Analytical Chemistry course in the fourth semester of the 2025/2026 academic year. A random sampling strategy was used to choose the sample from a somewhat homogeneous population. Two classes were randomly assigned as the experimental and control groups. While the control group used traditional teaching resources supplied by the institution, the experimental group was instructed utilizing a virtual laboratory focused on green chemistry that was combined with project-based learning.

Research Procedures

The research procedure followed the ADDIE model, consisting of Analysis, Design, Development, Implementation, and Evaluation stages. The analytical phase entailed identifying learning difficulties in redox titration through literature review and student questionnaires, including limitations in laboratory facilities and the need for innovative and environmentally friendly media. In the design stage, the learning flow, content structure, virtual experiment scenarios, and user-friendly interface were developed, along with the integration of Project-Based Learning through mini-project planning. The development stage focused on creating a green chemistry-oriented virtual laboratory equipped with project-based activities, such as determining vitamin C concentration, which was complemented by experimental procedures, data analysis guidelines, and reflection activities. The product was then validated by experts based on content, presentation, language, and graphical aspects and revised accordingly. In the implementation stage, the media was applied over three weeks using a pretest–posttest design to measure students' learning outcomes. During the first week, both the experimental and control groups completed the pretest to assess students' initial understanding of redox titration concepts. In the second week, the experimental group used the developed Green Chemistry-based virtual laboratory integrated with mini-project activities, while the control group received instruction using conventional learning resources provided by the university. In the third week, both groups conducted real laboratory practicum activities on redox titration, followed by the administration of the posttest to evaluate students' learning outcomes after the intervention. Lastly, by comparing the increases in learning outcomes between the two groups, the assessment stage evaluated the media's efficacy.

Data collection techniques

The instrument test consists of 10 multiple-choice questions that have been validated to measure student learning outcomes. The instrument was developed based on competency indicators related to redox titration and iodometric analysis, including: (1) identifying oxidizing and reducing agents in redox reactions, (2) analyzing changes in oxidation numbers and electron transfer processes, (3) applying stoichiometric principles in iodometric titration calculations, (4) determining concentrations and substance content based on titration data, (5) interpreting quantitative experimental data in redox titration, and (6) evaluating factors affecting the accuracy of titration results and potential experimental errors. The test items covered cognitive levels ranging from C3 (applying), C4 (analyzing), to C5 (evaluating). The instrument was validated prior to implementation to ensure its suitability for measuring students' learning outcomes. Validation data and test instrument analysis were processed using Microsoft Excel, while hypothesis testing was conducted using SPSS version 26 for Windows.

A student response questionnaire and an expert validation sheet were the non-test tools employed in this investigation. The green chemistry-based virtual laboratory's applicability was evaluated using the validation sheet in accordance with BSNP criteria, which address elements of content, presentation, language, and visuals. Subject matter specialists and media professionals carried out the evaluation to ascertain the generated product's quality. Students' opinions of the usage of virtual labs in redox titration instruction were also ascertained using the student response questionnaire.

Data analysis techniques

The research data were analyzed using inferential statistical techniques with the aid of IBM SPSS Statistics version 26 for Windows. Before hypothesis testing, prerequisite tests namely the normality test and the homogeneity test—were conducted. The normality test was performed using the Shapiro–Wilk test to determine whether the research data were normally distributed, given that this test is appropriate for relatively small sample sizes. The data were considered normally distributed if the significance value (Sig.) was > 0.05. Next, a homogeneity test was performed using Levene's Test to determine the equality of variances across groups. The data were considered homogeneous if the significance value (Sig.) was > 0.05.

The choice of hypothesis testing technique was tailored to the characteristics of the data distribution. If the data met the assumptions of parametric statistics, the Independent Samples t-test was used to compare student learning outcomes between the experimental and control classes. However, if the data did not meet the assumptions of a normal distribution, a nonparametric statistical approach was used. In this study, the Wilcoxon Signed-Rank Test was used to analyze the differences in pretest and posttest scores within each group because this test is appropriate for paired data that do not meet parametric assumptions, particularly the assumption of normality. Meanwhile, the comparison of learning outcomes between the experimental and control classes was analyzed using the Independent Samples Test. The basis for decision-making in hypothesis testing was based on the significance value (Sig.), namely, if Sig < 0.05, the null hypothesis (H_0) was rejected and the alternative hypothesis (H_1) was accepted.

▪ RESULT AND DISCUSSION

Result

Analysis

The preliminary needs analysis, performed by literature study and questionnaires to students and lecturers, shown that many students have trouble grasping the basic ideas of redox titration, especially abstract aspects like oxidation–reduction processes, electron transfer and their relation to calculations. As a result, students tend to memorize procedures rather than develop a conceptual understanding. The same difficulties were faced in the practicum activities where the students failed to follow the procedures and relate them to theoretical concepts. Limited laboratory experience, problems using the practicum guides, and the potential dangers of using chemicals make effective learning difficult. Moreover, the use of technology in learning is still not optimal, most students have never experienced virtual laboratories, despite their urgent need for more engaging, adaptable, and secure educational materials. These findings suggest the need for an instructional innovation to enhance student involvement and overcome practical learning's shortcomings. A solution is proposed, being the integration of Project-Based Learning with a virtual laboratory based on green chemistry, allowing students to conduct preliminary simulations, better understand experimental procedures and concepts, and improve learning outcomes, in a safer and more meaningful learning environment.

Design

The design phase consisted of the selection and arrangement of instructional materials relevant to redox titration for use in the developed media. At this stage, the media was designed by the researcher and prepared the supporting components such as learning materials, practice questions, instructional videos, visual elements, and project-based assignments. The development of the virtual laboratory based on green chemistry was in accordance with the curriculum used in the learning process, namely the independent curriculum with a block system. Content has been carefully adapted to the scope and learning outcomes of the course.

Development

The project-based virtual laboratory on redox titration was developed using Canva Premium by leveraging the integrated features such as visual elements and animation tools to produce interactive learning media. It provides direct access without the need for additional programming or other link generating applications. It is also cross-platform and runs on web, desktop and mobile devices. The virtual laboratory developed has several main components, namely an introductory interface and a main menu with structured learning instruction, concept maps, materials, instructional videos, simulations, evaluations and information about the developers. This design promotes a flexible and independent learning, where students are able to review the material as many times as necessary to achieve better understanding and meet the expected competencies.

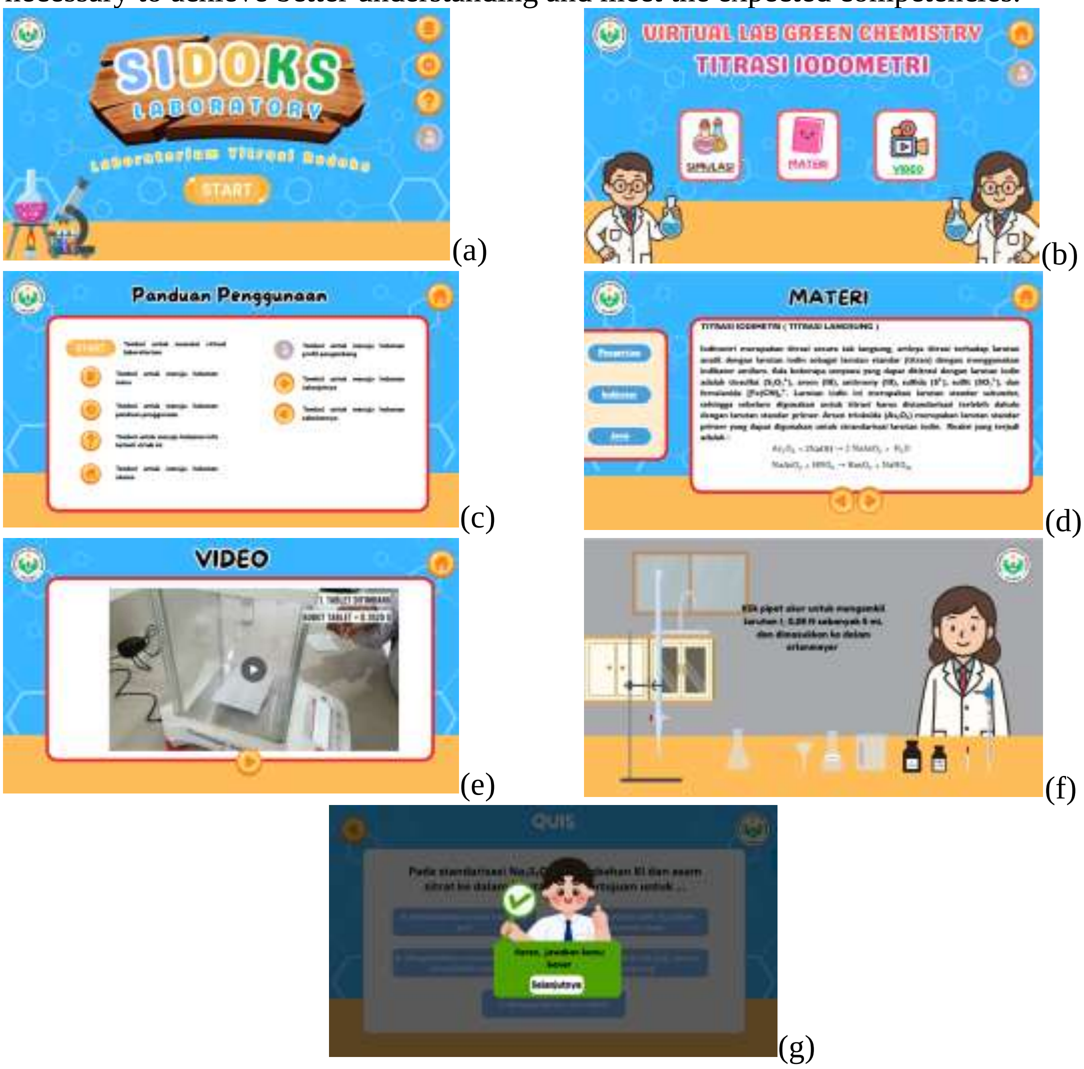

Figure 1. The view of virtual laboratory of redox titration with project: (a) Initial view of the virtual laboratory, (b) Menu display from virtual laboratory, (c) User guide, (d) Material of virtual laboratory, (e) Video, (f) Simulation of redox titration experiment, (g) Quizzez

To maintain quality, the developed media were validated by three expert validators from chemistry lecturers at Medan State University. The results of the evaluation were accompanied by constructive feedback which became a basis for revising and improving the virtual laboratory according to the recommendations of experts.

Table 2. Summary of validation results

No	Aspects	Validator Response	Information
1	Content Eligibility	3,36	Highly Feasible
2	Language Eligibility	3,40	Highly Feasible
3	Presentation Eligibility	3,46	Highly Feasible
4	Graphical Eligibility	3,46	Highly Feasible
	Average	**3,42**	**Highly Feasible**

The outcome of the standardization of the virtual laboratory based on green chemistry indicate that all aspects measured met the eligibility criteria. The average BSNP score was 3.42. Content, language, presentation and graphics were rated valid with respective scores of 3.36, 3.40, 3.46 and 3.46. The findings indicate that the developed media can be utilized as a redox titration learning aid without requiring any editing.

Implementation

In the implementation phase, both experimental and control groups were administered a pretest using a validated multiple-choice instrument. The experimental group was then instructed through a project-based, green chemistry-based virtual laboratory, and the control group was instructed through a conventional method with standard teaching materials.

In the experimental class, the students first investigated the material and conducted virtual simulations before performing the actual laboratory practicum. Students were better able to comprehend experimental techniques and the underlying ideas thanks to this sequence, which offered a more participatory and repeatable learning experience. The control group's pupils received instruction in the conventional manner, without simulation in advance and thus it was difficult for them to participate and to be conceptually prepared for the laboratory work. After conducting the learning, a post-test was conducted on both classes.

Table 3. Students Learning Outcomes on Implementation Redox Titration

No	Assesment Components	Learning Outcomes M±Sdv	
		Experiment	Control
1	Pretest	47,73 ±6,85	30,00±11,18
2	Posttest	79,55±5,75	64,55±13,94
3	N-Gain	0,61	0,49

As shown in Table 3, the experimental class outperformed the control class., the experimental class performs better. The control group's average pretest score was 30.00±11.18 and the experimental class was 47.73±6.85. In the posttest, the control class averaged 64.55±13.94, still lower than the experimental class which averaged 79.55±5.75

Evaluation

The effect of implementing Green Chemistry Oriented Virtual Laboratory with project on improving student learning outcomes in Redox Titration teaching.

The hypothesis test was conducted to examine The impact of the execution of a virtual laboratory based on green chemistry with a project on student learning outcomes with pretest and posttest data in the experimental class. Before the analysis, a normality test was performed at a significance level of 0.05 using the Shapiro-Wilk method. The result showed that the significance values of pretest and posttest were less than 0.05. It meant that the data were not normally distributed, then Wilcoxon signed rank test was carried out.

Table 4. Hypothesis Test of Pretest-Posttest Learning Outcomes Data in Experimental Class

	Pretest - Posttest
z	-4,247
Asymp.Sig. (2-tailed)	.000

With a significance threshold of 0.000 ($p < 0.05$), the Wilcoxon Signed-Rank Test findings for the pretest and posttest data revealed a Z value of -4.247. This shows that the pupils' pretest and posttest results differed statistically significantly. Therefore, the alternative hypothesis (Ha) is accepted, suggesting that the implementation of a green chemistry-based virtual laboratory with project-based activities significantly improved student learning outcomes in redox titration.

The effectiveness of Green Chemistry Oriented Virtual Laboratory when compared to traditional teaching methods, Redox Titration instruction improves student learning results.

By comparing the improvement in learning outcomes between the experimental and control groups, learning effectiveness was assessed using the N-Gain score. Despite being classified as moderate, the experimental class's N-Gain score (0.61) was greater than the control class's (0.49). Prerequisite tests were carried out before hypothesis testing. The N-Gain data for both the experimental (Sig = 0.132) and control classes (Sig = 0.352) were found to be normally distributed ($p > 0.05$) by the Shapiro-Wilk test. Nevertheless, Levene's test for homogeneity revealed that the data were not homogenous ($p < 0.05$).

An independent samples t-test with unequal variances (equal variances not assumed) was used to examine the difference in learning efficacy between the two groups since the assumption of normality was satisfied but homogeneity was not.

Table 5. Hypothesis Test of N-gain Score Data in Experimental and Control Class

Independent Sample Test	
	Sig. (2-tailed)
Equal variances not assumed	.003

The independent samples t-test (equal variances not assumed) produced a significance value of 0.003 ($p < 0.05$) based on the findings of the hypothesis test. This suggests that the experimental and control groups' learning efficacy differed statistically significantly. As a result, the alternative hypothesis (Ha) is accepted, showing that using a virtual laboratory based on green chemistry in conjunction with project-based learning improves student learning outcomes in redox titration more successfully than traditional training.

Discussion

The purpose of this study is to create and execute a virtual laboratory based on green chemistry that is connected with a redox titration project, and to assess how this will affect student learning results. The preliminary analysis's findings show that students continue to struggle to grasp the abstract fundamental ideas of redox titration, such as electron transfer and its relationship to quantitative calculations. This condition causes students to tend to memorize procedures without understanding their conceptual meaning, so that learning becomes mechanistic. This result is consistent with studies conducted by (Renvall & Kurtén, 2024) it declares that difficulties in chemistry are often caused by students' inability to connect macroscopic, submicroscopic, and symbolic representations in an integrated manner.

These problems are exacerbated by limited practical activities, both in terms of facilities, time, and the risk of using hazardous chemicals. Nevertheless, practical experience remains a crucial component in building conceptual understanding and analytical skills. In this context, the use of virtual laboratories is a relevant alternative. Virtual laboratories allow students to safely and flexibly simulate experiments and provide initial experience (pre-lab) before actual practical work. This is supported by research by (Nurfatimah, 2025) It demonstrates that the application of virtual laboratories can improve conceptual understanding and the effectiveness of science learning.

However, the use of technology alone is not enough to address learning issues comprehensively. Without the right pedagogical approach, virtual laboratories have the potential to become merely passive visual media. Therefore, in this study, virtual laboratories were integrated with a Project-Based Learning (PjBL) approach. This integration allows students to actively engage in the learning process through contextual project activities. This approach aligns with (Chang et al., 2024) who found that integrating real-world context in PjBL significantly heightened student involvement and facilitated deeper understanding, as students actively engaged with authentic problems beyond the classroom.

In terms of media development, the virtual laboratory was systematically designed through the ADDIE process, integrating materials, simulations, learning videos, and project activities into a single interactive platform. Expert verification showed that the developed media met the eligibility criteria based on BSNP standards, with an average score in the valid category.

The findings of this study demonstrated that the implementation of a Green Chemistry-based virtual laboratory integrated with project activities significantly improved students' learning outcomes in redox titration. The significant difference between pretest and posttest scores in the experimental class, as confirmed by the Wilcoxon Signed-Rank Test, indicates that students experienced meaningful conceptual improvement after the intervention. This improvement may be attributed to the opportunity for students to repeatedly explore redox titration procedures through virtual simulations before engaging in actual laboratory work. Through repeated exposure to simulations, students were able to visualize abstract redox processes, familiarize themselves with laboratory procedures, and strengthen their procedural understanding in a safe and flexible learning environment. Consequently, students entered the real practicum with greater conceptual readiness and confidence, which may explain the higher posttest achievement in the experimental class compared to the control class.

Furthermore, although both groups demonstrated improvement in learning outcomes, the experimental class achieved a higher N-Gain score (0.61) than the control class (0.49), indicating greater learning progress. This finding suggests that the integration of virtual laboratory activities with project-based learning elements provided a more meaningful learning experience than conventional instruction. Unlike the control group, which relied primarily on textbooks and conventional instruction prior to practicum, students in the experimental class had opportunities to independently rehearse experimental procedures and connect theoretical concepts with practical applications before entering the laboratory. Such experiences may have reduced procedural uncertainty and enhanced students' conceptual understanding during practical implementation.

It is important to acknowledge that the experimental and control groups demonstrated different initial abilities, as reflected in the pretest scores, where the experimental class obtained a higher average score than the control class. This difference may indicate variation in students' prior knowledge before the intervention despite the random assignment of classes. However, the effectiveness of the developed virtual laboratory was not evaluated solely based on posttest scores, but also through the N-Gain score, which measures students' relative improvement from their initial level of understanding. The higher N-Gain score obtained by the experimental group suggests that the Green Chemistry-based virtual laboratory contributed positively to students' learning progress beyond differences in their baseline competencies. Therefore, the improvement observed in the experimental class may reasonably be attributed not only to students' initial abilities but also to the instructional advantages provided by repeated virtual practice and project-based learning experiences.

Despite the positive findings, this study has several limitations. First, the difference in initial pretest scores between the experimental and control groups suggests a potential imbalance in students' prior knowledge, which may have influenced the learning outcomes despite the use of N-Gain analysis to evaluate relative improvement. Second, the implementation period was relatively short, consisting of only three weeks, which may not fully capture the long-term impact of the Green Chemistry-based virtual laboratory on students' conceptual retention and laboratory skills. Third, the study involved a limited number of participants from a single institution, which may limit the generalizability of the findings to broader educational contexts. Therefore, future studies are recommended to involve larger and more diverse samples, implement longer intervention periods, and explore the effectiveness of this virtual laboratory on other chemistry topics involving complex and hazardous experimental procedures.

These results are in line with research by (Ajayan et al., 2025), which showed that interactive simulations in science education, especially when paired with active and collaborative learning strategies, can improve students' conceptual understanding through dynamic representations that make invisible phenomena visible. Additionally, (Edgar et al., 2022) stress that using virtual simulations in conjunction with suitable educational techniques can improve student learning results, especially in the development of cognitive and emotional abilities.

Beyond its impact on learning outcomes, a key contribution of the developed virtual laboratory lies in its grounding in green chemistry principles, which represents the core novelty of this study. In conventional redox titration practicum, students are typically exposed to concentrated and hazardous oxidizing agents such as potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$), which pose significant risks to health and generate toxic laboratory waste. In the developed virtual laboratory, these substances are replaced with safer reagents at lower concentrations and in reduced quantities, directly applying the green chemistry principles of hazard reduction, waste minimization, and safer chemical use. Furthermore, the alignment between the virtual procedures and real laboratory practice ensures that when students transition to actual practicum work, they can do so using greener and more sustainable methods. This integration of sustainability into the learning process not only reduces environmental impact but also cultivates students' awareness of responsible chemical practices, a dimension that is often overlooked in technology-based chemistry learning media. In this regard, the virtual laboratory serves not merely as a digital simulation tool, but as a vehicle for embedding green chemistry values into students' scientific competencies.

Overall, the study's findings show that the gap between conceptual knowledge and laboratory practice can be closed by combining project-based learning with virtual laboratories based on green chemistry.This approach not only provides a safer and more flexible learning experience but also enhances the effectiveness of learning regarding redox titration. Thus, the use of innovative learning media combined with an appropriate learning model is a crucial element in raising the standard of chemistry instruction in higher education.

CONCLUSION

This study successfully developed a green chemistry-oriented virtual laboratory integrated with Project-Based Learning (PjBL) for redox titration material using the ADDIE model. Expert validation showed that the media met the eligibility criteria based on BSNP standards across all four aspects content, language, presentation, and graphics with an average score of 3.42, categorized as Highly Feasible.

The findings of the implementation showed that the experimental class, which made use of the created virtual laboratory, outperformed the control class, which employed traditional teaching techniques, in terms of learning outcomes. The experimental class's average posttest score (79.55 ± 5.75) was significantly higher than the control class's (64.55 ± 13.94). The Wilcoxon Signed-Rank Test confirmed a statistically significant difference between pretest and posttest scores in the experimental class ($Z = -4.247$, $p = 0.000$). Furthermore, the N-Gain score of the experimental class (0.61) was higher than that of the control class (0.49), and the independent samples t-test revealed a significant difference in learning effectiveness between the two groups ($p = 0.003$). Therefore, it can be concluded that the use of a green chemistry-based virtual laboratory integrated with project-based learning is significantly more effective in improving student learning outcomes in redox titration compared to conventional instruction.

Several suggestions are made for different stakeholders based on the study's findings. For lecturers and educators, the green chemistry-oriented virtual laboratory integrated with Project-Based Learning is recommended as an alternative instructional medium, particularly for redox titration topics that involve abstract concepts and the use of hazardous chemicals, as this approach can provide a safer, more flexible, and more interactive learning experience. To improve the findings' generalizability, future researchers are urged to extend the use of this virtual laboratory to a wider and more varied population and may also explore its integration with other learning models or examine its impact on other chemistry topics involving complex and potentially hazardous experimental work. At the institutional level, curriculum developers are advised to consider incorporating green chemistry principles and virtual laboratory technologies into analytical chemistry courses as a means of supporting sustainable, safe, and innovative chemistry education in higher education. Finally, in terms of further product development, it is recommended to conduct usability testing across a wider range of devices and platforms to ensure optimal accessibility, and to periodically update the virtual laboratory's material to reflect the most recent advancements in green chemistry and laboratory safety regulations.

REFERENCES

Ajayan, P., Cao, R., & Eichler, J. F. (2025). Promoting Conceptual Learning Using Scaffolded Activities That Incorporate Interactive Simulations. *Education Sciences*, *15*(5). Https://Doi.Org/10.3390/Educsci15050566

Batubara, A. A., & Situmorang, M. (2025). Development And Implementation Of A Virtual High Performance Liquid Chromatography (HPLC) Laboratory To Enhance Learning Outcomes In Analytical Chemistry. *Jurnal Pendidikan Dan Pembelajaran Kimia*, *14*(3), 55–72. Https://Doi.Org/10.23960/Jppkv2.1435

Bretz, S. L. (2019). Evidence For The Importance Of Laboratory Courses. In *Journal Of Chemical Education* (Vol. 96, Number 2, Pp. 193–195). American Chemical Society. Https://Doi.Org/10.1021/Acs.Jchemed.8b00874

Chang, Y., Choi, J., & Şen-Akbulut, M. (2024). Undergraduate Students' Engagement In Project-Based Learning With An Authentic Context. *Education Sciences*, *14*(2). Https://Doi.Org/10.3390/Educsci14020168

Dwiningsih, K., Sukarmin, Nf., Muchlis, Nf., & Rahma, P. T. (2018). Pengembangan Media Pembelajaran Kimia Menggunakan Media Laboratorium Virtual Berdasarkan Paradigma Pembelajaran Di Era Global. *Kwangsan: Jurnal Teknologi Pendidikan*, *6*(2), 156–176. Https://Doi.Org/10.31800/Jtp.Kw.V6n2.P156--176

Edgar, A. K., Macfarlane, S., Kiddell, E. J., Armitage, J. A., & Wood-Bradley, R. J. (2022). The Perceived Value And Impact Of Virtual Simulation-Based Education On Students' Learning: A Mixed Methods Study. *BMC Medical Education*, *22*(1). Https://Doi.Org/10.1186/S12909-022-03912-8

Fadhilah, N. F., Widya, R. D., Angriani, N., Daulay, S., Zannah, M., Bariah, K., Nurhasanah, R., & Muchtar, Z. (2025). Development Of Interactive Learning Media Based On Augmented Reality Technology With Discovery Learning Model On Hydrokarbon Materials. *Jurnal Pendidikan Dan Pembelajaran Kimia*, *14*(1), 42–49. Https://Doi.Org/10.23960/Jppk.V14.I1.32894

Fadillah, N., & Sutiani, A. (2025). Development Of An Acid-Base E-Module Based On Project-Based Learning (Pjbl) Assisted By Canva Application. *Jurnal Pendidikan Dan Pembelajaran Kimia*, *14*(1), 182–196. Https://Doi.Org/10.23960/Jppk.V14.I1.33538

Lasia, I. K., Gunamantha, I. M., & Budiada, I. K. (2014). Jwlmanager,+Januari+12+_5 (1). *Widya Laksana*, *3*(1), 44–56.

Mustapa, S., & Si, M. S. (2025). *Kimia Analitik I*.

Mutiah, M. (2021). Analisis Penerapan Problem Based Learning (PBL) Untuk Meningkatkan Pemahaman Konsep Pada Perkuliahan Kimia Analitik. *Jurnal Pijar Mipa*, *16*(3), 353–357. Https://Doi.Org/10.29303/Jpm.V16i3.2495

Nainggolan, B., Hutabarat, W., Situmorang, M., & Sitorus, M. (2020). Developing Innovative Chemistry Laboratory Workbook Integrated With Project-Based Learning And Character-Based Chemistry. *International Journal Of Instruction*, *13*(3), 895–908. Https://Doi.Org/10.29333/Iji.2020.13359a

Nurfatimah, Li. (2025). *Efektivitas Pembelajaran Berbantuan Simulasi Virtual Lab*. *5*(1), 543–555. Https://Doi.Org/10.51903/Q4eexy46

Pakpahan, D. N., Situmorang, M., Sitorus, M., & Silaban, S. (2021). *The Development Of Project-Based Innovative Learning Resources For Teaching Organic Analytical Chemistry*.

Puspita Sari, D., Sitorus, M., Situmorang, M., & Sudrajat, A. (2020). *Implementation Of Project-Based Learning Resources With Multimedia To Improve Student Learning Outcomes In Teaching Cation Analysis*.

Reni Andriani, & Zulkarnain Gazali. (2024). Pengembangan Modul Kimia Berbasis Masalah Untuk Meningkatkan Kemampuan Berpikir Kritis Pada Materi Reaksi Redoks. *Jurnal Pendidikan MIPA*, *14*(2), 455–465. Https://Doi.Org/10.37630/Jpm.V14i2.1568

Renvall, G., & Kurtén, B. (N.D.). Talking Chemistry In Small Groups: Challenges With Macroscopic, Submicroscopic And Symbolic Representations Among Students Aged 14-15 Years. In *Renvall & Kurtén FMSERA Journal* (Vol. 6, Number 2).

Salame, I. I., Etwaroo, N., Khalil, A., & Kolozian, T. (2022). Examining Some Of Students' Challenges And Use Of Algorithmic Problem-Solving Approaches In Electrochemical Titrations. *International Journal Of Instruction*, *15*(3), 465–482. Https://Doi.Org/10.29333/Iji.2022.15326a

Saraswati, R., Sudiana, I. K., & Suja, I. W. (2026). E-Book Of Risk Management In High School Chemistry Laboratories As An Effort To Enhance Occupational Safety And Health. *Hydrogen: Jurnal Kependidikan Kimia*, *14*(1), 106–113. Https://Doi.Org/10.33394/Hjkk.V14i1.19451

Situmorang, M., Bariah, K., Pardosi, I., Purwanto, R., Sitorus, M., Sutiani, A., & Simanjuntak, H. (2026). Active Learning Oriented To Green Chemistry With Virtual Laboratories To Promote Higher Order Thinking Skills To Achieve Quantitative Analytical Chemistry Competency. *Chemistry Teacher International*. Https://Doi.Org/10.1515/Cti-2025-0096

Susanti, R., Dewi Maharani, S., & Anwar, Y. (2025). *Penerapan Unsur-Unsur Difusi Inovasi Dalam Teknologi Pendidikan Berupa Virtual Lab*. Http://Jiip.Stkipyapisdompu.Ac.Id

Wahyuningsih, A. S., Multazam, M. T., Nandiyanto, A. B. D., Abdullah, A. G., & Widiaty, I. (2018). Green Chemistry Principles: An Alternative Approach To Practice Laboratory Safety And Health. *IOP Conference Series: Materials Science And Engineering*, *288*(1). Https://Doi.Org/10.1088/1757-899X/288/1/012001

Wiratma, I. G. L., & Subagia, I. W. (2014). *Pengelolaan Laboratorium Kimia Pada Sma Negeri Di Kota Singaraja: (Acuan Pengembangan Model Panduan* (Vol. 3, Number 2).