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Comparison of Vocational Students' Conceptual Understanding in Acid-Base Titration Using Virtual Lab-Based Learning and Lab-Based Learning with Chemical and Natural Indicators

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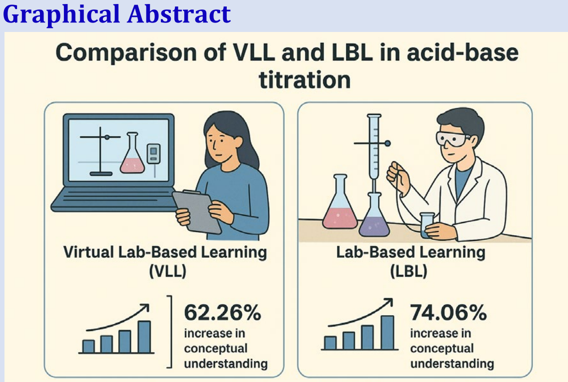
Abstract

This study compared the effectiveness of Virtual Lab-Based Learning (VLL) and Lab-Based Learning (LBL) in improving students' conceptual understanding of acid-base using chemical and natural indicators. A quantitative quasi-experimental design with a pretest-posttest control group was implemented involving 30 vocational high school students from the Industrial Chemistry program at SMK PGRI 3 Malang, divided equally into two groups. The LBL group conducted hands-on laboratory experiments, while the VLL group utilized the ChemCollective virtual simulation platform. Both groups studied the same topic with equal instruction time and guidance from the same teacher. The results indicated that both learning models significantly improved students' conceptual understanding of acid-base titration, with the LBL group achieving a higher post-test increase (74.06%) than the VLL group (62.26%). This suggests that direct laboratory practice fosters greater procedural accuracy, conceptual comprehension, and cognitive engagement. However, VLL remains a useful alternative for schools with limited laboratory access, providing an interactive means for students to visualize titration steps, color changes, and pH variations. The incorporation of natural pigments from red cabbage and hibiscus further enhanced student interest and contextual learning outcomes. Despite these promising results, the limited sample size constrains the generalization of findings, and future studies with larger, more diverse samples are recommended to validate the consistency of these results across broader educational contexts.

Graphical Abstract



Keywords:

Acid-Base Titration; Virtual Lab-Based Learning; Lab-Based Learning; Conceptual Understanding

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Introduction

Acid–base titration is a fundamental topic in analytical chemistry education at vocational high schools (SMK), requiring both conceptual understanding and practical laboratory skills such as preparing solutions, using apparatus correctly, observing color changes in indicators, and accurately recording titrant volumes. Zhang & Cheng (2022) highlighted the importance of instructional innovation in fostering meaningful learning experiences that enhance students' academic performance. Effective learning facilitates active engagement, deep conceptual comprehension, and practical application of knowledge. Lab-Based Learning (LBL) has long been implemented in teaching titration concepts as it allows students to interact directly with laboratory instruments and chemical reagents. However, its implementation is often constrained by limited equipment, materials, time, and safety considerations.

As an alternative, Virtual Lab-Based Learning (VLL) has emerged as a technology-supported approach that allows students to simulate laboratory activities in a safe and interactive environment. Putri & Kurniawati (2021) reported that VLL significantly improves students' critical thinking skills in titration, including drawing conclusions, elaborating explanations, and designing experimental strategies. Similarly, Suarni et al. (2022) found that VLL enhances high school students' performance in titration practices. Nevertheless, further investigation is required, particularly within vocational education contexts that demand the mastery of applied laboratory competencies relevant to industrial needs.

In addition to learning approaches, the success of titration is strongly influenced by the choice of indicators. While synthetic indicators such as phenolphthalein and methyl orange remain widely used, natural indicators derived from *Hibiscus rosa-sinensis L.* have been proven effective in identifying acidic and basic properties (Hawa & Mulyanti, 2021) and in developing students' scientific reasoning skills (Putri et al., 2021). Nuswowati et al. (2020) also demonstrated that nature-based laboratory practices significantly improve students' abilities to observe, formulate hypotheses, and draw conclusions.

Based on these considerations, this study aims to compare the effectiveness of LBL and VLL in teaching acid–base titration using natural indicators, focusing on students' conceptual understanding and the percentage of learning improvement. The findings are expected to contribute to the development of contextual, applicable, and skill-oriented chemistry learning in vocational education.

Method

This study employed a quantitative approach using a quasi-experimental design to evaluate the effectiveness of Lab-Based Learning (LBL) and Virtual Lab-Based Learning (VLL) in teaching acid-base titration. The participants were 30 eleventh-grade students from the Industrial Chemistry program at SMK PGRI 3 Malang, selected purposively and then randomly assigned into two groups of 15 students each.

The first group received instruction through the VLL model, guided by the same teacher, using the *ChemCollective Virtual Lab* platform (https://chemcollective.org/vlab) to simulate titration activities such as solution preparation, acid-base reactions, and endpoint determination. The second group learned through the LBL model, conducted directly in the school laboratory under teacher supervision, involving hands-on experiments using glassware, standard reagents, and both chemical and natural indicators.

The research design followed a pretest-posttest control group format, where the pretest measured students' initial understanding, followed by a 180-minute instructional intervention facilitated by the same teacher to ensure consistency, and concluded with a posttest to assess learning gains. Research instruments consisted of a conceptual understanding test and a student perception questionnaire. The conceptual test comprised 20 multiple-choice items and one essay question, assessing mastery of titration principles, calculation of titrant volume, identification of end points, and interpretation of pH changes using natural indicators. The perception questionnaire evaluated students' views regarding learning motivation, content clarity, engagement, and the relevance of learning activities to chemical practice in professional settings.

Content validity of the instruments was examined through expert judgment by two chemistry education lecturers and one experienced chemistry teacher, while reliability testing was conducted prior to implementation. Data were analyzed descriptively and inferentially to evaluate score improvements and test significant differences between the two learning models, focusing on students' understanding of titration fundamentals, endpoint identification, and interpretation of indicator color changes. Ethical considerations were observed by obtaining students' consent and ensuring data confidentiality.

This study is expected to contribute to the development of contextual, effective, and vocationally relevant chemistry learning, particularly for topics that require intensive laboratory skills such as acid–base titration.

Results & Discussion

This section presents the results of the study and their interpretation based on the research objectives. The data compares students' conceptual understanding of acid–base titration between Lab-Based Learning (LBL) and Virtual Lab-Based Learning (VLL). The findings are supported by statistical analysis and observations made during the learning process.

Table 1. Average Pre-Test and Post-Test Scores for VLL and LBL Models

Learning Model	**Pre-Test Mean Score**	**Post-Test Mean Score**	**Improvement (%)**
Lab-Based Learning (LBL)	50.33	87.60	74.06
Virtual Lab-Based Learning (VLL)	50.00	81.13	62.26

Both groups were initially given the same pretest to assess their prior understanding of acid–base titration concepts. After the intervention, Table 1 showed that the LBL model increased post-test scores by 74.06%, while the VLL model showed an improvement of 62.26%. Bazie et al. (2024) also reported that the use of virtual laboratories can significantly improve students' chemistry learning outcomes compared to conventional classroom instruction. However, direct laboratory experience, such as handling apparatus and reagents, provides a greater contribution to strengthening students' conceptual understanding and observational skills, which cannot be fully replicated in a virtual environment. Consequently, although virtual laboratories are effective, hands-on laboratory practice continues to yield the highest learning achievement.

Avci (2022) reported that students were able to effectively learn acid–base topics online using virtual simulations. The study demonstrated that experimental procedures, pH changes, and indicator color transitions can be visualized digitally, thereby supporting students' conceptual understanding in an engaging and interactive way. Similarly, Manyilizu (2022) found that the use of virtual laboratories effectively improved students' conceptual understanding compared to text- or worksheet-based learning, particularly in schools with limited access to physical laboratory facilities. Nevertheless, the effectiveness of virtual laboratories still does not fully match that of real laboratory experiences in developing practical and manipulative experimental skills.

The higher score improvement in the LBL group compared to the VLL group confirms that hands-on laboratory learning promotes more comprehensive cognitive and affective engagement among students. Furthermore, the use of natural indicators, such as pigments extracted from red cabbage and hibiscus flowers, not only produced distinct color changes but also actively involved students in the process of extraction and testing. Cruz et al. (2022) explained that flavylium compounds containing anthocyanins, such as those found in red cabbage and hibiscus, undergo structural changes due to pH variation, resulting in characteristic color transitions from red to purple to blue. These properties make anthocyanins effective natural indicators for teaching acid–base concepts. This finding is supported by Im et al. (2023), who reported that natural pigments isolated and embedded in agar media produced sharp color changes across various pH ranges, making them suitable for educational, environmentally friendly, and engaging chemistry learning.

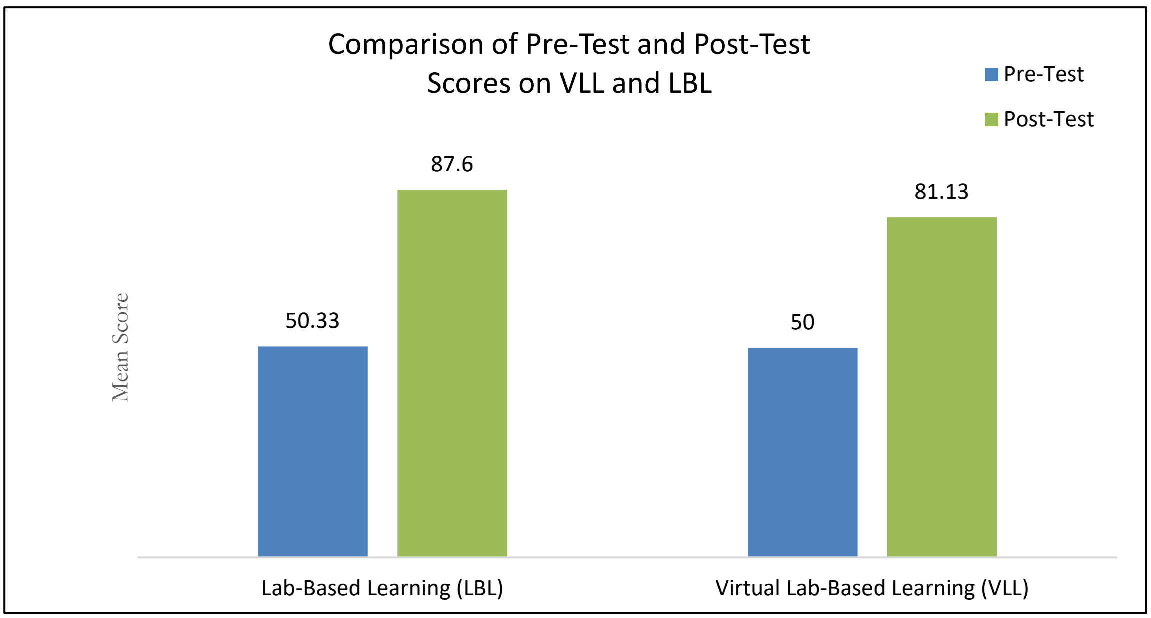

Figure 1. Comparison of pre-test and post-test scores between VLL and LBL groups.

Figure 1 illustrates an increase in scores between the pre-test and post-test for both learning groups. The VLL group increased from 50.00 to 81.13, while the LBL group improved from 50.33 to 87.60. The nearly identical pre-test averages suggest that differences in post-test scores are more likely attributed to the learning model applied rather than variations in students' initial abilities. These results indicate that both models were effective in enhancing students' conceptual understanding of acid–base titration.

Figure 2 shows that the LBL method resulted in a score increase of 74.06%, while the VLL method achieved a 62.26% increase. This indicates that both models were effective in improving students' conceptual understanding. Wen et al. (2024) explained that the use of visual guidance and attentional cueing in virtual laboratory environments can reduce extraneous cognitive load and help students focus on essential experimental steps, thereby enhancing information processing within working memory. Similarly, Alhashem and Alfailakawi (2023) found that integrating virtual laboratories enables students to better understand experimental concepts and procedures prior to real laboratory work, as visualizing steps and chemical indicator changes supports the formation of more stable mental representations of acid–base concepts.

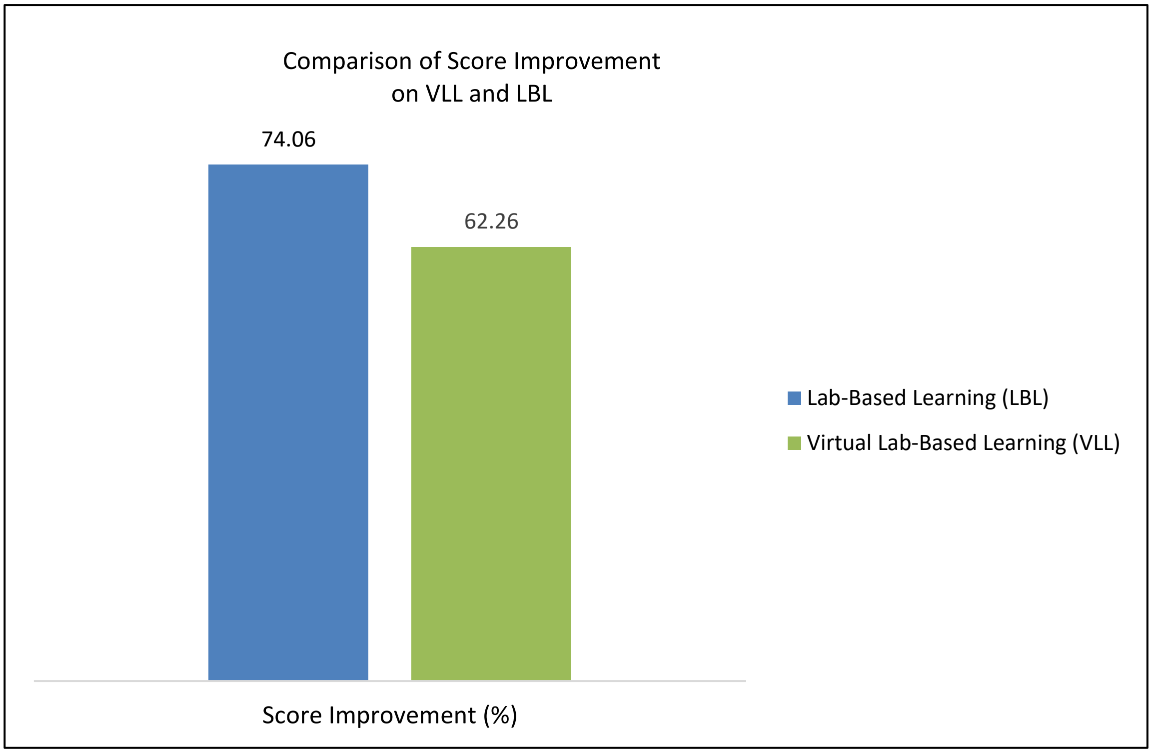

Figure 2. Average score improvement of VLL and LBL groups.

Manyilizu (2022) also reported that using virtual laboratories before conducting real experiments can improve students' performance more effectively than starting directly with hands-on practice. This approach allows learners to build foundational conceptual understanding of experimental procedures, pH changes, and indicator functions through visual and simulated media, making them cognitively more prepared for real laboratory sessions. Fitriyana et al. (2024) further confirmed that integrating virtual chemistry laboratories into blended learning significantly enhances academic achievement and learning independence, particularly in schools with limited laboratory resources. However, Ali & Ullah (2020) noted that virtual laboratories are often less effective in developing direct manipulative skills, such as operating apparatus, recognizing reagent odors, and handling experimental errors, which are more optimally acquired through real laboratory experiences.

The main limitation of this study lies in the relatively small sample size, consisting of only 30 students, which may reduce statistical power and increase variability in the results. Nguyen & Karunaratne (2024) explained that small datasets may lead to findings that are "unreliable, tentative, or biased" if the analysis relies solely on a single method without contextual or theoretical support. However, they emphasized that applying multiple analytical perspectives, triangulating data sources, and grounding findings in established learning theories can strengthen the reliability of studies with small samples. Hidayah et al. (2023) also found that small-scale experimental activities can still effectively improve students' conceptual understanding, instrument-handling skills, and awareness of laboratory safety and efficiency. Thus, despite the limited sample size, the considerable percentage increase in both groups reinforces the claim that both LBL and VLL effectively enhance students' conceptual understanding, particularly within the context of vocational chemistry education.

Comparison of Students' Ability in Answering Questions

To further illustrate students' procedural understanding, examples of written responses from both groups are shown below.

Explain in order and detail the procedural steps for conducting an acid-base titration correctly, starting from the preparation of tools and materials, the titration process, up to the determination of the end point! Also explain the role of the indicator in this titration process.

- Preparation of Tools and Materials

1. Prepare the burette, stand, Erlenmeyer flask, volumetric pipette, and glassware.
2. Prepare the base solution (for example, NaOH) or acid solution (for example, HCl) with a known concentration.
3. Prepare the acid or base solution that will be titrated.
4. Select an appropriate indicator for the type of acid-base titration, such as phenolphthalein or methyl red.

- Titration Process

1. Rinse the burette with the standard solution to ensure there is no contamination.
2. Fill the burette with the standard solution up to the desired volume.
3. Pipette the sample solution into the Erlenmeyer flask at a known volume.
4. Add several drops of the selected indicator to the sample solution.
5. Gradually add the standard solution from the burette into the sample while stirring until a color change occurs, indicating the endpoint of the titration.

- Determination of the End Point

1. Observe the color change in the sample solution during the titration process.
2. The endpoint of the titration is reached when the color change in the sample becomes permanent.
3. Record the volume of the standard solution used to reach the titration endpoint.

- Role of the Indicator

The indicator functions as a marker for the endpoint of the titration. It changes color within a specific pH range, signifying that the endpoint has been reached. Thus, the indicator helps determine the completion of the neutralization reaction between the acid and base.

Figure 3. Example of Student Response from the LBL Group.

Explain in order and in detail the procedural steps for conducting an acid-base titration correctly, starting from the preparation of tools and materials, the titration process, and the determination of the endpoint! Also explain the role of the indicator in this titration process.

- Preparation of Tools and Materials

1. Equipment: burette, stand, clamp, beaker, volumetric pipette, and stirrer.
2. Materials: acid or base solution to be titrated, standard acid or base solution, and acid-base indicator.

- Titration Process

1. Cleaning the equipment.
2. Filling the burette.
3. Taking the sample.
4. Adding the indicator.
5. Performing the titration.
6. Determining the endpoint.

Figure 4. Example of Student Response from the VLL Group.

Figures 3 and 4 illustrate a comparison of students' ability to explain and systematically write the acid-base titration procedure between the LBL group (Figure 3) and the VLL group (Figure 4). Observational data and analysis of students' written responses indicate that students in the LBL group were more capable of structuring the titration steps in a systematic manner. This included preparing solutions, using measuring instruments such as burettes and pipettes, and observing color changes in the indicator at the endpoint.

This advantage arises because students engaged in the LBL model experienced each stage of the titration process firsthand in the laboratory. Physical interaction with the apparatus and materials allowed them to comprehend the procedures concretely, fostering stronger procedural memory (Fajriati et al., 2024). In contrast, students in the VLL group, although exposed to visual simulations of the procedures, tended to experience learning passively. The simulations often lacked emphasis on critical technical details such as accurate volume measurements, dropwise titration techniques, and controlled titrant addition rates.

The absence of hands-on practice in the VLL group led students' procedural understanding to remain largely conceptual rather than practical. Several students in this group tended to describe experimental procedures in general terms without specifying essential technical details. Consequently, the LBL approach plays a pivotal role in bridging conceptual understanding with laboratory skills, thereby enhancing students' ability to analyze data, interpret unexpected outcomes, and critically evaluate experimental methods. Such integration is essential for developing authentic laboratory competence among vocational high school students (Schmidt et al., 2021).

Students' Preference for Learning Models

Students' preferences toward the two learning models were analyzed to identify which approach they found more engaging and effective during the acid-base titration learning process.

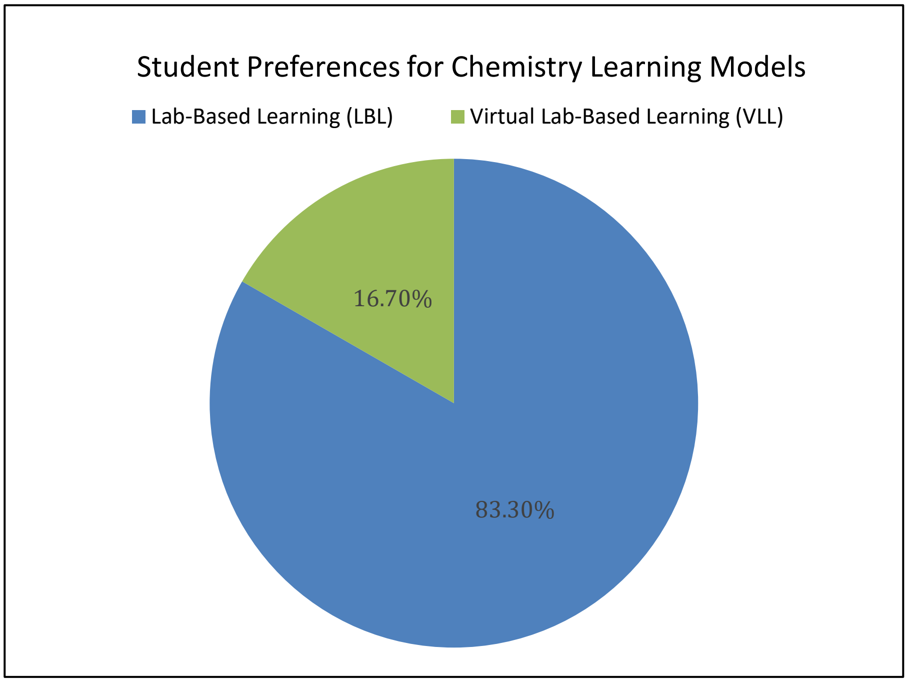

Figure 5. Students' Learning Model Preferences in Acid-Base Titration

Figure 5 presents a summary of student preferences regarding the two learning models for acid-base titration. Out of 30 students, 25 (83.3%) selected Lab-Based Learning (LBL) as their preferred learning model, while only 5 students (16.7%) chose Virtual Lab-Based Learning (VLL). These results indicate that the majority of students favor direct, hands-on experiences in a real laboratory environment. The strong preference for LBL is likely due to students' active engagement in authentic experimental activities, which enable them to develop technical skills, directly observe indicator color changes, and experience the entire titration process firsthand. Physical interaction with laboratory instruments and reagents also provides a more tangible and contextual learning experience.

In contrast, although VLL offers interactive visualisations and flexible access to experiments, some students perceive that virtual simulations do not provide the same level of practical experience and sensory engagement as real laboratory work. This finding underscores the importance of LBL in chemistry education, particularly at the vocational school (SMK) level, where mastering laboratory competencies is a key educational objective.

Conclusion

The results of the study show that both Lab-Based Learning (LBL) and Virtual Lab-Based Learning (VLL) are effective in improving students' conceptual understanding of acid-base titration. LBL produced a higher score increase, highlighting its superiority in developing students' practical skills, observational abilities, and comprehensive cognitive and affective engagement. Meanwhile, VLL remains a relevant alternative for schools with limited laboratory facilities because it helps students understand experimental procedures and pH concepts through interactive simulations. The use of natural indicators such as pigments from red cabbage and hibiscus flowers also demonstrates strong educational potential in promoting contextual and environmentally friendly learning. However, the findings of this study are limited to the context of vocational high schools with a small sample size, so generalization to other educational levels or contexts should be approached cautiously. Further research involving larger samples and a wider variety of natural indicators is needed to test the consistency of these findings within broader chemistry learning contexts and their applicability in non-vocational education settings.

AI-assisted technology statement

During the preparation of this manuscript, the author used ChatGPT (OpenAI) to improve grammar, language clarity, readability, and to assist in the visual layout of the graphical abstract. All AI-assisted outputs were carefully reviewed and refined by the author to ensure that the manuscript accurately reflects the actual research findings.

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