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# Augmented Reality-Based Virtual Laboratory Application as Chemistry Learning Media for Acid-Base Titration Material

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**ABSTRACT**

**Purpose –** This research aims to develop an augmented reality-based virtual laboratory application that is feasible as a chemistry learning media for acid-base titration material, assessed as valid, practical, and effective.

**Methodology –** This study is a type of research and development using the 4D (Define, Design, Develop, and Disseminate) model, which is limited to the development stage only. The research was conducted at SMAN 2 Sidoarjo with 40 science students of class XI as the limited trial subjects. Data were collected from validation questionnaires, student response questionnaires, student activity observation sheets, and learning outcome tests, such as pretest and posttest. Descriptive quantitative methods were used to analyze the data.

**Findings –** Validity results show that the developed application is valid with a mode score of 4 (good category) on both content and construct validity. Practicality analysis shows that the developed application is efficient, with an average percentage of student responses of 96% and a relevant student activity percentage of 93,32%, both of which fall into the outstanding category. Effectiveness analysis based on the Wilcoxon signed-rank test results revealed a significant difference between the pretest and posttest scores, with a significance value obtained of 0,000 (which is less than the significance value of 0,05), indicating that the developed application is efficacious in improving students' learning outcomes. Therefore, it is concluded that the augmented reality-based virtual laboratory application developed is feasible as a chemistry learning medium for acid-base titration material.

**Contribution –** An innovative chemistry learning media that facilitates a more visual and interactive understanding of the acid-base titration concept, providing an alternative solution to overcome limited laboratory facilities in schools and supporting more efficient implementation of chemistry practicum activities.

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## INTRODUCTION

Chemistry learning often presents distinct challenges for students. Chemistry subjects require students to have a deep understanding and mastery of concepts and demand critical thinking, practical laboratory skills, and the development of scientific attitudes as emphasized in science education (Depdiknas, 2003). The study by Maksum et al. (2017) revealed that students' conceptual understanding in chemistry remains relatively low. This statement is supported by research from Priliyanti et al. (2021), which found that approximately 86% of senior high school students had not yet achieved mastery in understanding chemistry concepts, as evidenced by learning outcomes that fell significantly below the expected learning objectives (Suarni et al., 2022). One of the main factors contributing to this low level of understanding is the abstract and complex characteristics of many chemistry concepts (Sariati et al., 2020). This statement is further reinforced by the results of a preliminary questionnaire conducted in SMAN 2 Sidoarjo, which revealed that all students in one observed class perceived chemistry as a difficult subject because the material is abstract and complex, involves the presence of numerous confusing formulas and calculations, and contains unfamiliar terminology that is difficult to comprehend.

One of the chemistry topics that is perceived as particularly difficult by students is acid-base titration. In learning acid-base titration, students are required to understand titrants, titrates, acid-base indicators, the equivalence point, the endpoint of titration, and titration curves, all of which involve the theoretical knowledge, hands-on experiments, and complex calculations (Salame et al., 2022). Furthermore, acid-base titration encompasses a broad scope of material and is closely linked with other chemistry topics such as acids and bases, buffer solutions, and salt hydrolysis. This requires students to understand each of those fundamental concepts, making the topic even more challenging (Rinta & Fitriza, 2022). The complexity of acid-base titration often causes confusion and conceptual errors. If left unaddressed, those misconceptions can lead to more profound misunderstandings and negatively affect students' overall concepts in chemistry.

One of the solutions proposed by Marzuki and Astuti (2017) to address and minimize misconceptions in acid-base titration material is to provide a meaningful understanding through direct observation and laboratory activities, enabling students to be more actively involved in the learning process. However, in practice, laboratory activities in many schools are still far from optimal due to various constraints, such as inadequate laboratory facilities, limited availability of supporting equipment and chemicals, insufficient time allocation for practical sessions, and shared use of laboratories among multiple classes (Rahman et al., 2015). This condition was also observed at SMAN 2 Sidoarjo, where the chemistry laboratory is shared across several classes, practical sessions are rarely conducted, and available laboratory equipment is incomplete, limiting students' opportunities to conduct experiments such as acid-base titration. Those factors contribute to a decreased frequency and intensity of school practical activities. Such limitations in implementing laboratory activities hinder the realization of ideal learning conditions in chemistry education, which may result in low student interest in learning chemistry, poor conceptual understanding, and an unmet development of 21st-century skills (Hauriyah et al., 2019; Ningsih et al., 2019).

As a solution to the limitations associated with laboratory practices, using learning resources based on technology, such as a virtual laboratory, has emerged as a promising alternative (Lestari et al., 2023). A virtual laboratory has a function to simulate laboratory activities in a virtual environment (Wati, 2021). As a product of interactive learning media, the virtual laboratory offers students the convenience of independently conducting a series of practical activities using smartphones, with unlimited access to repetition in order to reinforce their conceptual understanding (Abdjul & Ntobuo, 2018; Ikhsan et al., 2020). To ensure that the learning experience provided by a virtual laboratory closely resembles real-life practice, it is important to integrate additional technologies that can realistically visualize laboratory tools and materials. One such relevant technology is augmented reality (AR), which can merge virtual objects into the real world through two- or three-dimensional visuals (Permana et al., 2018). Augmented reality creates an interaction between the real and virtual worlds, in which all information can be added and displayed in real-time, making it appear interactive and realistic (Mustaqim, 2016).

Several studies have explored virtual reality, virtual laboratory, or augmented reality in chemistry education, but typically in isolation. For example, Hauriyah et al. (2019) demonstrated that virtual laboratory use significantly improved students' practical titration skills. Eli and Widiyanti (2020) reported improved learning outcomes using virtual lab animations for acid–base topics. Alfaro et al. (2022) developed a mobile AR application for acid–base titration, showing usability benefits but limited procedural features. Margoum et al. (2022) showed that microcomputer-based laboratories (MBLs) significantly enhanced conceptual understanding of acid-base titration at the university level.

Additionally, Johnson-Glenberg et al. (2023) improved student engagement and conceptual transfer using a mixed-reality system combining haptic 3D-printed burettes and titration simulation. These findings highlight that while individual components such as virtual labs, AR tools, MBLs, and haptic simulations have been studied, there remains a research gap, where no existing study integrates mobile augmented reality with interactive virtual laboratory simulations (including procedural steps), 3D equipment visualization, and automated titration calculation specifically for high school acid-base titration. This gap underscores the novelty and importance of the present research.

Combining virtual laboratory technology and augmented reality integration can create a more visual, interactive, and contextual learning experience. This allows students to conduct acid-base titration practices that resemble real laboratory activities. Unlike previous studies focusing on virtual laboratory or augmented reality as separate tools, this research integrates both technologies in a single platform designed explicitly for acid-base titration learning. The application includes interactive features such as 3D visualization of laboratory equipment and materials, step-by-step simulation of titration procedures, and automated calculation of titration results, which have not been extensively explored in earlier research. Considering the previously provided background, this research aims to create an augmented reality-based virtual laboratory application that is feasible to use as a chemistry learning media for acid-base titration material, assessed based on its validity, practicality, and effectiveness. This study contributes to the field by offering an innovative and accessible alternative for schools with limited laboratory facilities, enhancing students' conceptual understanding through a visual and interactive approach, and providing a replicable development model for other chemistry topics.

## METHODOLOGY

### Research Design

This research uses methods of research and development (R&D) with the 4D model developed by Thiagarajan et al. in 1974. This model was chosen due to its structured yet straightforward development stages, which are practical to implement within a limited timeframe for the research process and data analysis. The 4D model consists of four main stages: define, design, develop, and disseminate (Thiagarajan et al., 1974). However, the implementation of the 4D model in this study was only restricted to the development stage, as the primary goal was to create an augmented reality-based virtual laboratory application that is feasible to be used as a chemistry learning media on acid-base titration material and be tested through a limited-scale implementation.

The define stage aims to determine, identify, and establish various problems that arise in school according to the requirements needed for the learning process (Haviz, 2013; Mesra et al., 2023), particularly in chemistry subjects on acid-base titration material. After identifying the problems, the design stage comes next, which intends to create a prototype of an augmented reality-based virtual laboratory application. The design stage includes the development of criterion-referenced assessments, selecting appropriate media and formats, and creating the initial design, which is adjusted to the school's needs (Akker et al., 1999). After completion, the first draft created will be saved and used in the development stage. Lastly, the development stage seeks to produce an augmented reality-based virtual laboratory application as a chemistry learning media on acid-base titration material after revisions based on suggestions and feedback from expert validators.

**Participants**

This research involved 40 eleventh-grade students at SMAN 2 Sidoarjo as the limited trial participants. All students had previously received instruction on acid-base titration material in their chemistry classes, but had not conducted the corresponding laboratory experiment due to limitations in available laboratory facilities and materials. This context was considered appropriate for evaluating the practicality and effectiveness of the developed augmented reality-based virtual laboratory application.

**Data Collection**

***Questionnaire Method***

In this research, the questionnaire method was applied in the validation sheet to obtain expert assessments regarding the feasibility of the application developed, which was made up of 2 chemistry lecturers and one chemistry teacher. In addition, the questionnaire method was also used in the student response sheets to collect student feedback, opinions, and responses after using the application developed.

***Observation Method***

The observation method is a data collection technique that involves direct observation. In this research, the observation method was applied in the observation sheet to directly observe the behavior, interactions, or student activities during learning activities using the application developed.

***Test Method***

The test method was applied through student learning outcome test, which consisted of five essay questions related to acid-base titration material. In this research, two tests were administered: a pretest and posttest, which aimed to measure and compare students' prior knowledge and learning outcomes before and after using the application developed. To ensure the assessment instrument's quality, validity and reliability were examined before use. The validity was assessed by two chemistry education experts and one senior high school chemistry teacher, focusing on each question's relevance, clarity, and alignment with the intended learning objectives. Meanwhile, the reliability testing was carried out using Cronbach's Alpha and yielded a coefficient of 0,87, which indicates high internal consistency. These results confirm that the test instruments were valid and reliable for accurately measuring students' conceptual understanding of acid-base titration.

**Data Analysis**

The developed application's feasibility in this research was evaluated through validity, practicality, and effectiveness. Validity analysis was carried out based on the validators' assessment through validation sheets, which consist of content and construct validity. A Likert scale is used to process the obtained validity data, and descriptive quantitative techniques are used for analysis.

**Table 1.** Likert Scale

| Scale | Category |
|---|---|
| 5 | Very Good |
| 4 | Good |
| 3 | Good Enough |
| 2 | Not Good |
| 1 | Very Not Good |

Adapted from (Riduwan, 2012)

The validity results obtained in this research are the type of data based on ranking and sorted from highest to lowest value or vice versa (ordinal data), and therefore are considered equivalent and cannot be calculated mathematically (Riduwan, 2012). Consequently, the validity data in this research were analyzed using the most frequently occurring score, or mode, for each indicator aspect. The developed application is considered valid if the validators' assessment results have a minimum mode score of four (Mo ≥ 4), which falls into the good category. If the validators' assessments have a mode score of less than four, the application is considered invalid and requires revision and revalidation until it reaches the specified criteria.

The practicality analysis was done through the distribution of student response questionnaires after implementing the application, which were then reinforced with student activity observation results during learning activities. Data from the response questionnaires were analyzed using the Guttman scale, which is designed for precise and consistent answer choices (Riduwan, 2012). The Guttman scale consists of two response options: "Yes" and "No."

**Table 2.** Guttman Scale

| Response | Answer | Score |
|---|---|---|
| Positive | Yes | 1 |
| | No | 0 |
| Negative | Yes | 0 |
| | No | 1 |

Adapted from (Riduwan, 2012)

The percentage of student response questionnaire results was calculated using the following formula.

$$\text{Percentage (\%)} = \frac{\sum \text{obtained score}}{\text{maximum score}} \times 100\%$$

The data obtained from student activity observations were used to support the student response questionnaires. These observation data were collected through direct observation of relevant and dominant student activities during implementation of developed application. Observations were carried out by 5 observers, which each assigned to observe one group that consisting of 8 students. The observation sheets were filled in by the observer at intervals of every 3 minutes for 90 minutes of learning session. The following formula was used to calculate the percentage of student activity.

$$\%\text{student activities} = \frac{\sum \text{frequency of activity that occurs}}{\sum \text{frequency of overall activity}} \times 100\%$$

To determine the practicality of the application developed, percentage that obtained from the student response questionnaires and student activity observations were analyzed using descriptive quantitative methods and interpreted as follows.

**Table 3.** Interpretation of Practicality Percentage

| Percentage (%) | Category |
|---|---|
| 81–100 | Very Good |
| 61–80 | Good |
| 41–60 | Good Enough |
| 21–40 | Not Good |
| 0–20 | Very Not Good |

Adapted from (Riduwan, 2012)

Referring to practicality interpretation shown in Table 3, the developed application is considered practical if the average score obtained from the student response questionnaires and relevant student activity time reaches at least percentage of 61% and is categorized as good.

Effectiveness was analyzed according to the improvement of the students' learning outcomes, which was measured through cognitive tests in pretest and posttest. A difference test was conducted to compare pretest and posttest scores to determine whether the improvement is statistically significant. However, before conducting the difference test, a normality analysis was conducted to assess the data distribution pattern. If the significance value exceeds 0,05, the data are interpreted as following a normal distribution, and the paired sample t-test (a parametric test) is applied. Conversely, if the significance value falls below 0,05, the data are regarded as not normally distributed, and the Wilcoxon signed-rank test (a non-parametric test) is employed. In the Wilcoxon signed-rank test, a significance value below 0,05 (sig < 0,05) leads to the rejection of the null ($H_0$) hypothesis and the acceptance of the alternative ($H_1$) hypothesis, suggesting a statistically significant difference between the pretest and posttest scores. On the other hand, a significance value exceeding 0,05 (sig > 0,05) leads the $H_0$ to be retained and $H_1$ to be rejected, indicating no meaningful difference between the pretest and posttest outcomes.

## FINDINGS

This study is research and development regarding the 4D model Thiagarajan et al. (1974) developed, which was limited to the development stage only. Each stage of this model is described as follows.

### Define

The definition stage is carried out to identify and understand the fundamental problems comprehensively related to chemistry learning in schools, especially in the acid-base titration material. The information obtained at this stage was based on literature studies and preliminary research, which included observation activities, interviews with chemistry teachers, and the distribution of pre-research questionnaires and pretest questions to students. The results of the pre-research questionnaire indicated that most students still faced difficulties learning and understanding the concept of acid-base titration due to its abstract characteristics (difficult to visualize), complexity, and the presence of many unfamiliar terms and calculations that were hard to comprehend. The pretest results further reinforced this issue, which showed that none of the students had achieved the expected learning objectives.

Students' challenges in understanding acid-base titration material generally occur due to a learning method that is still conventional, which relies heavily on lectures and is rarely accompanied by chemistry practicum activities at school due to the limited availability of adequate laboratory facilities. As a result, students lose the opportunity to directly experience scientific processes, a core component of chemistry learning. Hence, developing instructional media that serve as an alternative to practical laboratory activities and help strengthen students' conceptual understanding of acid-base titration is crucial.

### Design

The design stage aims to create an initial prototype of the learning media to be developed. This stage begins by identifying a learning medium aligned to the acid-base titration characteristics. In this research, the learning media chosen to be developed is an augmented reality-based virtual laboratory application, which provides alternative virtual practical activities regarding acid-base titration so that it can visualize and simulate interactive titration experiments. The virtual laboratory feature enables digital simulation of laboratory activities that can be repeated anytime and anywhere, offering flexibility and accessibility for students. Meanwhile, the augmented reality feature lets students see three-dimensional representations of laboratory tools and materials directly through smartphone cameras. The developed application interface can be seen in the figure below.


**Figure 1.** Home Page of Virtual Laboratory Application

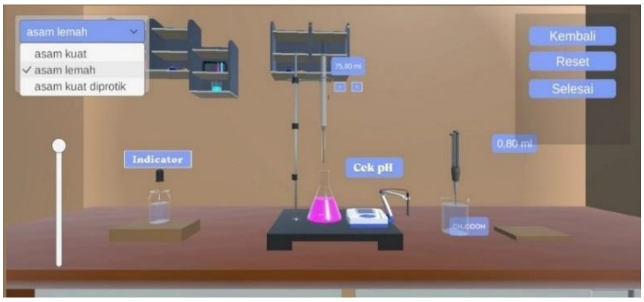


**Figure 2.** Menu of Virtual Laboratory

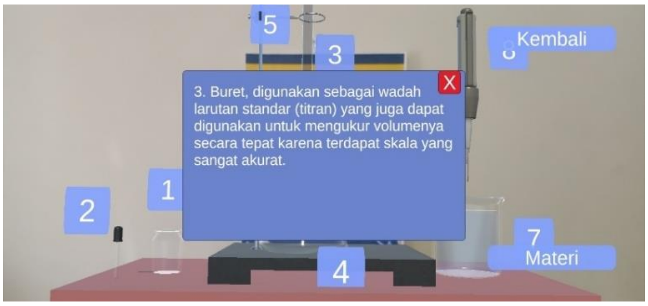


**Figure 3.** Menu of Tools and Materials with Augmented Reality-Based

**Develop**

Develop stage seeks to create an augmented reality-based virtual laboratory application which is feasible to be used as chemistry learning media after revisions according to suggestions and feedback given from expert validators. The validity assessment consisting validity of content and construct. Data of validation obtained from the three validators, which include two chemistry lecturers and one chemistry teacher, are shown in Table 4 as follows.

**Table 4.** Results of Content and Construct Validity

| Assessment Aspects | Mode Score | Category |
|---|---|---|
| Validity of Content | | |
| Relevance of Learning Material | 4 | Good |
| Suitability and Clarity of Concept | 4 | Good |
| Suitability of Practicum Activity | 4 | Good |
| Suitability of Evaluation Activity | 4 | Good |
| Accuracy of Scientific Concept | 5 | Very Good |
| Overall Mode of Content Validity | 4 | Good |
| Validity of Construct | | |
| Suitability of Design and Appearance | 4 | Good |
| Suitability of Presentation | 4 | Good |
| Suitability of Language | 4 | Good |
| Overall Mode of Construct Validity | 4 | Good |

Based on the results above, the overall mode for content and construct validity was 4, which falls into the good category. These validity results indicate that the content or learning material and the interface and presentation of the augmented reality-based virtual laboratory application that has been developed have met the valid criteria, so it is suitable for use in a limited trial stage with students. A limited trial was conducted to evaluate the practicality and effectiveness of the virtual laboratory application within a classroom learning environment. This limited trial was conducted using a one-group pretest–posttest design on 40 samples of eleventh-grade students who had previously studied acid-base titration material. The diagram below presents the student's learning outcomes.

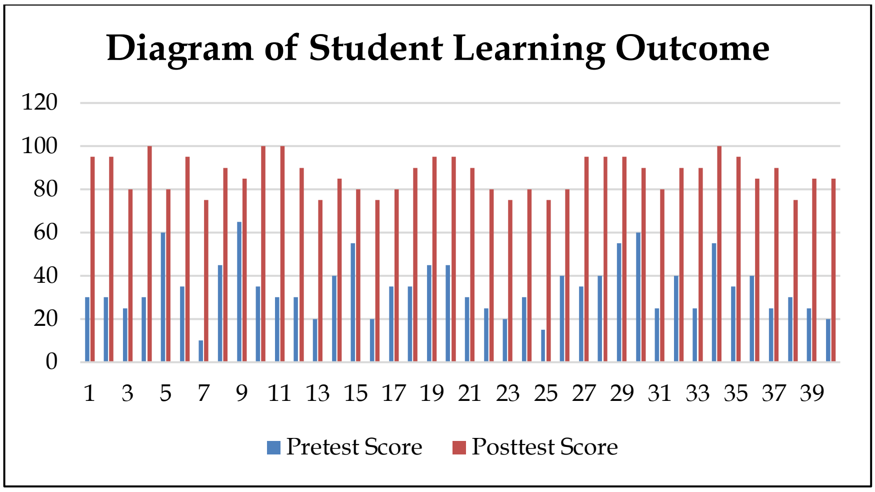


**Figure 4.** Diagram of Student Learning Outcomes

The diagram presented in Figure 4 shows that all students experienced increased learning results on the acid-base titration material after using the developed application. A difference test must be conducted to ensure the improvement is statistically significant. However, before performing the difference test, a normality test was first carried out using the Shapiro-Wilk test because the number of samples was less than 50 ($n < 50$). The normality test results using IBM SPSS Statistics 25.0 software are presented as follows.

**Table 5.** Result of Shapiro-Wilk Normality Test

| | Test of Normality Shapiro-Wilk | | |
|---|---|---|---|
| | Statistic | df | Sig. |
| Pretest | 0,951 | 40 | 0,079 |
| Posttest | 0,912 | 40 | 0,004 |

Significance value obtained for the pretest was 0,079, which exceeds 0,05, so it is considered normally distributed. However, the significance value for the posttest was 0,004, which is lower than 0,05, so it is interpreted as not normally distributed. Since one dataset was not normally distributed, the difference test used was the non-parametric Wilcoxon signed-rank test.

The output of the Wilcoxon signed-rank test indicated a significance value of 0,000, which falls below the significance level of 0,05 (sig < 0,05). Hence, $H_0$ is rejected and $H_1$ is accepted, indicating a significant difference between the pretest and posttest scores. Furthermore, the ranks test analysis showed that all 40 students are included in the positive ranks category, meaning that every student had a higher posttest score than the pretest score. Thus, it can be inferred that the augmented reality-based virtual laboratory application developed in this research effectively improved students' learning outcomes.

**Table 6.** Result of Wilcoxon Signed Ranks Test

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| Posttest – Pretest | Negative Ranks | 0[a] | 0,00 | 0,00 |
| | Positive Ranks | 40[b] | 20,50 | 820,00 |
| | Ties | 0[c] | | |
| | Total | 40 | | |

a. Posttest < Pretest
b. Posttest > Pretest
c. Posttest = Pretest

| | Posttest – Pretest |
|---|---|
| Z | -5,526 |
| Asymp. Sig. (2-tailed) | 0,000 |

In the limited trial stage, students were also asked to fill out a response questionnaire to evaluate the practicality of the application developed. The results of the students' response questionnaire are as follows.

**Table 7.** Recapitulation of Student Response Questionnaire

| Assessment Aspects | Percentage (%) | Category |
|---|---|---|
| Attracting Students' Interest in Learning | 100 | Very Good |
| Ease of Use of Media | 100 | Very Good |
| Clarity of Information Delivered | 93 | Very Good |
| Effectiveness of Visualization and Simulation | 96 | Very Good |
| Benefits of Media for Learning Outcomes | 93 | Very Good |
| Average Percentage | 96 | Very Good |

Referring to the student response questionnaire findings, each assessed aspect achieved a percentage above 90%. The average acquisition of each aspect reached 96% which is classified as very good. These positive responses are reinforced by data on student activities, which were obtained through observations carried out during the implementation of the application developed. Recapitulation of student activity observation outcomes is presented in Table 8.

**Table 8.** Recapitulation of Student Activity Observation

| Student Activities | Percentage (%) | Category |
|---|---|---|
| Relevant Activities | 93,32 | Very Good |
| Irrelevant Activities | 6,68 | Very Not Good |

Such as validity, practicality, and effectiveness. Validity assesses or measures the extent to which a learning medium accurately and appropriately performs its intended function (Nursalam, 2012). The validation process was conducted by two chemistry lecturers and one chemistry teacher. The validity assessment consisted of assessing the validity of the content and construct. Content validity describes the extent to which the content of a learning product reflects the intended competencies or learning outcomes (Akker et al., 1999). In this research, content validity was assessed based on several aspects, such as the relevance of learning material, the suitability and clarity of concepts, the suitability of practicum activity, and the suitability of evaluation activity. Each aspect achieved a mode of 4 and was categorized as good. In addition, content validity also assessed the accuracy of scientific concepts, which received a mode of 5 and was classified as very good. Considering all indicators within the content validity evaluation, the overall mode score obtained was 4, with a good category. Therefore, it can be inferred that the content and material presented in the application developed in this research are relevant and accurate, adjusted to curriculum requirements, and supportive of both evaluation and practicum activities for students.

Construct validity is intended to evaluate the extent to which components in a learning medium reflect the aspects that should be developed in line with theoretical principles and the attributes of an ideal learning product (Akker et al., 1999). In this research, construct validity was assessed through three main aspects: the suitability of design and appearance, the suitability of presentation, and the suitability of language used. Those three aspects received an overall mode score of 4, which falls into the good category. Therefore, it can be said that the application developed in this research is not only visually attractive, but also presents relevant information and features, and uses language appropriate to the students' characteristics. These validity findings are supported by the study of Muchson et al. (2019), who developed an Android-based virtual laboratory for acid-base titration material and obtained a content validity score of 84,67% and a construct validity score of 85,44%, both falling into the "highly feasible" category. Similarly, research by Herman et al. (2022) reported high validity for an Android-based augmented reality medium, with a content validity score of 0,83 and a construct validity score of 0,87, both categorized as "very high". In addition, the study conducted by Rusdi et al. (2023) achieved a validity score of 3,85 (within the interval $3,5 < X < 4$), which is classified as "very valid". The alignment between the findings of this study and previous relevant research indicates that virtual laboratory and augmented reality learning media demonstrate a high level of validity and can serve as an effective alternative medium for supporting chemistry learning.

Practicality refers to the extent to which a learning medium that has been produced is easy to use and manage. Practicality is evaluated based on several aspects, such as ease of preparation, usage, interpretation, outcome acquisition, and storage of the learning media (Arikunto, 2018). Direct assessments from students through response questionnaires must be aligned with the observations of student activity in real class, which are based on five evaluation objectives. Those five objectives reflect the important aspects in measuring the practicality of the learning media, such as attracting students' interest in learning, ease of use, clarity of information delivered, effectiveness of visualization and simulation, and the usefulness of the media in supporting learning outcomes. The response questionnaire results showed an average percentage of 96%. They were categorized as very good, which indicates that students felt helped, interested, and found the application easy to use during the learning process. These findings were further reinforced by observation data, which showed that student activities relevant to the learning process reached a percentage of 93,32% with a very good category, where this figure is significantly higher than the percentage of irrelevant activities. The high student engagement in learning-supportive activities suggests that the application was easy to use and effectively directed students' attention toward more active and meaningful learning experiences. Therefore, the augmented reality-based virtual laboratory application developed in this research is considered very practical and feasible to be used as a learning medium of chemistry, particularly in acid-base titration material.

The findings regarding the practicality of the application developed in this study are supported by Muchson et al. (2019), whose research showed that a virtual laboratory on acid-base titration material was rated as highly practical, with student response percentages reaching 89,27%. This is further reinforced by Herman et al. (2022), where the augmented reality–based media they developed achieved practicality scores of 0,78 from teachers and 0,842 from students, both falling into the "high" category. Similarly, Rusdi et al. (2023) demonstrated that virtual laboratory learning media integrated with augmented reality could facilitate the implementation of chemistry practicum activities, obtaining a practicality score of 3,6, categorized as "very practical". Based on these findings, the application developed in this study can be considered highly practical in supporting both independent and structured chemistry learning.

Effectiveness is a measure that indicates the extent to which a learning media successfully achieves predetermined learning objectives (Lestanata & Pribadi, 2016). This research assessed effectiveness based on students' learning outcomes by analyzing the differences between pretest and posttest results to evaluate students' knowledge before and after using the application developed. The Wilcoxon signed-rank test results analysis indicated a statistically significant difference between the pretest and posttest scores, with all students showing higher posttest scores than their pretest results. This demonstrates a consistent enhancement in students' learning outcomes. Moreover, the posttest responses indicated that all students successfully achieved the predetermined learning objectives, which is reflected by a better and more comprehensive understanding of acid–base titration fundamental concepts after using the developed application. Therefore, the augmented reality-based virtual laboratory application developed in this research has proven to be very effective in enhancing student learning outcomes.

The research findings on effectiveness indicate that the application developed in this study successfully assists students in gaining a deeper understanding of acid–base titration concepts through interactive learning experiences. This aligns with the results of Rusdi et al. (2023), which showed that using augmented reality-based virtual laboratories can improve practical skills, as evidenced by an average practicum portfolio score of 90. Their study emphasizes that learning supported by interactive media, such as augmented reality, facilitates conceptual understanding and enhances students' analytical abilities. Therefore, the findings of this study reinforce that the developed application is efficient in supporting chemistry learning activities, particularly in the topic of acid–base titration.

The augmented reality-based virtual laboratory developed in this study is valid, practical, and effective in enhancing students' conceptual understanding of acid-base titration, offering a visual and interactive alternative to conventional laboratory activities. This contributes to the advancement of digital learning media in chemistry education by integrating augmented reality technology with a virtual laboratory environment, enabling meaningful practicum experiences even in schools with limited laboratory facilities. The novelty of this study lies in its combination of augmented reality-based tools with a virtual laboratory simulation that focuses explicitly on acid-base titration, an area of chemistry learning that often faces implementation challenges due to limited equipment, chemicals, and laboratory access in many schools. This innovation directly addresses the urgency identified in the introduction, where practical laboratory experiences are frequently replaced with purely theoretical explanations, reducing students' opportunities for hands-on engagement. By providing an accessible, interactive, and curriculum-aligned platform, the developed application enables students to visualize complex titration processes and practice virtual experiments that closely resemble real laboratory procedures.

From a broader scientific perspective, integrating augmented reality and virtual laboratory technology in this research can have long-term implications for chemistry education. As digital learning environments become increasingly relevant in supporting flexible and inclusive education, the application model developed in this study can be a reference for future research and development in chemistry and other science subjects. The scalability of this technology allows it to be adapted for various topics and contexts, including distance learning scenarios, potentially improving students' conceptual understanding, procedural skills, and motivation to learn science. Therefore, the findings of this research not only contribute to solving current educational challenges but also open new opportunities for the application of immersive technologies in the future of science education.

Nevertheless, this study has several limitations. The application is currently compatible only with Android devices, restricting its accessibility to users of other operating systems. Furthermore, some students with mild visual impairments reported difficulty reading certain text elements due to the small font size and low contrast between text and background. These findings suggest that future development should improve device compatibility and optimize user interface design to ensure broader accessibility. Future research could also expand the application's content to cover broader topics, involve larger and more diverse participants, and evaluate its long-term impact on students' learning outcomes.

## CONCLUSION

The augmented reality-based virtual laboratory application developed in this research has proven valid, practical, and effective in enhancing students' learning outcomes. Therefore, it is considered feasible as a chemistry learning media that supports understanding of acid-base titration concepts in a more visual and interactive way. Additionally, this application offers teachers an alternative approach to address the challenges posed by limited laboratory facilities in schools, thus encouraging the more accessible and efficient implementation of chemistry practicum activities under various conditions and providing students with a deeper and more meaningful learning experience.

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