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Enhancing Chemistry Learning through an Android-Based Virtual Laboratory on Acid-Base Titration

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Abstract: Chemistry practicums in many schools are constrained by inadequate laboratory facilities, while acid-base titration requires learners to connect macroscopic observations with submicroscopic and symbolic representations; a preliminary study at the research site found limited equipment and a mean mastery score of 62.6, below the school minimum. This study aimed to develop an Android-based virtual laboratory for acid-base titration and to evaluate its validity, readability, practicality, and effectiveness. A research and development design following the ADDIE model was applied at SMAN 1 Suwawa. The product was built in Adobe Animate with ActionScript 3.0 and compiled as an Android application. It was validated by a media expert, a material expert, and a chemistry teacher; readability was trialled with 12 students, and 64 students joined the large-scale trial with a pre-test, post-test, and response questionnaire (Cronbach's alpha = 0.905). Validity, readability, and practicality were analysed as percentages, and effectiveness through N-Gain. The virtual laboratory obtained 88.1% validity, 89.7% readability, and 84.72% practicality, while the mean score rose from 9.45 to 16.02, giving an N-Gain of 0.768 (high category). The product is therefore valid, practical, and effective, and offers a workable virtual practicum for schools where laboratory facilities are the binding constraint.

Keywords: Acid-base titration; ADDIE model; Android application; Conceptual understanding; Virtual laboratory

Introduction

Laboratory work occupies a central place in chemistry education because it is the setting in which observable phenomena are connected to the theoretical models that explain them. Acid-base titration is one of the topics in which this connection is most demanding. Learners are expected to move continuously between what they can see in the flask, the particulate events that produce the colour change, and the symbolic notation used to quantify them. Johnstone (1991) characterised this demand through the three levels at which chemistry is represented, namely the macroscopic, the submicroscopic, and the symbolic, and argued that learning difficulties arise when instruction requires learners to operate at several levels simultaneously without support. Titration is precisely such a task: the endpoint is a macroscopic event, its cause is submicroscopic, and its interpretation is symbolic. It is therefore unsurprising that persistent misconceptions about the nature of acids and bases, the meaning of pH, and the interpretation of titration curves have been reported repeatedly (Avcı, 2022), and that conventional "cookbook" practicums, in which learners follow fixed procedures without inquiry, do little to resolve them (Goeltz & Cuevas, 2021).

These conceptual demands are compounded by structural constraints. Many schools operate laboratories that are inadequately equipped, poorly maintained, or insufficiently funded, so that hands-on titration is performed rarely or demonstrated by the teacher rather than carried out by learners. The disruption caused by the COVID-19 pandemic made the consequences of this dependence on physical facilities visible, as institutions moved to remote instruction without a workable substitute for practical work (Broyer

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et al., 2020; Mahaffey, 2021). A preliminary study conducted at the research site reproduced this pattern: laboratory equipment and reagents were limited, titration practicums were seldom conducted, and learners' mastery of the topic remained below the school's minimum criterion. The problem addressed in this study is thus not hypothetical but locally documented.

Virtual laboratories have emerged as a response to both problems. By simulating apparatus, reagents, and procedures in a digital environment, they allow learners to manipulate variables, repeat experiments, and observe outcomes without the cost, risk, and scheduling constraints of physical facilities (Agbonifo et al., 2020; Wu et al., 2019). The accumulated evidence is encouraging but qualified. A systematic review of virtual chemical laboratories found them to be more effective than passive modes of instruction and broadly comparable to hands-on work, with the strongest results obtained when virtual and physical laboratories are combined rather than substituted (Chan et al., 2021). A recent three-level meta-analysis likewise reported a moderate positive effect of virtual technologies on chemistry learning, with effect sizes moderated by educational stage, learning content, and the form of the virtual environment (Song et al., 2025). Comparable conclusions have been drawn for science education more generally (Santos & Prudente, 2022) and for laboratory consciousness and skills at the tertiary level (Kolil & Achuthan, 2024; Kurniawati et al., 2023; Thayban et al., 2020). What these syntheses share is a common qualification: outcomes depend less on the presence of a virtual laboratory than on how it is designed and integrated.

This qualification indicates where the design of such media should be anchored. The cognitive theory of multimedia learning holds that learners process verbal and pictorial information through separate channels of limited capacity, and that meaningful learning occurs when they select, organise, and integrate the incoming material with prior knowledge (Mayer, 2024). Cognitive load theory adds that instructional formats should minimise the extraneous load imposed by the presentation itself so that the available working memory can be devoted to schema construction (Sweller et al., 2019). Taken together, these frameworks translate into concrete design decisions for a titration simulation: presenting narration and visualisation in complementary channels rather than duplicating them, segmenting the procedure into manageable steps, scaffolding early attempts, and providing immediate feedback. They also explain why a simulation is pedagogically valuable in this particular topic, since animation can render the submicroscopic level of Johnstone's triplet directly observable instead of leaving it to be inferred.

The development process itself requires an equally systematic basis. The ADDIE model, comprising the Analysis, Design, Development, Implementation, and Evaluation phases, provides a structure in which each design decision is traceable to an identified need and each product claim is supported by evidence gathered at a defined stage (Branch, 2010). Its iterative evaluation cycle is what distinguishes systematic instructional design from ad hoc media production, and it has been applied productively in previous virtual laboratory development studies (Galang et al., 2022; Kharki et al., 2021).

Three considerations nevertheless indicate that the available evidence is incomplete. First, the reviewed literature is dominated by desktop three-dimensional environments and, more recently, by immersive virtual reality (Chan et al., 2021); both presuppose hardware that schools with limited resources do not possess, whereas the Android smartphone is already in learners' hands and requires no additional institutional investment. Second, studies of virtual titration media in the Indonesian context tend to report either the feasibility of a product or its effect on learning outcomes, so that validity, readability, practicality, and effectiveness are seldom documented within a single, complete development cycle (Rusdi et al., 2021; Sari et al., 2021; Solikhin et al., 2019). Third, design decisions in such studies are rarely justified in terms of an explicit learning theory, which makes it difficult to attribute observed gains to particular design features. An Android-based virtual laboratory for acid-base titration, developed through a full ADDIE cycle and grounded in multimedia and cognitive load principles, therefore addresses a gap that is at once technological, methodological, and theoretical.

Accordingly, this study aimed to develop an Android-based virtual laboratory for acid-base titration and to evaluate its quality as a learning medium for senior high school chemistry. Three questions guided the work: (1) Is the developed virtual laboratory valid according to media experts, material experts, and chemistry teachers? (2) Is it readable and practical from the perspective of the learners who use it? (3) Is it effective in improving learners' conceptual understanding of acid-base titration? By answering these questions, the study contributes a theoretically grounded and empirically evaluated model of mobile virtual practicum that is deployable in schools where laboratory infrastructure is the binding constraint.

Method

Research Design

This study employed a research and development (R&D) design guided by the ADDIE instructional design model, which organises the work into five sequential phases: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2010; Creswell, 2014). The model was selected because its embedded evaluation cycle allows each product claim to be traced to evidence collected at a defined stage, and because it accommodates the iterative revision that media development requires. The complete research procedure, including the activities and outputs of each phase and the revision loop applied at the validation stage, is presented in Figure 1.

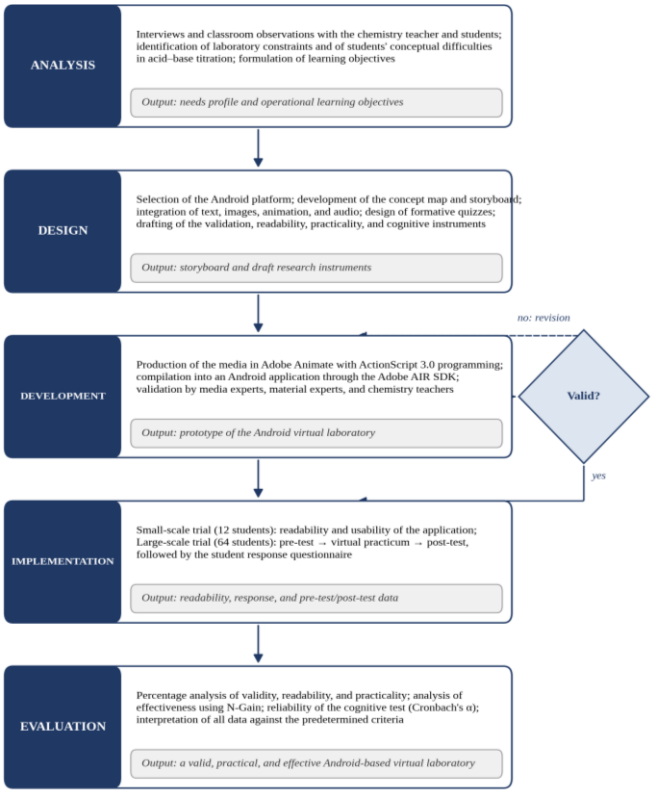


Figure 1. Research procedure based on the ADDIE model

The study was conducted at SMAN 1 Suwawa. The product was validated by three groups of experts, comprising a media expert, a material expert (both chemistry lecturers), and a chemistry teacher. The readability trial involved 12 students of class XII MIPA who did not take part in the main trial, while the large-scale trial involved 64 students who used the virtual laboratory during their practicum activities.

Research Procedure

In the Analysis phase, interviews and classroom observations were carried out with the chemistry teacher and students to identify the constraints of the existing laboratory and the conceptual difficulties encountered in acid-base titration, and to establish the learning objectives that the media would have to serve (Kharki et al., 2021).

In the Design phase, Android was selected as the delivery platform on the grounds of learner access, and a concept map and storyboard were prepared to specify the content structure, the interactive elements, and the integration of text, images, animation, and audio. Formative quizzes were designed to support active processing, and the research instruments were drafted in this phase (Galang et al., 2022; Hutama & Hidayah, 2022; Iftitah Hauriyah et al., 2019; Linda Ardianti et al., 2025; Wahab et al., 2021; Zhang & Liu, 2024).

In the Development phase, the media were produced using Adobe Animate with ActionScript 3.0 programming and compiled into an Android application through the Adobe AIR SDK. The prototype was then submitted to expert validation; products that did not yet meet the validity criteria were revised and re-evaluated before proceeding, as indicated by the revision loop in Figure 1 (Solikhin et al., 2019).

In the Implementation phase, the application was trialled in two stages. The small-scale trial with 12 students examined the readability and usability of the application. The large-scale trial with 64 students integrated the virtual laboratory into the learning process: a pre-test was administered before the virtual practicum and a post-test afterwards, followed by a response questionnaire (Agbonifo et al., 2020; Mahaffey, 2021).

In the Evaluation phase, all data on validity, readability, practicality, and effectiveness were analysed and interpreted against predetermined criteria in order to determine whether the product qualified as a valid, practical, and effective learning medium.

Instruments

Five instruments were used. An interview and observation guide supported the needs analysis. Validation sheets covering content and media aspects were completed by the three validators. A readability questionnaire was administered in the small-scale trial, and a response questionnaire measuring support for learning objectives, ease of use, and overall user experience was administered in the large-scale trial. Conceptual understanding was measured by a cognitive test administered as a pre-test and a post-test. The reliability of the test instrument was confirmed with a Cronbach's alpha of 0.905, which exceeds the conventional threshold of 0.70 (Astuti et al., 2020; Rizki et al., 2024; Silva, 2023).

Data Analysis

Data from the validation sheets and the readability and response questionnaires were analysed descriptively as percentages using the following formula:

$$P = (\Sigma x / \Sigma xi) \times 100\% \quad (1)$$

where P is the achieved percentage, Σx is the total score awarded, and Σxi is the maximum possible score. The resulting percentages were interpreted against the criteria presented in Table 1.

Table 1. Interpretation criteria for Validity, Readability, and practicality

Percentage range (%)	Category	Decision
85.00 - 100	Very valid / very good	Usable without revision
70.00 - 84.99	Valid / good	Usable with minor revision
55.00 - 69.99	Fairly valid / fair	Usable with major revision
< 55.00	Not valid / poor	Not usable

The effectiveness of the virtual laboratory was determined from the pre-test and post-test scores using the normalised gain:

$$\mathrm{N-gain} = \frac{S_{post} - S_{pre}}{S_{max} - S_{min}} \quad (2)$$

where S_pre and S_post are the mean pre-test and post-test scores and S_max is the maximum attainable score. The resulting index was interpreted using the conventional categories, namely high for N-Gain ≥ 0.70, moderate for 0.30 ≤ N-Gain < 0.70, and low for N-Gain < 0.30. A product was regarded as feasible when it satisfied the validity, readability, and practicality criteria simultaneously, and as effective when the N-Gain reached at least the moderate category.

Result and Discussion

Analysis Phase

The development of the Android-based virtual laboratory followed the ADDIE model, beginning with a thorough analysis phase involving interviews and observations at SMAN 1 Suwawa. Key findings included a lack of tools and resources for practical activities, teacher hesitance in conducting certain procedures, and students' limited understanding of acid-base titration, as evidenced by an average test score of 62.6, below the passing criteria. Observations revealed that the chemical laboratory was neglected and under-equipped. These findings align with established research emphasizing the importance of needs assessment for context-aware virtual laboratory development (Kharki et al., 2021; Silva et al., 2016). This analysis established a clear foundation for designing media that directly addresses identified gaps and constraints.

This initial stage was critical in ensuring that the virtual laboratory met actual educational needs and technological realities. Integrating qualitative and quantitative data allowed a comprehensive understanding of learner readiness and infrastructure limitations, fostering a realistic and targeted development approach (Ernawati & Ikhsan, 2021).

Design Phase

The design of the virtual laboratory adhered to established principles aimed at enhancing engagement and effective learning, based on prior analysis including media format selection and storyboard creation that integrated multimedia elements such as videos, animations, and 3D models (Astuti et al., 2020; Mahaffey, 2021).

Key design elements included interactive features allowing manipulation of titration variables, realistic simulations reflecting laboratory conditions, and immediate feedback systems to guide student learning (Hensen et al., 2020; Silva et al., 2016).

Cognitive load management strategies such as scaffolding and segmented information supported learner comprehension (Agbonifo et al., 2020). The learning media, developed as an Android application, contained interconnected information in text, graphics, animations, and audio. Testing by subject matter and media experts used validation instruments developed by the researcher, with iterative refinements based on pilot feedback (Zhang & Liu, 2024).

The design phase focused on media design and content/animation material based on the storyboard or media concept map. The storyboard developed can be seen in Table 2. Effective storyboarding and media design translated instructional goals into interactive, immersive experiences promoting active learning and conceptual understanding. User-centered design and expert feedback ensured pedagogically sound and accessible content (Silva et al., 2016).

Table 2. Storyboard of Virtual Laboratory

Activity	Visual	Audio
Title	Written: M-THE Titration: Virtual Chemistry Laboratory Acid-Base Titration	Background Music
Main Menu	Button Animation and Transition Menu: Introduction, Practicum, Quiz, and Report	Effect Button
Main Sub menu: Introduction	Animation Button and Transition Sub-sub menu: Basic competencies, Practicum Objectives, and Theory Base	Effect Button
Sub-sub menu: Basic Competencies	Written: Basic competencies that must be achieved	Background Music
Sub-sub menu: Practicum Outline	Written: Practicum Outline	Background Music
Sub-sub menu: Basic theory	Written: Basic theory of Acid-Base titration	Background Music
Main Sub menu: Practicum	Animation Button and Transition Sub-sub menu: Tools and Materials, Procedure, Simulation, and Result	Effect Button
Sub-sub menu: Tools and Materials	Written: Tools and Materials	Background Music
Sub-sub menu: Procedure	Written Procedure For three experiment	Background Music
Sub-sub menu: Simulation	Written: Experiment 1, Experiment 2, Experiment 3	Effect Button
Sub-sub menu: Result Observation	Written: Result Observation	Background Music
Main Sub menu: Quiz	Written: Quiz question of Acid-Base Titration	Background Music
Main Sub menu: Report	Written: Report Form	Background Music

Development Phase

The virtual laboratory media was developed using Adobe Animate with ActionScript 3.0 programming, creating interactive buttons and embedding content related to acid-base titration, competency standards, learning objectives, practicum activities, audio, and images to enrich the experience. After completing animations, coding was finalized.

The product was compiled into an Android application via Adobe AIR SDK installation and publish settings to enable mobile accessibility. This approach ensured interactivity and multimedia richness critical for engagement and understanding (Pang et al., 2022; Silva et al., 2016). The process of developing the virtual laboratory media and its final results can be seen in Figure 2 and Figure 3 respectively.

The development phase successfully converted design specifications into a functional tool optimized for accessibility and usability, enhancing the learning experience consistent with educational technology best practices (Astuti et al., 2020).



Figure 2. The process of developing virtual laboratory



Figure 3. The results of virtual laboratory development

Implementation Phase

The Implementation phase consisted of two trial stages: a small-scale trial followed by a large-scale trial. In the small-scale trial, the virtual laboratory product was tested on 12 students from class XII MIPA SMAN 1 Suwawa, who were not part of the main trial group. This phase focused on evaluating the readability and usability of the product using a questionnaire designed to assess readability prior to broader testing. The large-scale trial involved 64 students who used the virtual laboratory during virtual practicum activities integrated within the learning process. Before the practicum, students completed a pre-test to measure their conceptual understanding of acid-base titration, and afterward, a post-test was administered to assess the virtual laboratory's effectiveness.

Additionally, response questionnaires were administered following the completion of the learning and practicum process to gauge user satisfaction and the practicality of the virtual laboratory product. These phased trials facilitated iterative improvements based on feedback, consistent with methodologies supported

by educational media evaluation literature (Badarudin et al., 2024; Davy & Quane, 2021).

The staged implementation facilitated refinement before broad deployment, balancing innovation with practical usability and effectiveness. Small group trials identified usability issues, whereas larger samples confirmed the virtual laboratory's positive impact on learning outcomes and user experience (Kharki et al., 2021).

Evaluation Phase

All data gathered during implementation, comprising expert validation scores, readability results, practicality responses, and pre-test and post-test scores, were analysed and interpreted against the criteria established in the Method. The four criteria are reported in turn below, each followed by an interpretation of the pattern in the data and a comparison with previous studies.

Product Validation

Validation was carried out by three groups of experts, namely a media expert, a material expert, and a chemistry teacher. As presented in Table 3, the media expert awarded 80.6%, the material expert 90.1%, and the chemistry teacher 93.6%, yielding a mean of 88.1% and placing the product in the very valid category.

The mean alone, however, conceals the more informative feature of these data. The three scores differ by 13.0 percentage points, and the difference is systematic rather than random: the two highest ratings concern the accuracy of the subject matter and its alignment with the curriculum, whereas the lowest concerns the media and technical presentation of the application. The material expert and the teacher assessed content that had been derived directly from the objectives formulated in the Analysis phase, and found few substantive gaps. The media expert, by contrast, assessed interface layout, navigational consistency, typography, and the balance between visual and auditory channels, dimensions that were constrained by developing the application in Adobe Animate with ActionScript 3.0 within a chemistry education team rather than with a dedicated interface designer. Read in this way, the validation data do not merely certify the product; they locate precisely where the next development iteration should be invested, namely in interface refinement rather than in content revision.

Table 3. Virtual Laboratory Validation Results

Validators	Score of Validation (%)	Criteria
Media Expert (Chemistry Lecture)	80.6	Valid
Material Expert (Chemistry Lecture)	90.1	Very Valid
Chemistry Teacher	93.6	Very Valid
Average	88.1	Very Valid

The overall figure is consistent with what has been reported for comparable products. Muchson et al. (2018), who developed an Android-based virtual laboratory for the acid-base topic at the same educational level, obtained 85.44% for its function as a learning medium and 84.67% for conceptual accuracy, both categorised as highly feasible. Reny et al. (2018) reported valid ratings across all measured aspects for an interactive multimedia virtual laboratory on acid-base titration, and Rusdi et al. (2021) recorded a very good mean rating from material, information technology, and practitioner validators for a virtual laboratory on the same topic. The value obtained here therefore falls within the band that characterises this class of media in the Indonesian context. Two qualifications are nevertheless necessary. First, percentages produced by different validation instruments and rating scales are comparable at the level of category rather than of magnitude, so the convergence reported above should be read as agreement about feasibility and not as evidence of superiority. Second, a panel of three validators is small, and the influence of any single rater on the mean is correspondingly large; the 80.6% awarded by the media expert would shift the mean by more than four percentage points if it were revised after interface improvement.

Theoretically, the high content ratings are what a needs-based design procedure would predict. Because the objectives were established from interviews and observations before any material was produced, and because the presentation followed multimedia design principles by combining verbal and pictorial channels, segmenting the procedure into discrete steps, and providing feedback at each stage (Jaeggi et al., 2017; Mayer, 2024; Sweller et al., 2019), the validators encountered a product whose content and structure were internally coherent.

Product Readability

The readability test was administered to 12 students who did not take part in the main trial. As shown in Table 4, the mean score was 89.7%, which places the application in the very good category.

The distribution behind this mean is more informative than the mean itself. Individual scores ranged from 80.0% to 97.5%, a spread of 17.5 percentage points, with a median of 90.5% and a standard deviation

of 4.69. Ten of the twelve students scored at or above 85%, and no student fell below 80%. Two implications follow. First, the favourable mean is not produced by a small group of enthusiastic users offsetting students who struggled: every participant rated the application within the very good band, so readability holds across the group rather than on average. Second, the lower boundary of the distribution is what constrains the claim. The two scores in the low eighties indicate that text density and the depth of the navigational hierarchy still impose a noticeable burden on some users, which is consistent with the expectation from cognitive load theory that identical multimedia material imposes unequal loads on learners who differ in prior knowledge and in familiarity with the device (Sweller et al., 2019). Reducing the amount of text presented simultaneously and shortening the path to the simulation menu are the two revisions these data support.

Table 4. Results of Product Readability Test Analysis

Respondent	Questionnaire Result (%)	Criteria
01	90.5	Very Good
02	83.5	Very Good
03	86.6	Very Good
04	93.3	Very Good
05	92.8	Very Good
06	89.2	Very Good
07	97.5	Very Good
08	80	Very Good
09	88.2	Very Good
10	90.5	Very Good
11	92.5	Very Good
12	91.9	Very Good
Average	89.7	Very Good

The result is closely comparable to previous work. Muchson et al., (2018) trialled their Android-based acid-base virtual laboratory with a group of the same size and obtained a student perception score of 89.27%, which is within half a percentage point of the value recorded here. The convergence of two independently developed Android applications on nearly identical readability ratings with comparable sample sizes suggests that the result reflects the suitability of smartphone delivery for this population rather than a feature peculiar to one product.

Practical Assessment

Practicality was assessed through a response questionnaire completed by the 64 students who participated in the large-scale trial, covering support for the learning objectives, ease of use, and overall user experience. The mean response was 84.72%, which falls in the very practical category (Figure 4).

Because the questionnaire is a self-report instrument, this figure represents practicality as perceived by the users, and the claim is framed accordingly. Perceived practicality is a necessary but not a sufficient indicator: it establishes that students did not experience the application as an obstacle, but it does not by itself demonstrate that the medium is workable under routine classroom conditions. Three further pieces of evidence available in this study converge with the questionnaire result. The large-scale trial was completed by all 64 students within regularly scheduled lessons using devices they already owned, without additional laboratory equipment, reagents, or scheduling of laboratory access, which is a direct observation of feasibility rather than a perception of it. The readability results obtained from an independent group of students point in the same direction on the dimension of ease of use. Finally, the learning gain recorded in the same cohort is consistent with an interface that did not impede engagement with the task, since an application that obstructed use would be unlikely to produce a gain of this magnitude.

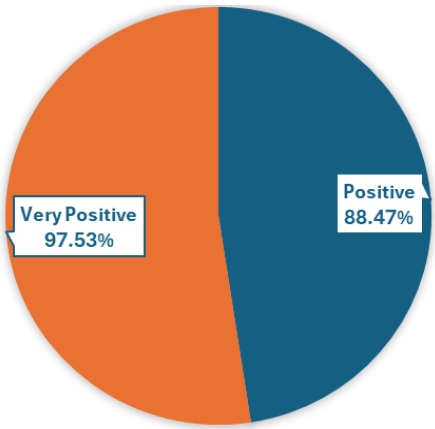


Figure 4. The findings of the examination of the students' response questionnaire

These practical advantages are the ones that reviews of virtual laboratories consistently identify: the removal of reagent and equipment costs, freedom from scheduling constraints, and the possibility of repeating a procedure as often as a learner wishes (Achuthan et al., 2018; Chan et al., 2021; Kolil & Achuthan, 2024). Comparable practicality levels have been reported for chemistry virtual laboratories developed in Indonesia, including the practical category recorded by Reny et al. (2018) for acid-base titration and the 89.27% user response obtained by (Muchson et al., 2018).

The limitation of the present evidence should nevertheless be stated plainly. Perceived practicality and observed practicality are distinct constructs, and only the former was measured. A stronger evidential basis would require classroom observation during implementation, usage logs recording time on task and the number of simulation repetitions, interviews with

the teacher responsible for delivery, and a trial conducted by a teacher who was not involved in developing the product. These are recommended for subsequent research.

Effectiveness: Pre-Test and Post-Test Results

Effectiveness was determined from the pre-test and post-test administered to the 64 students in the large-scale trial, with the reliability of the instrument confirmed at a Cronbach's alpha of 0.905. As presented in Table 5, the mean score rose from 9.45 before the virtual practicum to 16.02 afterwards, against a maximum attainable score of 18. Expressed as proportions of the maximum, mastery increased from 52.5% to 89.0%, an absolute gain of 6.56 items or 36.5 percentage points. The resulting N-Gain of 0.768 falls in the high category and indicates that 76.8% of the improvement margin still available to the cohort at pre-test was realised.

Table 5. Pre-test and Post-test Results

Data	Pre-test	Post-test
Student	64	64
Maximal Score	1.151	1.152
Score total	605	1025
Average	9.453125	16.015625
N-Gain		0.768

The more substantive question is where this improvement is located, and the design of the application makes four mechanisms plausible. First, the particulate animation renders visible the submicroscopic level at which titration is actually explained, addressing the well-documented difficulty learners have in relating the observable colour change at the endpoint to the underlying proton transfer, and thereby connecting the levels of representation that make this topic demanding (Johnstone, 1991). Second, the simulation can be repeated without consuming reagents, so learners can approach the endpoint repeatedly and observe the consequences of overshooting it, a form of practice that a single physical titration cannot provide. Third, the segmentation of the procedure into discrete steps, together with the immediate feedback supplied by the embedded quizzes, supports the selection, organisation, and integration of new material while limiting the extraneous load imposed by the presentation itself (Mayer, 2024; Sweller et al., 2019). Fourth, the report form requires learners to convert their observations into symbolic calculation, which links the macroscopic and symbolic levels within a single task.

These four mechanisms are consistent with the observed gain, but the present data cannot establish their individual contributions, because the cognitive test was analysed at the level of total scores rather than of individual items or concept indicators. Determining which aspects of titration understanding improved most, and which resisted improvement, would require an item-level or indicator-level analysis, and this is the most immediate methodological extension of the present work.

The magnitude of the gain is consistent with previous development studies on the same topic. Reny et al. (2018) reported an N-Gain of 0.785 for an interactive multimedia virtual laboratory used in an acid-base titration practicum, a value that differs from the present result by less than 0.02 and falls in the same high category. Comparisons of this kind should nevertheless be interpreted with care. The present study used a single-group pre-test and post-test design without a control class, so the N-Gain necessarily incorporates the effects of testing, instruction, and maturation alongside the effect of the medium. It is therefore not equivalent to the between-group effect sizes reported in meta-analytic work, such as the moderate average effect of virtual technologies on chemistry learning reported by Song et al. (2025), and it should not be read as evidence that the application outperforms conventional practicum. What the data support is the narrower and defensible claim that the cohort achieved a substantial improvement in conceptual understanding after using the product, in a school where the physical alternative was not available. This reading is congruent with systematic reviews concluding that virtual laboratories outperform passive modes of instruction and perform comparably to hands-on work, with the strongest outcomes obtained when the two are combined rather than substituted (Chan et al., 2021; Hensen et al., 2020; Thayban et al., 2021).

Limitations of the Study

Four limitations qualify the conclusions drawn above. The product was validated by a panel of three experts, so the mean validity score is sensitive to individual judgements. The trial was conducted in a single school, which limits generalisation to other settings and levels of device familiarity. Practicality was established from self-reported responses without accompanying observational or log data. Finally, the absence of a control group and of an item-level analysis means that the size of the gain cannot be attributed to the medium alone, nor distributed across the specific concepts that constitute understanding of acid-base titration. A quasi-experimental design incorporating a comparison class, an item-level analysis of the cognitive test, and a delayed post-test measuring retention would address these limitations directly.

Conclusion

This study developed an Android-based virtual laboratory for acid-base titration through a complete ADDIE cycle and evaluated it against four criteria. The product was judged very valid, with a mean expert rating of 88.1%, although the spread across validators indicates that its content and curricular alignment are stronger than its interface design. It proved very readable, with a mean of 89.7% and with every student in the small-scale trial rating it within the very good band, and it was perceived as very practical (84.72%) by the 64 students of the large-scale trial. Conceptual understanding rose from a mean of 9.45 to 16.02 out of a maximum of 18, giving an N-Gain of 0.768 in the high category, so that 76.8% of the improvement margin available to the cohort was realised. Because the study used a single group without a control class and analysed the test at the level of total scores, these results establish that the product is feasible and that the cohort improved substantially after using it, rather than that it outperforms conventional practicum. The virtual laboratory is therefore recommended as a practicum alternative where laboratory facilities are limited and as pre-laboratory preparation where they are available, with further research directed at a comparison class, item-level analysis of conceptual gains, and retention over time.

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Author Contributions
Conceptualization, M.S. and T.T.; methodology, H.M.; software, T.T.; validation, E.K.; data curation, E.K. and H.M.; writing—original draft preparation, T.T.; writing—review and editing, T.T.

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Conflicts of Interest
The authors declare no conflict of interest.

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