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Designing an Interactive Virtual Laboratory Learning Experience for Acid-Base Indicators

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ABSTRACT

Science education, especially chemistry, plays a vital role in the development of conceptual understanding and practical skills among students. In the modern digital era, the integration of technology into education is indispensable to meet the demands of modern curricula. Virtual laboratories provide a safe and efficient way of teaching chemical concepts without the hazards that come with physical laboratories. This research was conducted to design, validate, and determine the feasibility of interactive virtual laboratory learning media for acid-base indicators. This research used the ADDIE model: Analysis, Design, Development, Implementation, and Evaluation. There were 79 Phase F high school students, and seven expert validators involved in the research, comprising chemistry lecturers and teachers. The data collection used questionnaires and interviews, while the validation used Aiken's index. The results showed that the virtual laboratory achieved high validity scores across content, construct, and technical quality, ranging from 0.76 to 0.90. The results indicated that the interactive virtual lab significantly enhanced the students' visualization of abstract chemical concepts, thus improving their engagement and understanding. This illustrates the potential of integrating technology into chemistry education to create more effective and engaging learning experiences.

INTRODUCTION

The current era of information and communication technology is changing rapidly. Therefore, education needs to adjust to the more effective and engaging learning process of students. The use of Serious Game-based Virtual Laboratory learning media gives enough reason to be adopted for the enhancement of learning outcomes in this digital era. Georgiadis et al., 2019; Nicolaou et al., 2019a; and Shadiev & Yang, 2020a also present the same opinion. In a century characterised by rapid advancement in technology, which propels education methodologies forward, learning principles in the 21st century focus on acquiring important skills such as critical thinking, creativity, collaboration, communication, digital literacy, and problem-solving (Gosper & Dirk, 2014; Hadinugrahaningsih et al., 2017). Technology integration, especially regarding information and communication technology (ICT), will thus play an essential role in the integration of learning across disciplines in real-world challenges (Khan, 2015).

Within the context of chemistry education, some technologies like VR and virtual laboratories have great potential for innovation in teaching and learning. The use of virtual labs can enable students to carry out experiments safely, at low cost, and with much flexibility, minimizing dependence on physical resources and safety risks (Checa & Bustillo, 2020; Tatli & Ayas, 2010). For example, VR enables immersive simulations that can enhance students' conceptual understanding of abstract topics by visualizing molecules, reactions, and processes in a 3D environment (Chang et al., 2017). Such applications are particularly effective in fostering engagement and improving retention compared to traditional teaching methods.

Despite these advancements, traditional approaches to teaching certain chemistry topics, such as acid-base indicators, often face significant challenges. The subject requires abstraction, visualization at a molecular level, and relating the theory to the practical process, all of which become stumbling blocks to many students. In a research study comprising a sample size of 71 participants, in acid-base solution indicators, 43.7% of students experienced difficulty visualizing these abstract concepts; 36.6% stated that "some concepts are difficult for me to visualize" (Hussein et al., 2019). Furthermore, 38% of students used rote memorization because the visualizations were not clear and the explanations were too long, while 18.3% decided to avoid studying the topic altogether.

In this respect, acid-base indicators can be supported with virtual laboratory media that offer interactive and visually rich simulations, similar to real-life experiments. Unlike traditional hands-on labs, virtual labs offer the flexibility to repeat experiments without resource constraints, support real-time feedback, and allow for a greater focus on understanding chemical principles (Bellotti et al., 2013; Šumak & Šorgo, 2016). Moreover, gamified elements in virtual learning environments have been shown to increase motivation and engagement, making the learning process enjoyable and effective (Chan et al., 2021; Wimmer et al., 2022).

Previous studies have pointed out that virtual media can be very effective in enhancing students' understanding of abstract concepts of chemistry, such as reaction mechanisms and chemical equilibrium (Sany & Arofik, 2023). Few have focused on the use of virtual media for acid-base indicators; thus, there is still a gap in the literature regarding how virtual laboratories could enhance learning outcomes about acid-base indicators. Besides, there is a lack of evidence regarding how gamification within virtual labs can help to solve the challenges of engagement and retention in chemistry education.

METHODS

Research Design

This research uses the Research and Development design, a systematic procedure belonging to the creation of products with certain tests to see its effectiveness. R&D according to Sugiyono (2019), is not only directed at developing new products but also improving those that already exist. To that effect, Endang Mulyatiningsih states that R&D is designed in such a way that it produces a new media through its development processes. According to Mulyatiningsih (2011), the products that may result from R&D in education include models, media, tools, books, modules, evaluation instruments, teaching devices, curricula, and school policies. The process of R&D is systematic, directed, and deliberate in refining a product according to established criteria. Product outcome in this research is more on design or model, such as educational media. Therefore, the five stages involved in the research procedure within the ADDIE model are analysis, design, development, implementation, and evaluation.

- Analysis

The stage required for understanding needs and requirements involves stating problems, determining appropriate products, and then planning concepts for those products. Data collection is done through needs analyses, context analyses, and literature reviews.

- Design

Product concept design and detailed design from the very beginning of the planning; preparation of flowcharts and storyboards in the Virtual Laboratory media will be prepared accordingly.

- Development

At this stage, product development and its validation take place. Media production is done using software tools, while prototypes will be developed and validated regarding quality by the experts.

- Implementation

This is the actualization of the developed product and piloting for student and teacher feedback.

- Evaluation

The final step is to evaluate all the stages of the development process. Feedback from students and teachers that revise and enhance the product is included in it.

Research Target

The respondents in this research are five chemistry lecturers from FMIPA UNP as validators, one chemistry teacher of SMAN 3 Padang, one chemistry teacher of SMAN 2 Padang, and several students of both schools.

Research Data

The study uses both primary and secondary data. Primary data are original data, which are collected directly from sources through observation, interview, or experiment, and which have never been published before. Examples of primary data include surveys, interviews, and observations (Owan & Bassey, 2019). The secondary data were obtained from literature such as books and relevant research articles.

Research Instruments

The research employs the following instruments: initial research questionnaire: designed to collect data from chemistry teachers and students at SMAN 2 and SMAN 3 Padang regarding their needs and experiences in chemistry learning. Validity test questionnaire used to assess the validity of the developed Virtual Laboratory media, including content validity, construct validity, and media validity.

Data Analysis

Data analysis is a systematic process through which data from varied sources are collected and organized to develop understanding. In this study, media validity will also be included in the analysis. Techniques used in this regard are: using a modified Likert scale without a neutral option, and applying Aiken's Index to analyze the validity scores provided by validators (Aiken, 1985). The formula used is:

$$s = r - lo$$

$$V = \frac{S}{n(c-1)}$$

Where:

- s = Difference between a validator's score and the lowest score on the questionnaire
- r = Score by a validator
- lo = Lowest score on the questionnaire (in this study, 1)
- V = Validity index
- S = Sum of all scores from all validators
- n = Number of validators
- c = Number of response categories (1, 2, 3, 4)

Validity coefficients fall between 0 and 1; the larger the coefficient is, the greater is its validity. According to Aiken (1985), for estimating the degree or level of validity, one has to use a table on the validity coefficient.

RESULTS

The development of a virtual laboratory learning media based on serious game for the topic of acid-base indicator was conducted using the ADDIE model, namely analyze, design, development, implementation, and evaluation. However, this research was limited to the development stage only. Below are the results of the development of virtual laboratory learning media based on serious game for the topic of acid-base indikator.

Analyze Stage

Activities carried out in the analysis stage include needs analysis, determining the scope of the material, formulating instructional objectives, identifying student characteristics, setting boundaries, determining and collecting sources, developing a development process plan, and analyzing core competencies and basic competencies for idea development.

The results of interviews with chemistry teachers and students indicate that most chemistry teachers use presentation slide learning media. Students also confirm that this media is often used by teachers. When asked about virtual laboratory learning media based on serious games, both students and teachers stated that they had never used it, but they hoped for its use. They see that virtual laboratory based on serious games can be a useful reference and make learning more interesting. Chemistry teachers strongly support the use of this media because it can help students understand chemistry concepts better. The results of these interviews reflect that students find chemistry difficult to understand, a perception also reinforced by the results of the needs analysis questionnaire distributed to students. Below are the data results from the distribution of the student needs analysis questionnaire:

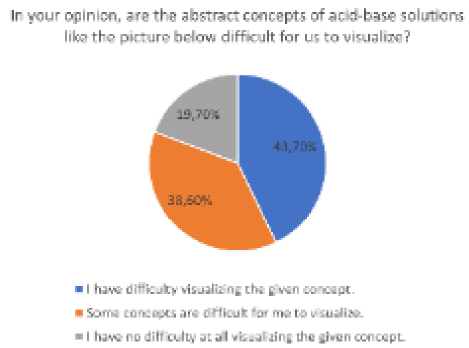


Figure 1. Percentage of students' responses to the level of difficulty in visualizing the working concept of acid-base solution indicators

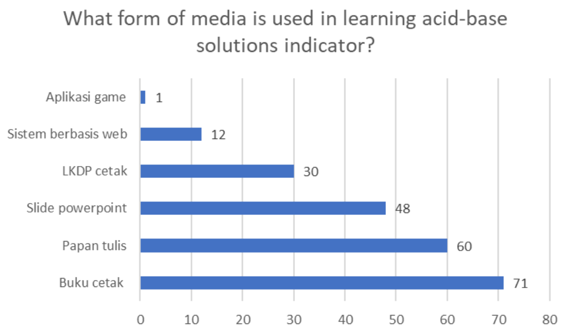


Figure 2. Percentage of media use in learning acid-base solution indicators

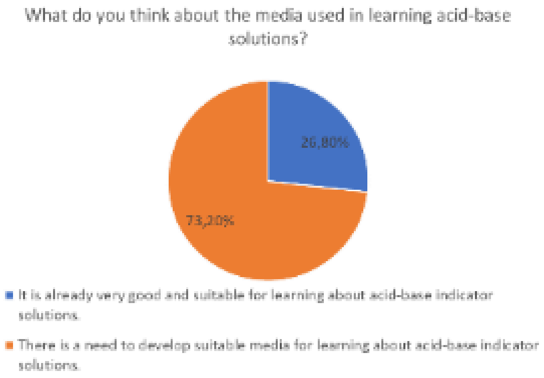


Figure 3. Percentage of students' views about the media used in learning acid-base solution indicators

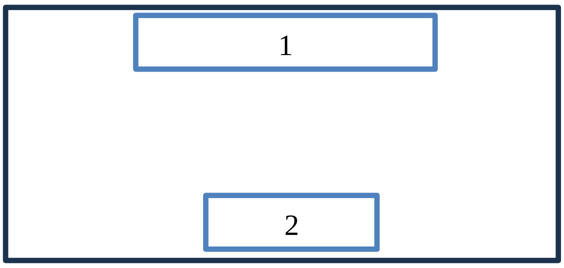
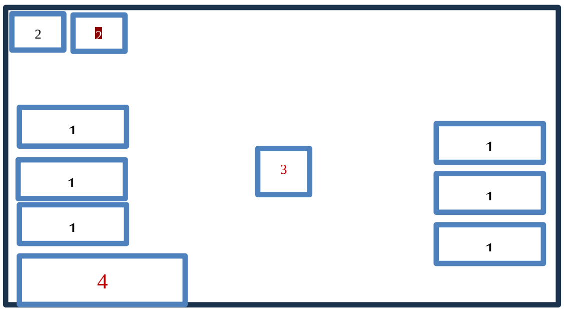
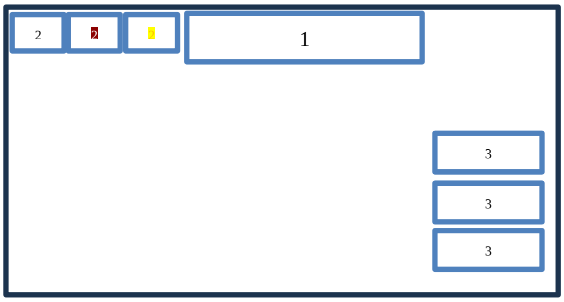
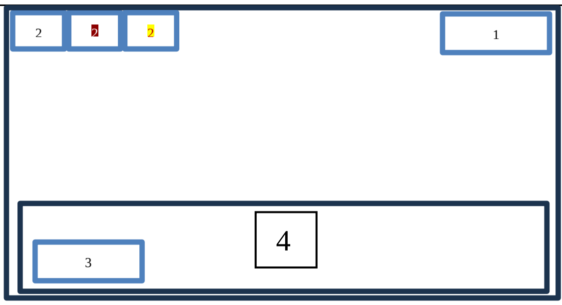
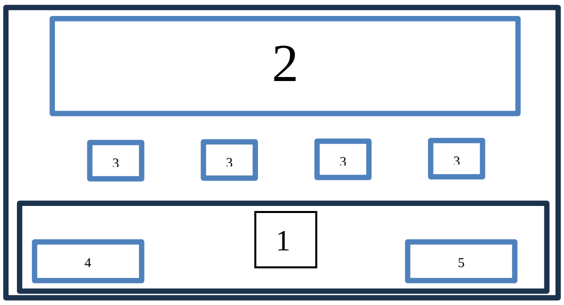
Based on the results of distributing the student needs analysis questionnaire it is apparent that most students face challenges in visualizing acid-base indicator concepts, with 43.7% of them experiencing difficulty in doing so. The use of media in learning also shows an interesting pattern, where although printed books remain the primary choice, there is a clear need for media variation, as stated by 73.2% of students. Therefore, this research confirms the necessity of developing appropriate learning media to meet students' needs, as per their views, and to enhance understanding of chemistry concepts more effectively. These findings align with previous studies that emphasize the importance of effective learning media in enhancing students' understanding of challenging chemistry concepts (Wang et al., 2022). It gives emphasis that the learning media needs to be developed further to increase students' understanding in subjects related to chemistry. As highlighted by Bintarti et al. (2024), the development of interactive multimedia based on Android, integrated with Problem-Based Learning (PBL), can significantly improve students' concept mastery, which resonates with the need for diverse and accessible media in chemistry education.

Design Stage

The design phase in the development of virtual laboratory learning media based on serious games focuses on organizing resources, developing materials, and creating validation instruments to support prototype creation. It involves compiling the chemistry materials on acid-base indicators, ensuring alignment with scientific accuracy; designing the 2D graphics and animations in an engaging manner; incorporating audio elements to enhance interactivity; and developing the source code to integrate all components seamlessly. Based on the needs analysis data, a conceptual framework was developed to match learning objectives with instructional design and media structure.

Then, a validity questionnaire using a modified Likert scale ranging from 1 to 4 without a neutral option was prepared to assess the systematic construction of content, construct, and media validity. The storyboard, already presented during the analysis stage, shall serve as a visual instructional guide in integrating the learning of acid-base indicator materials into the game-based environment. Its role in this stage is to ensure that instructional design adheres to media development objectives. This section provides emphasis on how the developed storyboard and conceptual framework could effectively guide the creation of a virtual laboratory learning media, ensuring consistency and avoiding redundancies.

Table 1. Storyboard of Serious Game Based Virtual Laboratory Learning Media

Section	Page view	Information
Start Menu		1. Virtual Lab's Title (Little Alchemist) 2. Start Button
Main Scene		1. Experiment tables with different topics of chemistry 2. **Black** = Exit button **Red** = Guide book 3. Avatar or Player's Character 4. Joypad = Tools to move the character
Experiment Menu Scene		1. Experiment Title 2. **Blavk** = Exit button **Red** = Developer's profile **Yellow** = CP and ATP 3. Kind of experiment (Litmus paper for Acid Base Indicator, Solution Indicator, Universal Indicator)
Experiment Scene		1. Button to start experiment step by step 2. **Black** = Exit to experiment menu **Red** = Experiment guide **Yellow** = Exercise (appears after all steps have been completed) 3. Tools and materials cupboard 4. Experiment table
Exercise Scene		1. Players character 2. Display for question and multiple choice question. 3. "Heading area" to choose A,B,C,D option 4. Control button to move player to left or right. 5. Jump Button to make character jump into the right answer choice

In this case, it is very relevant to mention serious games as the development of media. Some studies have shown, such as by Chen et al., (2020), that game-based learning media can enhance student motivation during the learning process in grasping abstract concepts into tangible and fun activities. This concept is also supported by the statement of research from Prensky (2003), which explains that serious games can improve critical thinking and problem-solving skills in students. Thus, the purpose of developing game-based learning media in this research will be an alternative to solving students' difficulties in studying chemistry topics by providing easier and more contextual learning in understanding the material.

This study is valuable, but it has some limitations, especially because it was conducted only in the development phase without the implementation and evaluation phases. Therefore, the effectiveness of the developed learning media to improve students' understanding cannot be directly determined. Further research involving implementation and evaluation is needed to assess the impact of this virtual laboratory learning media on chemistry education. Previous studies, such as by (Hamari et al., 2014), identified the evaluation stages as fundamental to ascertain whether the developed media is effectively reaching the proposed learning objectives.

Development Stage

The next stage in the development process of virtual laboratory learning media based on serious games is the development stage. Several activities were carried out in this stage to develop the learning media to be created. These activities include creating a prototype of the virtual laboratory learning media based on serious games, validating the prototype of the learning media, and revising the prototype of the virtual laboratory learning media based on serious games.

Development of Prototype of Virtual Laboratory Learning Media Based on Serious Games

In this stage, a learning media in the form of a virtual laboratory based on serious games for the topic of acid-base indicators was developed according to the previously designed storyboard. The stages of its development are as follows:

1. Digitization of 2D images: digitize 2D images/graphics based on storyboard sketches that have been created using the Adobe Illustrator, Pixelorama and Figma applications.

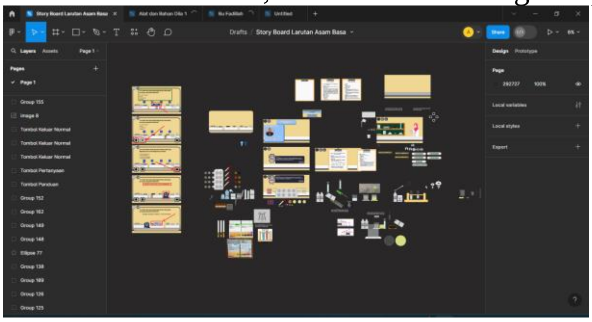


Figure 5. Figma as a 2D image and graphics resource manager

2. Creation of laboratory practice animations: Create practical animations based on learning media storyboards using the "Animation Player" feature in the Godot Engine software.

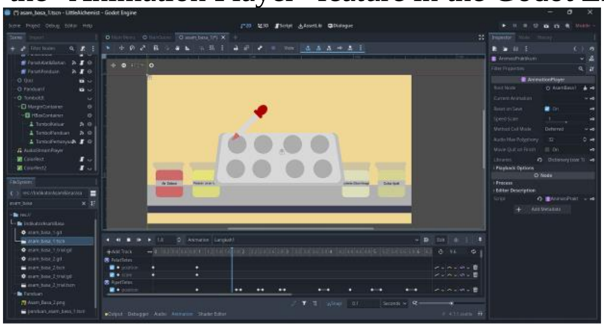


Figure 6. Animation Player feature on Godot Engine

3. Development of pages in the learning media application: developing pages on learning media applications consisting of an opening page, main page, practicum selection page, practicum page and practice questions page using Godot Engine software.

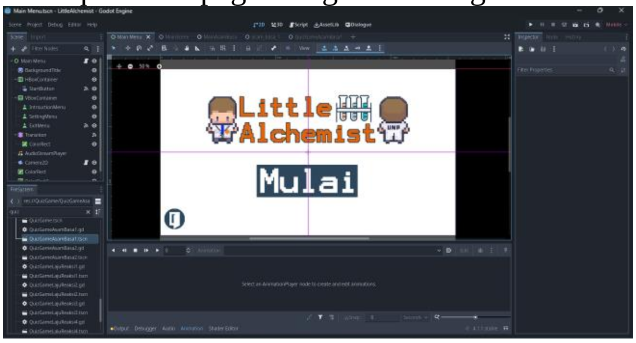


Figure 7. Opening page design

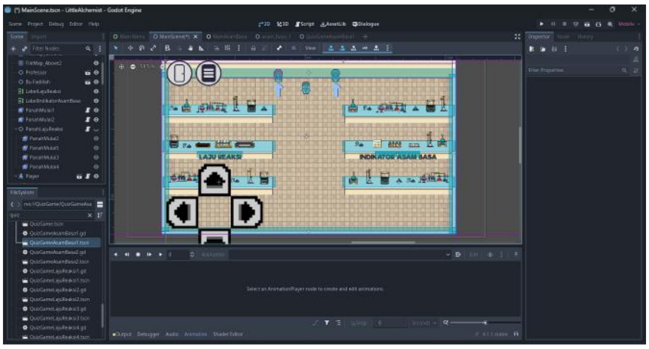


Figure 8. Main page design

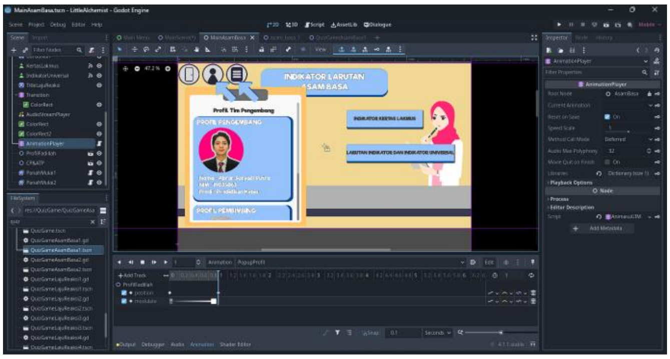


Figure 9. Experiments selection page design

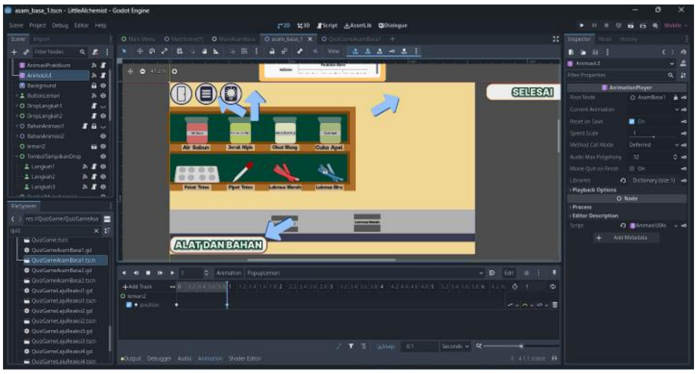


Figure 10. Virtual experiment page design

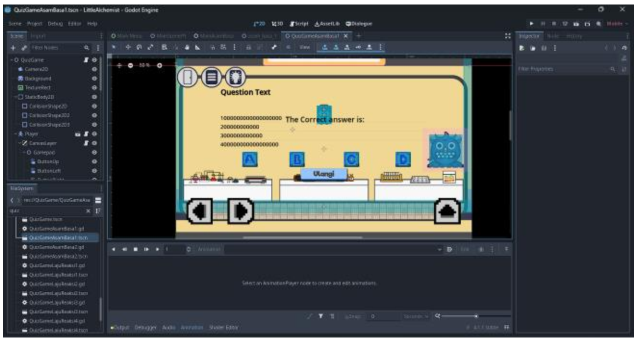


Figure 11. Design a quiz game page with practice questions

4. Programming the virtual laboratory learning media based on serious games using the Godot Engine: programming serious game-based virtual laboratory learning media with Godot Engine software to create features such as a joypad as a movement mechanism for the main character, buttons, dialogue, animation, audio, etc. The programming language used in developing this learning media is GDScript.

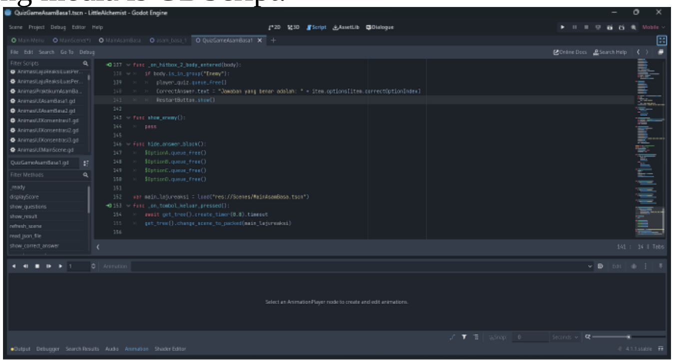
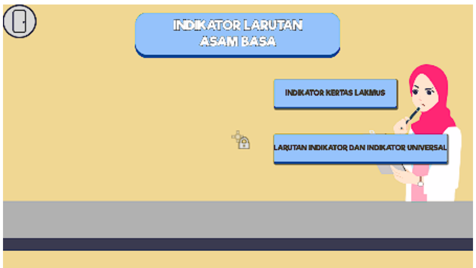


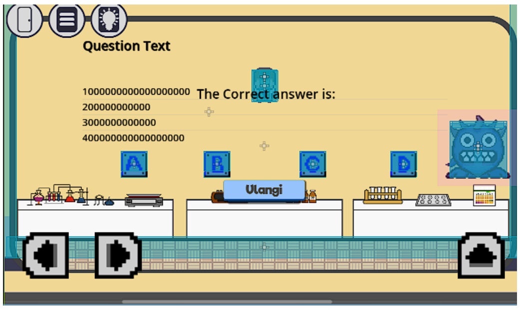
Figure 12. GDScript as the main programming language in the Godot Engine application

5. Self-evaluation: formative evaluation to obtain prototype II is by conducting a self-evaluation. Self evaluation was carried out using the check-list method to see the completeness of prototype I. The results of this evaluation are presented in the table below:

Table 2. Self-evaluation results

No	Assessment aspect	Result	Conclusion	
			Succeed	Fail
1.	Opening page	The opening display, music and buttons work well 	√	
2.	Main page	The main display, music, buttons and animations work well 	√	

<table>
<tr><td>3.</td><td>Experiment menu page</td><td>The test menu display, music, buttons and animations work well

</td><td>√</td></tr>
<tr><td>5.</td><td>Experiment page</td><td>The initial practicum display, music, buttons and animations work well

</td><td>√</td></tr>
<tr><td>6.</td><td>Exercise page</td><td>The experimental question practice page functions well

</td><td>√</td></tr>
</table>

Validation of Prototype of Virtual Laboratory Learning Media Based on Serious Games

Prototype III was obtained after expert review (expert assessment) through validity testing of the prototype II application. The validity testing of the virtual laboratory learning media based on serious games for acid-base indicator material was conducted with the help of seven validators, namely 5 chemistry lecturers from UNP and 2 chemistry teachers, each from SMA Negeri 3 Padang and SMA Negeri 2 Padang.

Table 3. Result of content validity test

Aspect	Average value from validators	Validity
Aspect 1	0,76	Valid
Aspect 2	0,81	Valid
Aspect 3	0,81	Valid
Aspect 4	0,86	Valid
Aspect 5	0,76	Valid
Aspect 6	0,86	Valid
Aspect 7	0,90	Valid
Aspect 8	0,76	Valid
Aspect 9	0,81	Valid

Table 4. Construct and technical quality validity test results

Aspect	Average value from validators	Validity
Aspect 1	0,86	Valid
Aspect 2	0,81	Valid
Aspect 3	0,90	Valid
Aspect 4	0,81	Valid
Aspect 5	0,81	Valid
Aspect 6	0,76	Valid
Aspect 7	0,86	Valid
Aspect 8	0,90	Valid
Aspect 9	0,81	Valid
Aspect 10	0,81	Valid
Aspect 11	0,86	Valid
Aspect 12	0,81	Valid
Aspect 13	0,90	Valid
Aspect 14	0,86	Valid
Aspect 15	0,90	Valid
Aspect 16	0,76	Valid
Aspect 17	0,81	Valid
Aspect 18	0,81	Valid

The result of the validity test through expert reviews, using questionnaires, indicates that every aspect evaluated on the content, construct, and technical quality validation sheet had a validity score greater than the minimum valid value threshold of 0.76. These results of validation mean that the developed learning application is valid in its content, construct, and technical quality. This again confirms Aiken's suggestion of 1985, stating that a validity score above 0.75 means that the instrument is valid to be used in research or media development contexts. Additionally, this aligns with the importance of valid and reliable educational tools highlighted by Laksono et al. (2024), who emphasize the need for well-developed lesson plans that integrate scientific explanations effectively.

Furthermore, the results of this validation provided feedback for the improvement to be made on the application, such as language adjustment according to EYD, and modification of exercise formats into a Super Mario Bros game style. This will surely increase the students' response and make it easier for students to understand the concepts taught to them. The use of varied instructional models, such as those seen in Paristiowati et al. (2024), where the flipped classroom model was applied, shows that integrating multiple digital media can help increase student engagement and activity in learning processes.

Revision of Prototype of Virtual Laboratory Learning Media Based on Serious Games

After validity testing, the developed application was revised. The results of the revisions made based on the suggestions and comments from the validators. Further research should be carried out regarding the implementation and evaluation of effectiveness in increasing students' understanding through developed learning media. Further study may also be conducted in terms of assessing the impact of using virtual laboratory learning media based on serious games in chemistry learning on student achievement over a longer period. This agrees with earlier research that used game-based learning to indicate that students' understanding and skills are positively and long-lastingly improved (Gee, 2003). Additionally, as Eralita (2023) suggests, incorporating hands-on, interactive components in the learning process, such as laboratory activities, can enhance students' science process skills and their understanding of chemical concepts.Finally, this research provides a new innovation in developing innovative and adaptive chemistry learning media and will be a source of information to direct further studies in developing adaptive chemistry learning media.

CONCLUSION AND RECOMMENDATIONS

Based on the research findings, data processing, and analysis conducted on the development of a virtual laboratory learning media application based on serious games for the topic of acid-base indicator solutions, the following conclusions can be drawn the development of virtual laboratory learning media based on serious games for the topic of acid-base indicator solutions using the ADDIE development model is feasible. The systematic approach provided by the ADDIE model facilitates the creation of effective learning resources tailored to the needs of chemistry students. The developed virtual laboratory learning media based on serious games for the topic of acid-base indicator solutions has been validated. Through expert reviews and validation surveys, the application's content, structure, and technical quality have been assessed and found to meet established validity criteria. This validation process ensures that the learning media effectively serves its intended educational purpose.

Furthermore, based on the research conducted, it is recommended that future researchers pursue further studies utilizing virtual laboratory learning media applications based on serious games for the topic of acid-base indicator solutions. These studies could delve deeper into various aspects, such as evaluating the long-term impact of such learning media on students' understanding and retention of chemistry concepts. Additionally, exploring different approaches to integrating technology into chemistry education could provide valuable insights into enhancing learning outcomes and engagement among students.In conclusion, the development and validation of virtual laboratory learning media based on serious games represent a significant step towards innovative and adaptive learning solutions in chemistry education. By continuing to explore and refine these approaches, educators and researchers can contribute to the ongoing evolution of teaching methodologies and ultimately enhance the learning experiences of students in the field of chemistry.

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