



Development of A Virtual Laboratory for Electrochem to Support Students' Critical Thinking Skills

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Abstract

The application of interactive learning media plays an important role in stimulating motivation and deepening students' understanding, especially in bridging the characteristics of abstract chemistry learning, one of which is the material of electrolyte and non-electrolyte solutions. The main problem in chemistry learning in Madrasah Aliyah is the limited physical laboratory facilities, which impacts the low critical thinking skills of students. This study aims to develop a Virtual Laboratory "Electrochem Lab" that supports critical thinking skills and to test its feasibility conceptually and practically. As a supporting instrument, Electrochem Lab is equipped with an evaluation feature in the form of a quiz consisting of 5 questions based on Higher Order Thinking Skills (HOTS) that have been adjusted to train students' critical thinking skills independently. The study adopts a Research and Development (R&D) framework, specifically following the Lee & Owens model, which progresses through phases of analysis, design, development, implementation, and evaluation. The experimental subjects involved two experts (materials and media), one chemistry teacher, and 13 students of grade XI IPA MAN 5 Batang Hari consisting of 3 students in one-to-one tests with heterogeneous cognitive representations and 10 students in small group tests. The data collection instrument used a Likert Scale questionnaire consisting of a media expert questionnaire and a material expert questionnaire, a student response questionnaire and a one-to-one trial instrument. Evidence of the validity of the instrument and product was obtained through expert assessments stating that the media was very suitable for testing. The results showed a feasibility percentage of 90% from media experts and 89.23% from material experts, both of which were considered very suitable. The practitioner's assessment (chemistry teacher) reached 94.55%, while the one-to-one test reached 86,6% and the small group trials reached 98% with a very good category. It can be concluded that the Android-based virtual laboratory "Electrochem Lab" is very suitable to be used as an innovative solution to bridge the understanding of abstract concepts through sub-microscopic visualization and support the training of students' critical thinking skills. The novelty of this research lies in the integration of a contextual approach in digital simulations that connect learning materials with the students' surroundings and the Madrasah Aliyah environment.

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INTRODUCTION

National education plays a crucial role in building a proud national character and civilization, as stipulated in Law Number 20 of 2003. This effort is realized through the learning process, which is essentially a process that enables

the transfer of information and knowledge through reciprocal relationships between educators and students (Asyhar, 2010). Furthermore, education develops not only knowledge but also behavior, speech, and

attitudes to achieve success and innovation, which are summarized in the educational character.

To address 21st-century challenges, the Indonesian education system is currently undergoing a structural transformation through the implementation of the Independent Curriculum (Kurikulum Merdeka). This framework shifts the pedagogical focus from rote memorization to the cultivation of holistic competencies and soft skills, including critical thinking, collaboration, and creativity (Utami et al., 2025). To optimize this transition, the Ministry of Primary and Secondary Education emphasizes a Deep Learning approach anchored in three fundamental pillars: mindful, meaningful, and joyful learning (Nabila et al., 2025). Theoretically, the efficacy of this approach is highly contingent upon classroom interactions, where educators are expected to facilitate students' synchronized behavioral, physical, and psychological growth (Wulandari, 2023). In practice, however, pedagogical creativity remains paramount, as external factors such as suboptimal teaching methodologies and a deficiency in instructional media continue to hinder student engagement and learning interest (Febriani et al., 2024).

In creating a meaningful learning environment, a contextual approach is highly relevant because the learning process occurs not only cognitively but also by connecting learning materials with real-world relevance (Mashudi & Azzahro, 2020). Implementing Contextual Teaching and Learning (CTL) facilitates profound student engagement by aligning curriculum content with authentic life experiences. This integration is instrumental in fostering critical inquiry and the development of constructive character attributes (Arwin et al., 2025). Critical thinking skills themselves are the ability to reason logically and systematically with the aim of understanding the relationships between various ideas and facts (Nadhiroh & Anshori, 2023).

Students who possess good critical thinking skills are generally better able to deepen their understanding of the subject matter, solve problems more effectively, and make more informed decisions (Ariadila et al., 2023). According to Ennis's conceptualization, critical thinking skills are measured through indicators such as delivering simple clarifications, building core competencies, drawing conclusions, offering

detailed explanations, and managing tactical strategies (Tan, 2007).

The need for critical thinking skills is particularly evident in science learning, particularly chemistry. Media plays a crucial role in the chemistry learning process, helping students understand the concepts being studied (Lena et al., 2020). This is because chemistry has unique characteristics that involve understanding at the macroscopic, sub-microscopic, and symbolic levels (Experenza et al., 2019). Topics such as electrolyte and non-electrolyte solutions are often considered abstract because they involve the concept of ionization, which is invisible to the naked eye. Difficulty understanding these ideas stems from a variety of factors, primarily the complex nature of the topic. Students often report confusion about specialized terms they've never encountered before. In particular, they struggled to remember formulas, technical terms, and symbols related to chemistry (Garingo & Cajucom, 2023). Therefore, the use of media as a teaching aid can be an important solution to overcome boredom in the learning process (Epinur & Miharti, 2024). Furthermore, the use of appropriate learning media has been shown to increase student motivation, thereby improving academic achievement (Ekaputra et al., 2023).

One of the supporting facilities that plays a crucial role in providing hands-on learning experiences for students is the laboratory. Laboratories are facilities used to conduct various experiments or research in scientific fields such as physics, chemistry, biology, and. The existence of laboratories is crucial as a means of verifying concepts to bridge the gap between theory and reality (Susanti et al., 2021). However, empirical reality shows that the gap in educational facilities remains large, with many schools in regional areas experiencing limited physical laboratory facilities (Mustika & Hamidah, 2025). This situation demands the existence of interactive and easily accessible technological learning media to accommodate various student learning styles (Zurweni & Malik, 2022).

As an innovative solution, virtual laboratories can provide macroscopic visualizations for both abstract and concrete materials, and facilitate students' safe and cost-effective experimentation (Sujono et al., 2023). Virtual laboratories are a representation of real laboratories, so students' practical learning experiences remain similar to

those in real laboratories (Yanto et al., 2022). Through this medium, students tend to be more engaged and enthusiastic in understanding learning concepts (Fadli et al., 2024).

Virtual laboratory research in chemistry learning consistently demonstrates a positive impact on student motivation and learning outcomes. For example, research conducted by Qurniati (2022) developed Adobe Flash-based media for macromolecules, which was shown to increase learning motivation. Consistent with these findings, Tangka & Tani (2022) utilized PhET simulations for acid-base learning and reported improved cognitive learning outcomes. Furthermore, Fauziah et al., (2024) examined the use of OLABS for chemical equilibrium and found a positive impact on learning motivation. However, existing digital tools are still general-purpose and lack a specialized framework to support critical thinking abilities within the specific scope of electrolyte and non-electrolyte topics.

This research addresses this gap by developing a virtual laboratory, "Electrochem Lab," integrated with critical thinking support components. This medium presents practical simulations based on contextual materials (such as coconut water and isotonic drinks), as well as interactive evaluations based on HOTS questions to practice analysis, inference, and problem solving. This development provides an innovative solution for Madrasah Aliyah (Islamic Senior High School) with limited practical facilities while supporting a meaningful learning approach to equip students with 21st-century competencies. However, this research has limitations in its development, which only focuses on the small-group trial stage to measure the level of validity, feasibility, and technical practicality of the media. This research has not yet reached the stage of large-group testing or testing the product's effectiveness on a large scale to comprehensively measure the significant impact on student learning outcomes or academic achievement.

METHOD

This study employs a Research and Development (R&D) approach to construct the virtual laboratory. The Lee & Owens (2004) framework was specifically selected as the developmental guide due to its specialized focus on multimedia

production. The research process adheres to five integrated phases: analysis, design, development, implementation, and evaluation. A visual representation of this systematic Lee & Owens (2004) procedure is illustrated in Figure 1.

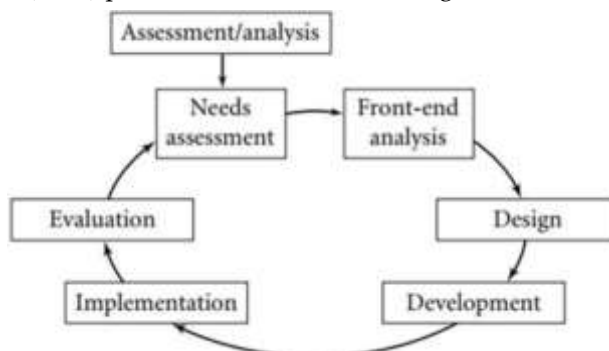


Figure 1. Multimedia Development Framework Proposed by Lee & Owens (2004)

Analysis

At the analysis stage, the researcher conducted an assessment of the actual conditions and learning issues at MAN 5 Batang Hari to serve as an empirical basis for media development. This phase is referred to as a needs assessment, which is a systematic process used to identify the gap between existing conditions and expected conditions (Awaludin et al., 2020). This process is divided into five main focus areas: first, analyzing learning needs to identify the essential requirements of both teachers and students; second, analyzing student characteristics to determine their interests and cognitive readiness; third, analyzing learning objectives to ensure the developed material is relevant to the target competencies; fourth, analyzing the electrolyte and non-electrolyte solution material to map out abstract concepts that require visualization; and fifth, analyzing educational technology to assess the availability of digital facilities supporting the use of the virtual laboratory.

Design

The design of the virtual laboratory commences with the development of a flowchart that serves as a systematic navigation guide, aligned with the Independent Curriculum's learning objectives for electrolyte and non-electrolyte solutions. This framework is further detailed in a storyboard to incorporate various multimedia components including text, graphics, videos, and animations across all pages. To maintain high standards of quality and feasibility, a validation phase is conducted with a panel of material specialists, media experts, and

educational practitioners. This process ensures that all design elements, from the navigational structure to the visual assets, adhere to the technical and pedagogical requirements that

support the training of students' critical thinking. Comprehensive data regarding the experts' academic backgrounds and professional experience are detailed in Table 1.

Table 1. Qualifications of Validator and Practitioner Team

No	Validator / Practitioner Name	Role	Academic Qualifications	Experience and Expertise
1	Dr. Dra. Zurweni, M.Si.	Media Expert	Doctoral Degree in Educational Technology	Expert in Educational Technology, Learning Models & Multimedia
2	Firdiawan Ekaputra, M.Pd.	Material Expert	Master's Degree in Chemistry Education	Academic in the field of chemistry education with expertise in Educational Evaluation, Educational Assessment.
3	Resti Effriani, S.Pd.	Practitioner	Bachelor's Degree in Chemistry Education	Chemistry teacher at Madrasah Aliyah level with classroom teaching experience.

Development

The development phase involves transforming the previously designed storyboard and flowchart into a product. The resulting product will be a virtual electrochem lab, consisting of a cover page, menu, user manual, learning objectives, materials, quizzes, laboratory, and developer profiles. Once the product is complete, it undergoes a validation process by a team of subject matter experts and media experts, and is assessed by practitioners. After expert validation, the product underwent formative evaluation through one-to-one and small-group trials to ensure its practicality and usability. Feedback

from these stages was used to finalize the virtual electrochem lab, resulting in a completed prototype ready for educational use.

Validation by Material Experts

To evaluate whether the depth and relevance of the instructional content within the virtual laboratory align with specified chemistry learning objectives, a validation process by subject matter experts is performed. This assessment specifically focuses on the integration of electrolyte and non-electrolyte solution topics with the intended learning outcomes. The detailed grid for the material validation instrument is provided in Table 2.

Table 2 Material Expert Validation Instrument Grid

No	Aspect	indicator	Item number
1.	Format	Consistency with core and basic competencies	1
		Alignment of indicators with basic competence	2
		Media interactivity capabilities	3
		Clarity of the flow of relationships between material concepts	4
		Material alignment with the applied curriculum	5
		Orderliness of material organization	6
		Attractiveness of material presentation	7
2.	Content	Ease of understanding material images within the media	8
		Depth of material presented in each sub-theme	9
3.	Language	Standardization of the language used	10
		Use of easily understandable language	11
4.	Assessment	Alignment between basic competencies and learning objectives in media questions	12
		Suitability of instructional time allocation for the material	13
Total			13

Validation by Media Experts

Evaluating the aesthetic standards and technical viability of the virtual laboratory involved a specialized media expert validation tool. The review process prioritized several key

dimensions, including user interface design, navigational flow, interaction capabilities, visual precision, and overall student accessibility. The structural outline for this validation instrument is presented in Table 3.

Table 3 Media Expert Validation Instrument Grid

No	Aspect	Indicator	Item number
1.	Relevance to Curriculum	Relevance between the virtual laboratory and the material	1
		Relevance between the virtual laboratory and learning outcomes	2
		Relevance between the virtual laboratory and Learning Objectives	3
		Relevance between the virtual laboratory and the Learning Objective Flow	4
2.	Layout	Consistency of the media display order	5
		Accuracy of user instructions	6
		Functionality of buttons and icons in the multimedia	7
		Consistency of images, text, and animations	8
3.	Language	Standardization of the language used	9
		Use of language that is easy to understand	10
4.	Aesthetics	Attractiveness of the component displays in the multimedia (images, videos, animations)	11
		Legibility of the font type	12
		Consistency of colors on each media page	13
		Consistency in the use of color combinations and gradients	14
5.	Assessment	Alignment between basic competencies and objectives in the media questions	15
		Suitability of instructional time allocation for the material	16
Total			16

Teacher Assessment

Teacher assessment is used to determine teachers' responses and assessments of the developed virtual laboratory. This instrument is administered after the media has been deemed

appropriate by experts, with the aim of obtaining additional input regarding content, presentation, and its usefulness in supporting the chemistry learning process. The Teacher Assessment Instrument Grid can be seen in Table 4.

Table 4 Teacher Assessment Instrument Grid

No	Aspect	Indicator	Item number
1.	Content or Material	Material alignment with basic and core competencies	1
		Clarity of material presentation	2
		Consistency of the conceptual presentation order within the virtual laboratory media	3
		Depth of the presented material	4
		Provision of practice questions to train critical thinking skills and conceptual understanding	5
2.	Instructional	The virtual laboratory media can be used independently	6
		Increasing students' interest in understanding concepts	7
		Providing assistance to students in understanding material concepts	8
3.	Display	Consistency of colors on each page	9
		Appearance of images and animations	10
		Ease of navigation	11
Total			11

The evaluation instrument in the form of a validation questionnaire was prepared to be filled out by material experts, media experts, and education practitioners according to their respective competencies in providing assessments. According to Widoyoko (2012), to calculate the results of expert validation and teacher assessment, use the following formula:

$$\text{Average score} = \frac{\text{Total Score}}{\text{Total test Item}} \times 100\%$$

To determine the final percentage scores, the following equation is employed:

$$\text{Percentage} = \frac{\text{total score obtained}}{\text{maximum score}} \times 100\%$$

Table 5. Eligibility Criteria For Validator And Teacher Assessment

Average Score	%	Eligibility Criteria
> 4,2 – 5,0	81-100	Very Feasible
> 3,4 – 4,2	61-80	Feasible
> 2,6 – 3,4	41-60	Less Feasible
> 1,8 – 2,6	21-40	Infeasible

1,0 – 1,8	< 21	Highly Infeasible
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One-to-One Trials

The one-to-one trial instrument is implemented to determine whether the developed virtual laboratory is usable across various student cognitive levels. This stage involves three students representing low, medium, and high cognitive abilities. The one-to-one test instrument grid can be seen in the table.

Table 6. One-to-one test instrument grid

No	Indicator	Item Number
1.	Causes of electrolyte solutions conducting electricity	1
2.	Characteristics of non-electrolyte solutions in a flame test	2
3.	Characteristics of strong electrolyte solutions in a flame test	3
4.	The degree of ionization value for strong electrolytes	4
5.	Ionization mechanism in weak electrolytes	5

Table 7. The grid for the student response questionnaire

No	Aspect	Indicator	Item Number
1.	Content or Material	Material is easy to understand	1
		Images displayed are consistent with the material	2
		Language used is easy to understand	3
		Potential to increase interest in learning	4
2.	Instructional	Potential to increase student learning motivation	5
		Potential to provide understanding and reinforcement of student concepts	6
		Consistency of background color with the text	7
		Placement and function of buttons within the media	8
Display	Display	Appearance of animations, videos, and images	9
		Ease of navigation	10
Total			10

The grid for the student response questionnaire can be seen in the table 7. The student response data obtained from this small-group trial were analyzed quantitatively to determine the practicality level of the virtual electrochem lab. According to Riduwan (2015), the determination Trial Instruments and student responses based on the average score can be calculated using the following formula:

$$K = \frac{F}{N \times I \times R} \times 100\%$$

Description:

K = Percentage of eligibility

F = Total respondent scores

N = Maximum possible score

I = Number of questionnaire items

No	Indicator	Item Number
6.	Physical signs (bubbles) in weak electrolytes	6
7.	Degree of ionization in non-electrolyte solutions	7
8.	Examples of strong electrolyte compound groups (Salts)	8
9.	Electrical conductivity properties of solid ionic compounds	9
10.	Ionization of polar covalent compounds in water	10

Small Group Trial

A small group trial was conducted after the one-to-one trial was completed. Ten students were randomly selected by the teacher for this trial. A questionnaire was administered to the students after they participated in the trial of using the learning media to determine their responses to the media..

R = Total number of respondents

Table 8 . Category Of Trial Instruments and Student Responses

%	Description of Criteria
81-100	Very good
61-80	Good
41-60	Not Good
21-40	Bad
<21	Very Bad

Implementation

In the implementation phase, the research focus shifted to ensuring the procedural readiness of the ElectroChem Lab virtual laboratory for use in classroom learning. Given that the research was limited to a small group trial involving 10 students and a one-to-one trial with 3 students,

the implementation phase did not aim to conclude the product's broad effectiveness on student learning outcomes. Instead, this phase prioritized the preparation of pedagogical infrastructure, such as a Lesson Plan (RPP) and relevant evaluation instruments, to support the systematic integration of the virtual laboratory into the chemistry curriculum. This step ensured that, despite the limited scale of the trial to a small group, the product was conceptually, procedurally, and instrumentally ready for future large-scale implementation.

Evaluation

The evaluation stage aims to assess the success level of implementing the Virtual Laboratory 'Electrochem Lab' in achieving the determined learning objectives. The evaluation results serve as a basis for refining the media, ensuring that the developed product is more effective and aligned with learning needs.

RESULTS AND DISCUSSION

Result

Analysis

The analysis phase revealed a gap between the demands of the Independent Curriculum and the availability of learning support facilities in schools. Although the curriculum emphasizes active and meaningful learning, limited physical laboratory facilities hampered the optimal implementation of practical activities. This resulted in a learning process that remained teacher-centered and dominated by one-way media, limiting students' opportunities for exploration, discussion, and independent investigation. Traditional approaches that focus

on memorization and one-way transfer of knowledge from teacher to student tend to produce shallow understanding. Students may be able to remember formulas and definitions, but often have difficulty when asked to analyze, evaluate, or create new solutions based on the concepts they have learned (Casmini et al., 2024). Limited practical experience also impacted students' ability to analyze problems and draw scientific conclusions, which are important indicators of critical thinking skills. Conceptually, the topic of electrolyte and non-electrolyte solutions is abstract because it involves ionization processes at the particle level that cannot be directly observed. This necessitated students' need for learning media that could concretely visualize concepts and relate them to everyday phenomena. Furthermore, an analysis of the technological environment demonstrated the potential for utilizing students' personal digital devices and the relatively adequate support of school internet infrastructure, although its use in science learning has not been maximized.

Design

The next stage after analysis is the design stage, which is the product design process. At this stage, an initial design is developed, which will later be developed into a product in the form of a virtual electrochemistry lab. In designing this virtual electrochem lab product, the researcher first determined the material structure and compiled an initial product design which was visualized through a flowchart. The flowchart for developing a virtual electrochem lab on the topic of electrolyte and non-electrolyte solutions can be seen in the figure 2.

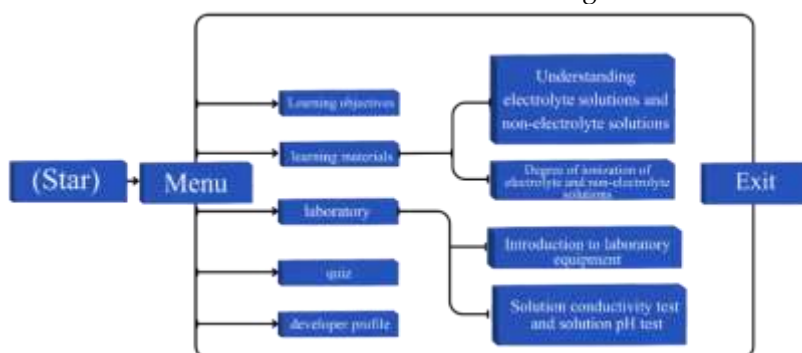


Figure 2. Virtual Laboratory Flowchart

Development

The development phase involves transforming the previously developed design into a product. The resulting product will be a virtual electrochem lab, consisting of a cover page, menu,

user manual, learning objectives, materials, quizzes, laboratory, and developer profile. The appearance of the virtual laboratory that was developed can be seen in Figure 3.



Figure 3. Visual overview of Key Features and Menus in "Electrochem Lab"

Material Expert Validation

The material validation was conducted by Mr. Firdiawan Ekaputra, M.Pd. The aspects assessed included the suitability of the material to the images, animations, and videos displayed in the virtual laboratory, as well as the alignment of the material with the learning outcomes, learning objective flow, and learning objectives. The validation process by material experts was carried out until a virtual laboratory deemed suitable for testing was obtained. The results of the validation can be seen in the table 10.

Table 10. Results of the First Stage of Material Expert Validation

Assessment Aspect	Score Obtained	Maximum Score
Format	12	20
Content	14	25
Language	5	10
Asesment	6	10
Total Score	37	65
Average Score	2,84	5

From table 10, the following graphic data results are obtained.

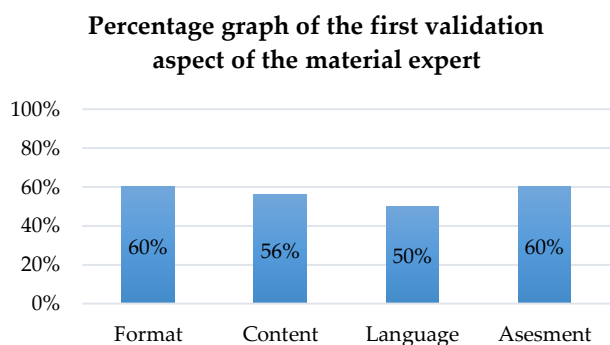


Figure 3. Percentage graph of the first validation aspect of the material expert

Based on the results of the first-stage validation conducted by the subject matter expert, a total score of 37 was obtained, with an average score of 2.84 and a feasibility percentage of 56.92%. This percentage falls within the 41%–60% range, indicating that the product is categorized as "Less Feasible." Aspect-based analysis shows that the language component received the lowest score, at 50%. This finding indicates several issues, including inconsistency in terminology usage, as well as ineffective sentence structures, particularly in the quiz section and practicum instructions. These issues may lead to ambiguity and potentially hinder students' conceptual understanding. The content aspect obtained a percentage of 56%. This result suggests that the material is generally relevant; however, it still requires refinement. Recommended improvements include restructuring the learning objectives to ensure alignment among Learning Outcomes (CP), Learning Objective Flow (ATP), and Learning Objectives (TP). In addition, revisions are needed in the introductory sentences and word choice when presenting examples, particularly in the topic of solutions, to ensure that the material is delivered in a more systematic and comprehensible manner.

Meanwhile, the format and assessment aspects each obtained a percentage of 60%. Although these scores are higher than those of other aspects, they still fall within the minimum feasibility threshold. In the assessment component, it is necessary to revise the structure and wording of the questions to better align with the indicators aimed at fostering critical thinking skills. Furthermore, in the virtual laboratory section,

more detailed and systematic practicum instructions should be added at each stage of the activity to support students' independent learning. Based on the above analysis, the product is not yet ready for field testing and requires comprehensive revisions before proceeding to the next stage.

Based on these revision notes, the researcher conducted comprehensive improvements on every aspect deemed weak, particularly in refining the language and the systematic organization of the material. Once all revision suggestions were integrated, the product was resubmitted for the second-stage validation process to ensure the final suitability and feasibility of the media before use. The results of the second-stage material validation can be seen in Table 11.

Table 11. Results of the Second Stage of Material Expert Validation

Assessment Aspect	Score Obtained	Maximum Score
Format	18	20
Content	22	25
Language	10	10
Assesment	8	10
Total Score	58	65
Average Score	4,46	5

From table 11, the following graphic data results are obtained:

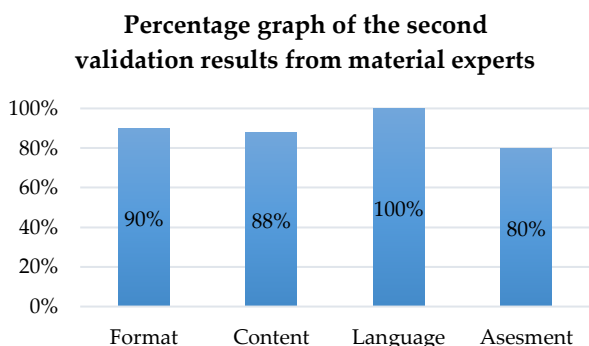


Figure 4. Percentage graph of the second validation results from material experts

Based on the data presented in Table 11, the results of the second-stage material expert validation show a very significant improvement in quality, with a total score of 58 and an average score of 4.46. This achievement resulted in a feasibility percentage of 89.23%, placing the media within the 81%–100% range under the category of “Highly Feasible.” The second-stage validation confirms that all aspects format, content, language, and assessment have met the

standards of material validity. Furthermore, the validator's comments indicate that the clarity of the material and the flow of presentation in the media are aligned with the learning objectives. Therefore, the product is considered materially feasible to be implemented in field testing without requiring further revision.

Media Expert Validation

Media expert validation was conducted by Dr. Dra. Zurweni, M.Si. The assessed aspects included curriculum alignment, layout, language, aesthetics, and assessment related to the Electrochem Lab virtual laboratory. The review process by media experts continued until the virtual laboratory was declared ready for testing. Details of the final findings from the media expert validation are presented in Table 12.

Table 12. Media Expert Validation Results

Assessment Aspect	Score Obtained	Maximum Score
Relevance to Curriculum	18	20
Layout	18	20
Language	10	10
Aesthetics	16	20
Assesment	10	10
Total Score	72	80
Average Score	4.5	5

From table 10, the following graphic data results are obtained.

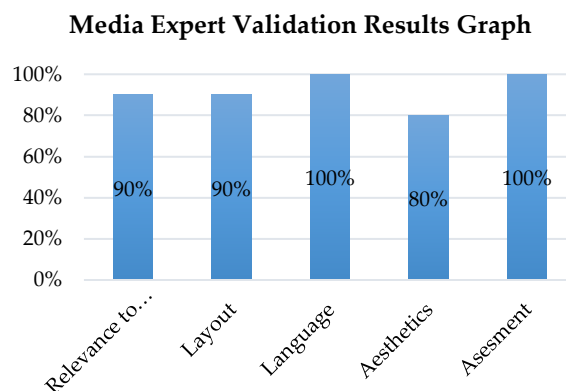


Figure 5. Media Expert Validation Results Graph

Based on the media expert validation results, a total score of 72 was obtained, with an average score of 4.5 and a feasibility percentage of 90%. This percentage falls within the 81%–100% range, placing the Electrochem Lab virtual laboratory in the “Highly Feasible” category. The validator suggested adding a password feature on the initial page to enhance security and user access management. Overall, the media was considered

to have met the technical standards and did not require further validation stages.

Aspect-based analysis demonstrated very strong performance, with the highest scores in the language and assessment aspects (100%), indicating clarity of language use and strong alignment of the assessment instruments. The relevance to curriculum and layout aspects each obtained 90%, reflecting consistency between the media design and the learning objectives. The aesthetics aspect received the lowest score at 80%, suggesting room for improvement in visual appeal and multimedia components. Overall, these findings indicate that Electrochem Lab is valid and ready to be implemented as a supporting medium for chemistry practicum activities.

Teacher Assessment

Before the product was implemented with students, an assessment and feedback session was conducted by a chemistry teacher as a form of practitioner validation. The results of the teacher's assessment and response to the product can be seen in Table 13.

Table 13. Teacher assessment results

Aspect	Score Obtained	Maximum Score
content or material	22	25
Instructional	15	15
Appearance	15	15
Total Score	52	55

Table 14. Results of the One-to-One Test

No	Indicator	Item Number			Total Score
		1	2	3	
1.	Causes of electrolyte solutions conducting electricity	10	10	10	30
2.	Characteristics of non-electrolyte solutions in a flame test	10	10	10	30
3.	Characteristics of strong electrolyte solutions in a flame test	10	10	10	30
4.	The degree of ionization value for strong electrolytes	0	0	10	10
5.	Ionization mechanism in weak electrolytes	0	10	10	20
6.	Physical signs (bubbles) in weak electrolytes	10	10	10	30
7.	Degree of ionization in non-electrolyte solutions	10	10	10	30
8.	Examples of strong electrolyte compound groups (Salts)	10	10	10	30
9.	Electrical conductivity properties of solid ionic compounds	0	10	10	20
10.	Ionization of polar covalent compounds in water	10	10	10	30
Total Score		70	90	100	260
Percentage		70%	90%	100%	86,6%

Based on the results of the one-to-one trial in table 14, a percentage graph was obtained for the cognitive level of each student, which can be seen in figure 7. Based on the table 14, it is known that the percentage of student answers is 86.6% which

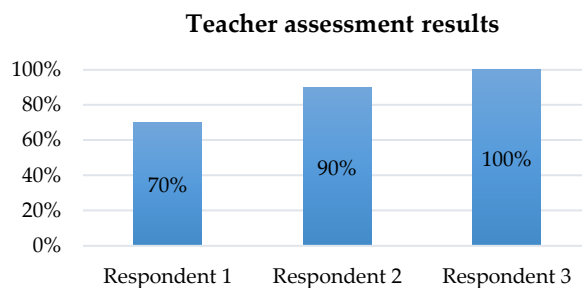


Figure 6. Teacher assessment results

Based on the assessment results conducted by the teacher, a total score of 52 was obtained with an average value of 4.72 and a percentage of 94.5% which is in the range of 81%–100%, so it is included in the "Very Feasible" category. These results indicate that the virtual laboratory is deemed worthy of being tested. The teacher also commented that the appearance of the developed Electrochem Lab virtual laboratory product is good, attractive, more challenging, and able to train students to think more critically.

One-to-one Test

At the trial stage, the virtual laboratory was first tested through a one-to-one trial aimed at obtaining information regarding the clarity, ease of use, sequence of operation, and completeness of the product components among students with varying levels of cognitive ability (low, moderate, and high). The sample selection for the one-to-one trial was based on the chemistry teacher's recommendation, taking into account the students' chemistry test scores.

is in the range of 81% - 100% with the criteria of "Very Good". In addition, students also gave general comments on the virtual laboratory that was developed, namely this virtual laboratory is easy to use and access on smartphones. The

product is also attractive. Students stated that it was easier to understand the subject material.

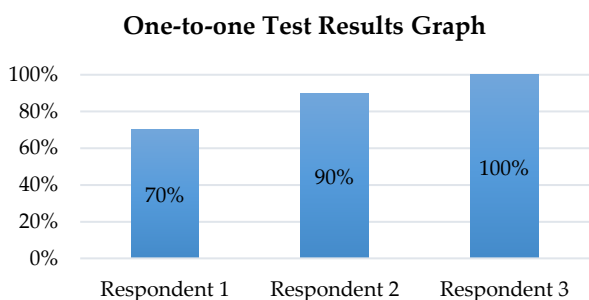


Figure 7. One-to-one Test Results Graph

Small Group Trials

The next stage was a small-group trial of the product involving 10 eleventh-grade science students at MAN 5 Batang Hari as research subjects. During the trial, the researcher distributed a product link to each student, allowing them to access it through their personal smartphones. Next, the researcher explained the content and features available in the virtual laboratory and then asked the students to operate the media independently using their respective devices.

Table 15. Result of Small Group Trials

No	Indicator	Respondent									
		1	2	3	4	5	6	7	8	9	10
1.	Material is easy to understand	5	5	5	4	5	5	5	5	5	5
2.	Images displayed are consistent with the material	5	5	5	5	5	5	5	5	5	5
3.	Language used is easy to understand	5	5	5	5	5	5	5	5	5	5
4.	Potential to increase interest in learning	5	4	4	5	5	5	5	4	5	5
5.	Potential to increase student learning motivation	5	5	5	5	5	5	5	5	5	5
6.	Potential to provide understanding and reinforcement of student concepts	5	5	5	5	5	5	5	5	5	5
7.	Consistency of background color with the text	5	5	4	5	5	5	5	5	5	5
8.	Placement and function of buttons within the media	5	5	5	4	5	5	4	4	5	5
9.	Appearance of animations, videos, and images	5	4	5	4	5	5	4	5	5	5
10.	Ease of navigation	5	5	5	5	5	5	5	5	5	5
Total		50	48	48	48	50	50	48	48	50	50
Overall Total Score		490									
Percentage		98%									

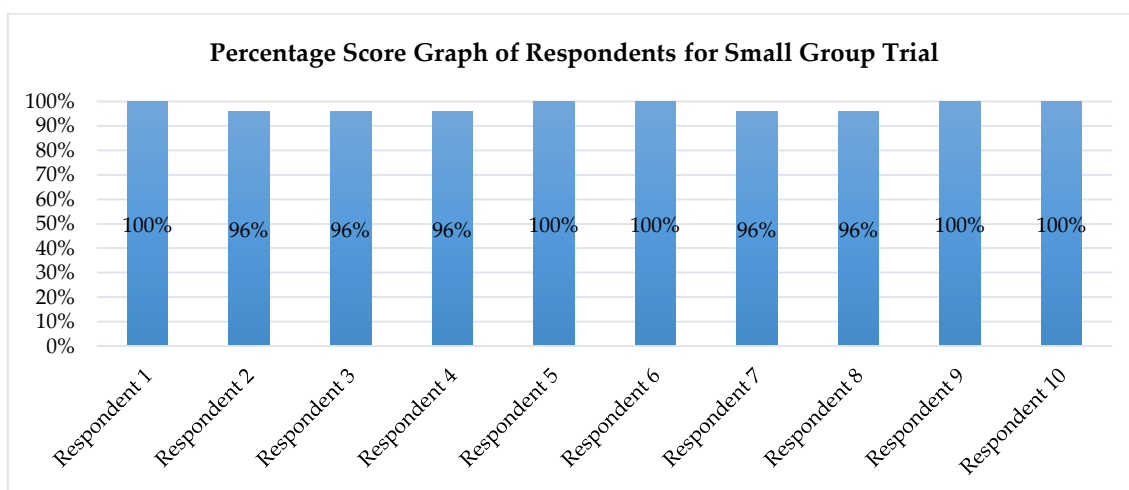


Figure 8. Percentage Score Graph of Respondents for Small Group Trial

Based on the results of the small group trial in the table 15, a presentation graph was obtained for 10 students which can be seen in Figure 8. The percentage of student answers was 98%, which is in the range of 81% - 100% with the criteria of "Very Good".

Considering the data obtained from teacher assessments and student responses, the researcher can conclude that the learning media developed is very good and interesting to support the learning process in the electrolyte and non-electrolyte solutions subject material.

Discussion

The development results of the Electrochem Lab virtual laboratory show a significant transformation in the quality of the instructional product through the implementation of the Lee & Owens model. In the first stage of material validation, a score of 56.92% (Not Feasible) was obtained, indicating a misalignment between the structure of content presentation and the sequence of Learning Outcomes (CP) and Learning Objective Flow (ATP). Scientifically, this disorganization has the potential to increase students' cognitive load because the abstract nature of electrolyte solution material requires highly systematic instructional organization. After revisions were made to clarify terminology and align the content flow with the CP-ATP framework, the feasibility percentage increased significantly to 89.23% in the second stage.

This improvement indicates that the quality of a virtual laboratory is not determined solely by its technical features, but largely depends on systematic content organization. Aligning the material with CP-ATP serves as crucial instructional scaffolding, without proper structure, even sophisticated media will be difficult to understand due to the high cognitive load caused by unorganized information. This finding confirms that well-developed instructional design is the primary foundation for effectively bridging the delivery of abstract chemistry material.

In the one-to-one trial, the score of 86.6% indicates that this media has a good level of readability and navigation for students with varying levels of cognitive ability. The score suggests that the interface design and instructions in Electrochem Lab are sufficiently communicative, thereby minimizing operational confusion when used individually. Meanwhile, the 98% response rate in the small-group trial reflects very high practicality and attractiveness of the media. The increase in learning motivation occurred because students were no longer passive observers; the drag-and-drop features and instant visual feedback (such as the light indicator) provided an interactive experimental experience. This simulation activity offers a more concrete learning experience compared to merely observing theoretical explanations, thereby helping students understand chemical processes without relying on a physical laboratory that is

unavailable at school. This finding is consistent with Abdelmoneim et al., (2022), who states that simulation applications are important in improving knowledge and science experiment learning, as well as in increasing in-depth understanding of experimental concepts.

The success of the media in supporting critical thinking skills is reflected in the shift of students' learning patterns, from passive recipients of information (such as through videos or PowerPoint presentations) to exploratory learners. Through practical simulations, students are actively engaged in conducting analysis, interpreting results, and drawing conclusions independently. With direct involvement in the simulations, students are encouraged to develop their analytical and inferential skills in a more systematic and meaningful manner.

The results of this study are consistent with the findings of Fauziah et al. (2024), who stated that virtual laboratories are effective in increasing motivation and understanding through simulated interaction. In addition, this study strengthens the argument of Eka & Munzil, (2024) that virtual laboratories serve as practical and efficient solutions for schools with limited laboratory infrastructure. Overall, Electrochem Lab has proven to be an alternative learning tool capable of ensuring the achievement of chemistry competencies despite limitations in physical facilities.

Theoretical Implication

Constructivist Theory

Constructivist theory emphasizes that students construct their own knowledge through direct learning experiences. This principle was applied in the development of the Electrochem Lab virtual laboratory based on a contextual approach through electrical conductivity experiments of solutions, which encourage students to actively engage in the learning process. In these activities, students do not merely receive information, but also perform scientific tasks such as observing phenomena, asking questions, collecting and analyzing data, and drawing conclusions based on the results of the virtual experiments they conduct. Through this virtual practicum, students are guided to explore the concepts of electrolyte and non-electrolyte solutions by relating them to real-life situations, making learning more meaningful. This exploratory process enables students to

understand the relationships between concepts independently while simultaneously developing critical thinking skills. This is in line with the opinion of Kusumawati et al., (2022), who state that constructivist theory emphasizes students' ability to discover and transform complex information, as well as to match new knowledge with their existing cognitive structures. Therefore, practicum activities in a virtual laboratory can facilitate the reconstruction of knowledge through active learning experiences.

Multimedia Learning Theory

The application of the multimedia learning theory in the development of the Electrochem Lab virtual laboratory is based on the assumption that learning becomes more effective when it involves dual channels visual and auditory while maintaining cognitive load within the limits of working memory capacity. In Electrochem Lab, the principle of essential processing is implemented through systematic and step-by-step practicum instructions, allowing students to focus on key phenomena such as the lighting of the bulb without being distracted by irrelevant information.

The principles of coherence and signaling are also integrated by eliminating distracting decorative elements and providing visual emphasis on essential components within the virtual laboratory. This aims to minimize extraneous processing that may hinder the understanding of abstract chemistry concepts.

Electrochem Lab promotes generative processing through interactive features that allow students to control their own learning pace (principle of interactivity). Through navigation buttons, interactive quizzes, and drag-and-drop simulations during the practicum, students are actively engaged in organizing and integrating new information with their prior knowledge.

The use of communicative language in the simulation instructions also applies the principle of personalization to enhance students' emotional engagement and motivation. In line with the view of Rahayu et al., (2024), multimedia design that carefully balances images and audio narration in this virtual laboratory has been proven to optimize cognitive processing, thereby helping students construct more meaningful understanding of electrolyte and non-electrolyte solution concepts.

Practical Implication

Practically, the presence of the Electrochem Lab virtual laboratory provides a significant breakthrough and concrete solution for Madrasah Aliyah or other educational institutions in various regions that face challenges due to the lack of physical laboratory facilities. Physical limitations, which often cause chemistry learning to lose its experimental essence, can now be addressed through digital media that is easily accessible via students' smartphones. This media enables students to conduct practicum experiments with full safety and cost efficiency. Ultimately, this practical application contributes to equalizing the quality of science education by ensuring that students' competencies and 21st-century skills are facilitated across diverse educational settings, regardless of infrastructure limitations.

The limitation in the development of the ElectroChem Lab virtual laboratory lies in the product testing stage, which did not yet allow the researcher to comprehensively assess the effectiveness of the media in improving students' critical thinking skills. This is because the study was limited to preliminary testing through one-to-one and small-group trials to determine user responses and ease of use; therefore, the impact of the ElectroChem Lab virtual laboratory on students' critical thinking skills has not been thoroughly measured.

Efforts to minimize this limitation were made by equipping the virtual laboratory with conceptual material features, simulation practicums for electrical conductivity tests and solution pH tests, as well as evaluation quizzes based on HOTS (Higher Order Thinking Skills) questions. These features were designed so that students not only understand concepts theoretically, but are also trained to analyze, evaluate, and draw conclusions from virtual practicum results. Thus, although the effectiveness measurement has not been conducted extensively, the developed product design has been directed toward supporting the development of students' critical thinking skills in chemistry learning.

CONCLUSION

This research and development study resulted in the creation of the Electrochem Lab virtual laboratory, which is valid, practical, and feasible to be used as a chemistry learning medium in

Madrasah Aliyah. The main finding of this study indicates that the integration of a contextual approach, interactive simulations, and design principles based on constructivism and the Cognitive Theory of Multimedia Learning is capable of bridging students' understanding of abstract electrolyte and non-electrolyte solution concepts while simultaneously directing the learning process toward the development of students' critical thinking skills. Thus, the objective of developing a learning medium that supports meaningful learning and is oriented toward 21st-century skills has been achieved.

The novelty of this research lies in the development of a virtual laboratory that not only focuses on sub-microscopic visualization of chemical concepts, but is also systematically designed to stimulate critical thinking processes through the integration of simulation-based practicum features, HOTS-based questions, and alignment of content with Learning Outcomes (CP) and Learning Objective Flow (ATP). This approach positions the virtual laboratory not merely as an alternative substitute for physical practicums, but as a pedagogically structured learning tool aimed at fostering students' knowledge reconstruction.

The impact of this study is both theoretical and practical. Theoretically, the findings reinforce the relevance of constructivist theory and the Cognitive Theory of Multimedia Learning in designing effective virtual laboratories. Practically, the developed product provides an innovative solution for schools with limited laboratory facilities, enabling chemistry learning to remain experimental, safe, flexible, and oriented toward the development of critical thinking skills. Therefore, Electrochem Lab contributes to the equalization of science education quality in Madrasah Aliyah and other educational institutions with infrastructure limitations.

RECOMMENDATION

Based on the research findings, several recommendations are proposed for future development and implementation. Subsequent researchers are advised to conduct field trials on a broader scale beyond the small group trial stage to verify the consistency of the media's effectiveness in various different educational environments. In addition, future research should

utilize experimental or quasi-experimental designs to quantitatively measure the improvement in students' critical thinking skills, for example through N-gain analysis, as a direct impact of using 'Electrochem Lab'. There is also significant potential to expand the scope of this virtual laboratory to other abstract chemistry topics that require sub-microscopic visualization to provide comprehensive solutions for schools with limited physical facilities.

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