



## Virtual Laboratory Science to Improve Students' Science Literacy Ability

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### ABSTRACT

Technological developments in education demand innovation in learning media to overcome the limitations of laboratory facilities and conventional methods, especially in elementary science education. Prospective elementary school teachers need to have strong scientific literacy to support meaningful learning. This study aims to develop a Virtual Science Laboratory (VSL) as a flexible, interactive, technology-based medium to improve students' Scientific Literacy Skills (SLA). The approach used is Research and Development (R&D) with the model Analysis, Design, Development, Implementation, Evaluation (ADDIE). Data were collected from 120 prospective elementary school teachers in Jakarta, Indonesia, aged 21–23 years. SSC was measured through a science literacy test (pretest-posttest) and analyzed with Normalized gain (N-Gain). The results showed that VSL significantly improved scientific literacy, with an average increase of 59.4% (moderate effect size). Each aspect of SLA increased: Explanation of Scientific Phenomena (61%), Interpretation of Data & Evidence (77%), Evaluation & Experimental Design (42%), Use of Scientific Evidence (58%), and Awareness of Scientific Applications (59%). These findings demonstrate the effectiveness of VSL as an innovative solution for technology-based science learning, particularly in contexts with limited physical lab space. VSL is recommended for integration into science education curricula as a 21st-century learning approach to support the professional competency of prospective teachers.

**Keywords:** virtual laboratory, science education, science literacy, student ability, learning innovation.

### INTRODUCTION

The evolution of digital technology necessitates a change in science education, especially regarding hands-on laboratory experiences. Nevertheless, restricted access to traditional lab facilities, high costs, and insufficient time for practical activities pose significant challenges to achieving science learning objectives. (Alema et al., 2024; Khan & Abid, 2021). Furthermore, traditional learning methods often lack interactivity and fail to develop students' scientific literacy fully. This challenge is exacerbated in distance learning, where hands-on experiments are difficult. Therefore, innovative solutions such as virtual laboratories are needed to address these issues while increasing student engagement in science learning (Asare et al., 2023; Sung et al., 2021).

The importance of this transformation is closely related to the mastery of scientific literacy, which trains students' critical and analytical thinking to solve complex problems (Kumar, Choudhary, & Singh, 2024). Universities are required to equip students with these skills to thrive in today's world (Doni et al., 2021). These skills are crucial for achieving the Sustainable Development Goals (SDGs), which aim to address poverty, hunger, and inequality (Chegini et al., 2021). Science, technology, and innovation are key drivers of this progress (Khan et al., 2022; Akerson & Bartels, 2023). In this context, science education is becoming increasingly important. Science education not only instills scientific knowledge but also valuable transferable skills such as collaboration, honesty, and perseverance, which prepare students for successful careers and contribute to a better future (Larsson & Larsson, 2020; Tchia & Rumjaun, 2023).

Science Literacy Ability (SLA) is a critical competency that encompasses understanding scientific concepts, evaluating scientific evidence, and applying knowledge in real-life contexts (Mönch & Markic, 2022; Osborne, 2023; Bybee et al., 2024; Vo et al., 2025). Research shows that students with high SLA tend to be better at critical thinking and solving complex problems. However, international surveys such as PISA reveal that many students still have low SLA, especially when applying scientific knowledge to new situations. The use of interactive media, such as virtual laboratories, is expected to improve SLA by providing a more immersive, context-rich learning experience.

Industry 4.0 presents significant challenges for education, demanding significant changes (Tortorella et al., 2020). Embracing digital technology in teaching and learning is key, enabling knowledge transfer to occur anytime, anywhere (Kalyani, 2024; Wong, 2020). Universities face increasing challenges (Baik et al., 2019). Internally, they must balance national educational standards with the need to produce graduates equipped for 21st-century demands. These include critical thinking, innovation, problem-solving, creativity, initiative, collaboration, and technological proficiency (Erdoğan, 2019; Siburian et al., 2019; Smith et al., 2018). This adaptability is crucial for navigating the rapidly evolving world of education. Education also needs to address the social impacts of modernization, such as social problems and inequalities arising from changing customs and lifestyles. Building systems to navigate these changes is crucial for sustaining progress in science, job creation, and social well-being (Devi, Margaret, & Avanthika, 2024). Therefore, education plays a crucial role in shaping future generations.

Epistemologically, scientific understanding will reach an optimal point when physical objects, energy, and curiosity interact dynamically (Sheehy, 2023). Imagine observing our everyday experience of how objects heat up—science explains the why (Wibowo, 2017). Engaging visuals can further unlock this understanding (Wibowo et al., 2021). The most enjoyable and effective way to understand science is through having fun, thinking critically (Khoiriyah & Suprpto, 2021), and practicing essential skills such as understanding the Scientific Inquiry Method, identifying Valid Scientific Arguments, evaluating the Validity of Sources, applying Scientific Knowledge, and Critical and Analytical Thinking. These skills prepare students for the complexities of future life and work environments.

However, there is a gap between learners' scientific literacy and problem-solving skills. Furthermore, student motivation for certain topics, such as modern and quantum science, often results in lower learning outcomes (Pereira & Solbes, 2021). Fortunately, scientific inquiry skills, a core component of problem-solving thinking, can bridge this gap (Çakır et al., 2021). Creativity, another essential 21st-century CS skill, empowers students to discover new solutions (Shirish et al., 2021). It is essentially a thinking process that allows us to solve problems in novel ways (Hursen, 2021). Through hands-on experiences, students construct their own understanding of concepts (constructivism) and relate them to real-world situations (contextual learning). Research shows that students enjoy using digital media for learning, making it a powerful tool for transforming experiences. It aligns with Education 4.0, which emphasizes the use of digital technology to equip

students with scientific literacy skills. By bringing technology into the classroom, we can personalize learning, making it more engaging and effective (Xhomara, 2022). Digital learning tools can help students overcome learning challenges and understand concepts more engagingly (Ødegaard et al., 2021).

Scientific literacy and problem-solving skills demand technological advances that require digitalization (Zhang et al., 2024). This requires researchers to be creative in developing teaching modules that align with competency requirements. Researchers are required to design and implement innovative learning tailored to students' interests. This demand aligns with the higher education curriculum's educational objectives, which require students to learn according to their interests (Harefa et al., 2023) and to develop independent learning and problem-solving skills in science (Badmus & Jita, 2024). An independent campus is a flexible learning model that aligns with an innovative learning culture and meets students' interests and needs. The challenges of global issues foster the development of critical thinking, problem-solving, collaboration, communication, and creativity (Abina et al., 2024). The transformation toward lifelong learning in the education sector is geared toward the 5.0 industrial revolution (Alharbi, 2023; Babu, 2024).

Furthermore, preliminary studies have shown that 21-CC is still low. There is a clear lack of use of digital media to illustrate scientific concepts at the microscopic level. This limits independent learning based on personal interests and the surrounding environment. This results in students' learning productivity being less enthusiastic about learning science and more negative.

As a technical response, various virtual laboratory tools have been developed as multisensory software that replicates physical laboratories in cyberspace (Kapici et al., 2019; Semenikhina et al., 2021; Fajri et al., 2022). A virtual laboratory can also be defined as multisensory software that provides interactivity to simulate real-world labs in cyberspace (Fajri et al., 2022). Virtual labs allow students to measure physical quantities using virtual tools to obtain data (Bogusevschi et al., 2020). In virtual labs, the lab tools can be engineered with a scale adjusted to suit the needs. When a real-world measuring instrument is unavailable for a physical variable, a virtual instrument can be provided. Students can see inside the devices they operate through visual displays, animations, and representations adapted from actual labs (Chans et al., 2022; Kapilan et al., 2021). Based on the above description, it can be said that virtual labs offer greater opportunities to conduct physics experiments or practicals than real labs do. The 105 virtual media related to science materials developed and available at PhET, a small portion are virtual labs, and the rest are virtual animations/simulations, as presented in Table 1.

**Table 1. Virtual Science Laboratories Available at PhET**

Title	URL
1. Circuit Construction Kit: AC - Virtual Laboratory	<a href="https://phet.colorado.edu/en/simulations/circuit-construction-kit-ac-virtual-lab">https://phet.colorado.edu/en/simulations/circuit-construction-kit-ac-virtual-lab</a>
2. Capacitor Lab	<a href="https://phet.colorado.edu/en/simulations/capacitor-lab-basics">https://phet.colorado.edu/en/simulations/capacitor-lab-basics</a>
3. Circuit Construction Kit: DC-Virtual Laboratory	<a href="https://phet.colorado.edu/en/simulations/circuit-construction-kit-dc-virtual-lab">https://phet.colorado.edu/en/simulations/circuit-construction-kit-dc-virtual-lab</a>
4. Faraday's Electromagnetic Lab	<a href="https://phet.colorado.edu/en/simulations/faraday">https://phet.colorado.edu/en/simulations/faraday</a>
5. Blackbody Spectrum	<a href="https://phet.colorado.edu/en/simulations/blackbody-spectrum">https://phet.colorado.edu/en/simulations/blackbody-spectrum</a>
6. Fourier: Making Waves, Molecules and Light	<a href="https://phet.colorado.edu/sims/html/molecules-and-light/latest/moleculesandlight_in.html">https://phet.colorado.edu/sims/html/molecules-and-light/latest/moleculesandlight_in.html</a>
7. Rutherford Scattering	<a href="https://phet.colorado.edu/en/simulations/rutherford-scattering">https://phet.colorado.edu/en/simulations/rutherford-scattering</a>
8. Photoelectric	<a href="https://phet.colorado.edu/en/simulations/photoelectric">https://phet.colorado.edu/en/simulations/photoelectric</a>
9. Davisson-Germer: Electron Diffraction	<a href="https://phet.colorado.edu/en/simulations/davisson-germer">https://phet.colorado.edu/en/simulations/davisson-germer</a>
10. Nuclear Fission	<a href="https://phet.colorado.edu/en/simulations/nuclear-fission">https://phet.colorado.edu/en/simulations/nuclear-fission</a>

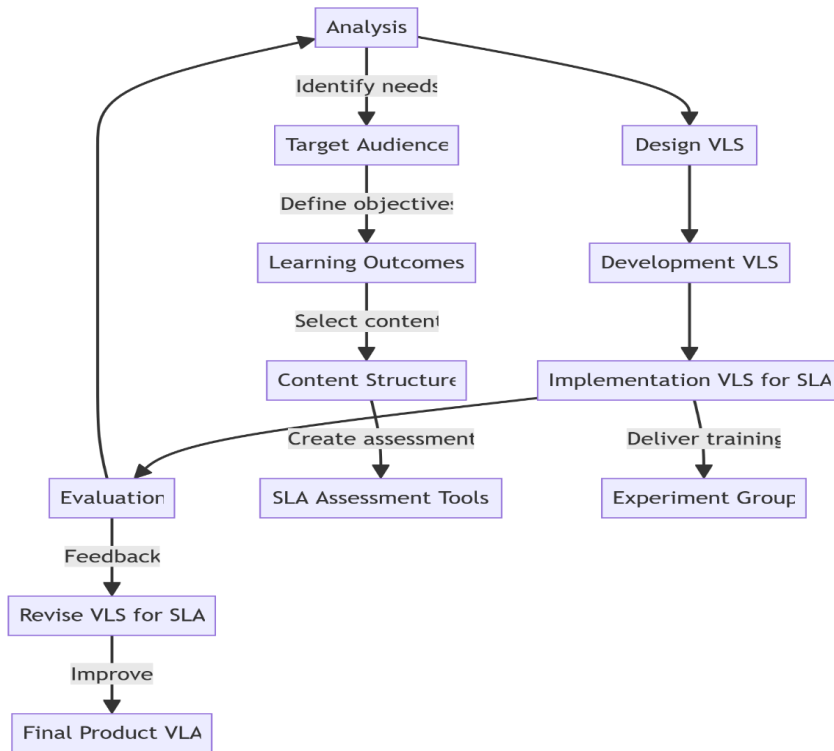
However, the developed virtual laboratories have not yet been trained to enhance scientific literacy and problem-solving skills. Therefore, based on the findings and research results above, it is deemed essential to develop a Virtual Laboratory Science (VLS) to improve the SLA of Elementary School Teacher Education (PGSD) students. Furthermore, the VLS learning media developed to improve the SLA must address the limitations of teaching materials and demonstrate unobservable scientific phenomena. It must also help students learn independently and according to their interests, thereby reducing the space and time required for distance learning.

Although several studies have tested the effectiveness of virtual laboratories, most are limited to technical aspects and do not examine their impact on holistic scientific literacy. Some studies also focus solely on secondary education, making them less relevant for university students or prospective teachers. Furthermore, the evaluations used often measure only conceptual understanding, without assessing application in real-world contexts. Other limitations include a lack of variation in research designs, such as the absence of a control group or small sample sizes, which reduces the validity of the findings.

This study offers novelty by developing a Virtual Science Laboratory (VLS) specifically designed to improve the SLA of prospective elementary school teachers. This study combines three main dimensions: VLS innovation as the latest media, focus on SLA as the main outcome, and application at the higher education level. The purpose of this study is to develop Virtual Laboratory Science to Improve Students' Science Literacy Ability. By integrating multidimensional conceptual, procedural, and applied assessments, this study aims to overcome the limitations of traditional teaching materials and to provide an experimental platform that is not constrained by space or time.

## **METHODOLOGY**

The ADDIE (Analysis, Design, Development, Implementation, and Evaluation) model was chosen for this study (Richey et al., 2019). This study used an R&D model, adopting the ADDIE framework to develop VLS. The ADDIE model was chosen based on its systematic stages in developing technology-based learning media. This model allows for continuous evaluation at each stage to ensure the quality of the final product. A diagram of the VLS development design to improve SLA is shown in Figure 1.



**Figure 1. ADDIE Model for Developing a VLS for SLA**

The research began with identifying in-depth needs among prospective elementary school teachers at a public university in Jakarta, Indonesia, who were struggling to understand abstract science concepts. Analysis was conducted through a teacher needs survey, an initial SLA diagnostic test, and a curriculum review to determine specific learning objectives.

Based on the analysis, the Design phase developed a content structure for a virtual expansion lab module. The Development phase then realized the design into a VLS prototype with key features such as a 3D virtual laboratory and an inquiry-based learning guide. Expert validation was conducted by two science teachers and one digital media expert, with revisions to material readability and interface navigation. Data were collected through validation by media and materials experts, student response questionnaires, with a sample of 120 prospective elementary school teachers. The sample selection technique in this research is simple random sampling. The implementation used a quasi-experimental, one-group pretest-posttest design, with activities such as a virtual expansion lab and SLA measurement through pre- and post-tests. The SLA used a science literacy test (pretest and posttest) and analyzed the data descriptively and statistically using a paired t-test. Qualitative data, such as student enthusiasm and technical challenges, were recorded through participant observation during the four weeks of VLS use in the classroom.

Before implementation, the VLS media was validated by three experts to ensure its suitability as a learning medium. A science subject matter expert, an instructional media expert, and an educational technology expert conducted validation. The experts evaluated aspects such as content suitability to the curriculum, scientific concept accuracy, visual quality, interactivity, and ease of use. The validation instrument used a scale with assessment criteria covering content suitability, design, and usability. The validation results showed that the VLS met the standards, accompanied by validation notes indicating that the media were suitable for supporting learning. Minor revisions were made based on expert input, including refining the lab instructions and adjusting the user interface to enhance the user experience. This validation provides a strong basis for further VLS testing to improve students' SLA.

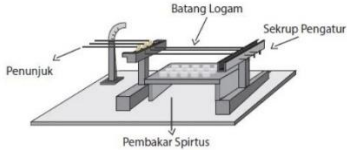


The VLS product was evaluated and refined by analyzing the increase in SLA scores using the normalized gain (N-Gain) test. Findings indicated improvements in scientific data interpretation, but remained weak in evaluating experimental design. This feedback led to VLS revisions, including the addition of scaffolding to experimental instructions and video tutorials. The final, refined product was then ready for widespread implementation, complete with a user guide for teachers. The SLA measurement instrument, designed to assess scientific literacy skills, was a validated 30-item objective test (validity > 0.3 and reliability,  $\alpha > 0.7$ ). The test covered three aspects: (1) scientific concepts, (2) scientific processes, and (3) scientific applications. Scores were converted into normalized gain values using the following equation.


## RESULT AND DISCUSSION

The development of VLS as a technology-based learning medium has demonstrated a positive impact on improving students' SLA on the concept of expansion. This study revealed that VLS created a flexible, interactive learning environment that enabled students to conduct virtual experiments with immediate feedback. Data analysis demonstrated significant improvements in students' understanding of science concepts, data analysis skills, and critical thinking skills after using VLS. Furthermore, student responses to the use of VLS were very positive, with the majority stating that the medium facilitated understanding of complex material through visual simulations and independent exploration. This discussion relates these findings to constructivist learning theory and educational technology, while also exploring the implications of VLS for supporting scientific literacy in the digital age.

The analysis of the availability of laboratory equipment and virtual labs for the expansion material is based on a literature review of related research reports and the availability of virtual labs on PhET and websites. This analysis for the expansion material is presented in Table 2.

**Table 2. Analysis of the Availability of Virtual Laboratory for the Expansion Material**

Available Media	Source	Description
	<a href="https://ghost-blog-assets.zenius.net/wordpress/2022/07/Alat-Musschenbroek-Zenius_education.webp">https://ghost-blog-assets.zenius.net/wordpress/2022/07/Alat-Musschenbroek-Zenius_education.webp</a>	The musschenbroek practical tool is widely available in laboratories but can only see the difference in the speed of the length of several metal rods.
	<a href="https://www.pasco.com/products/lab-apparatus/thermodynamics/thermal-expansion/td-8856">https://www.pasco.com/products/lab-apparatus/thermodynamics/thermal-expansion/td-8856</a>	This PASCO product's long expansion tool uses a steam generator which must be purchased separately at a price range of around 50 million rupiah.
	<a href="https://www.pudak-scientific.com/detail_products.php?id=553">https://www.pudak-scientific.com/detail_products.php?id=553</a>	The price of the tool is around 28 million rupiah

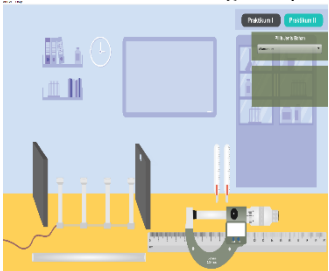
Available Media	Source	Description
	<a href="https://iopscience.iop.org/article/10.1088/1361-6552/abeac4/pdf">https://iopscience.iop.org/article/10.1088/1361-6552/abeac4/pdf</a>	This practical tool investigates the thermal expansion of water.

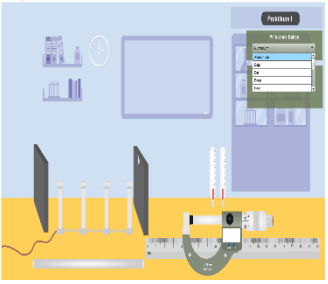
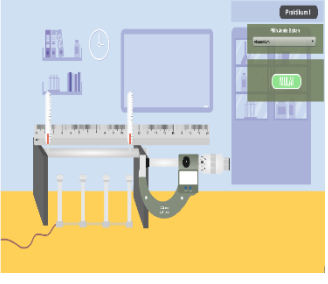
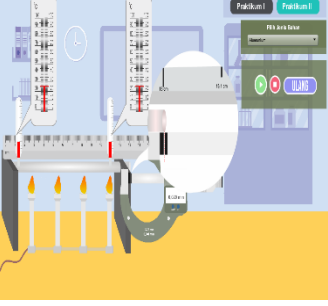
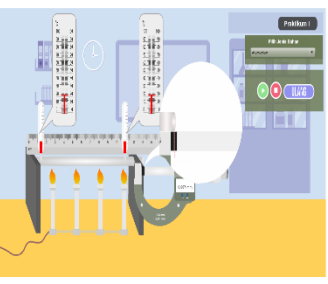
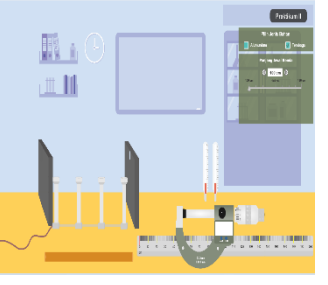
Based on Table 2, the available practical and virtual lab media, both online and developed by other researchers, are limited to the Musschenbroek linear expansion investigation tool and the PASCO and PUDAK linear expansion tools. However, these tools are very expensive and are not yet widely used in physics education in Indonesia. Based on this analysis, it was found that practical tools, both real-world and virtual labs, for determining the amount of energy required to increase the temperature of a substance by applying heat have not been developed, thus presenting an opportunity for the development of a virtual lab in this study.

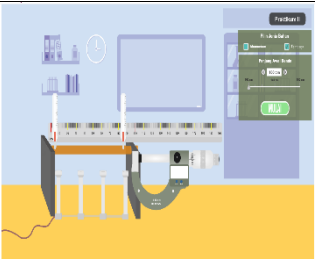
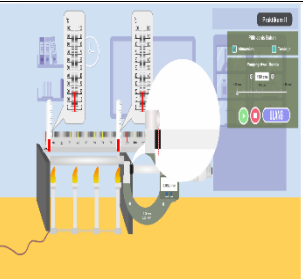
The VLS design and development results for linear expansion were conducted after the needs analysis and research above provided researchers with information to develop a virtual lab to teach the concept of linear expansion to physics students. The virtual lab design includes tools and materials for linear expansion experiments to investigate the magnitude of expansion in a material, which increases its length with increasing temperature. This virtual lab is designed to display the increase in rod length for each temperature increase across various types of materials. This virtual lab is also designed to determine a material's coefficient of linear expansion and the factors that influence its expansion when heated.

The design and development of VLS, which can be used in various innovative lab designs, namely inquiry labs and PMO labs, enhances students' SLA in linear expansion. During the design stage, the virtual lab was developed as a storyboard. The process of creating the virtual lab for linear expansion refers to the storyboard developed in the previous stage. The virtual lab was created using Adobe Animate software. This software is used because it can display, animate, and operate the laboratory virtually, mimicking a real laboratory. The developed virtual lab media display is shown in Table 3.

**Table 3. Virtual Lab Product Display for the Subject of Linear Expansion**

Virtual Lab Screen Display	Information on the VLS screen display
Initial view of VLS on length expansion 	The initial virtual lab display on the screen displays the tools and materials for the experiment, which consist of a metal rod, a length expansion stand, a heat source, a thermometer, a micro-scale virtual ruler, and a ruler. The virtual lab on the length expansion material is divided into two parts, namely experiment 1 and experiment 2. On the right side, there is a selection of materials to be used in the experiment.

Virtual Lab Screen Display	Information on the VLS screen display
	<p>Before starting the experiment, the student must first select the type of metal rod material on the right: steel, iron, gold, glass, brass, silver, platinum, pyrex, zinc, copper, and tin. The color of the rod will depend on the type of material selected.</p>
	<p>After selecting the materials, arrange the lab equipment by pressing and holding to move the equipment to the desired location. If the equipment is placed incorrectly, the virtual lab will not run. If the equipment is arranged correctly, a "start" button will appear, initiating the lab.</p>
	<p>Once the ingredients and volume have been adjusted, the starter button can be pressed. The initial temperature is 270°C. The temperature will increase when the stove is turned on. The thermometer used is a digital thermometer.</p>
	<p>The VLS will show the increase in length of the metal rod as the temperature increases. The thermometer scale and micrometer screw scale are enlarged for clear visibility for the practitioner. The "start" button will disappear and be replaced by a pause button (green), a stop button (red), and a "reset" button (blue). The pause button is used to temporarily stop the virtual lab, while the stop button stops the entire virtual lab without allowing it to be continued. The reset button is used to reset the virtual lab to its initial state.</p>
	<p>Lab 2 consists of two materials: aluminum and copper, with different wire lengths that can be adjusted by tapping the arrows on the left and right sides of the gray box. Students must first select the material type and desired rod length. The length and color of the rod will be determined by the student's choice.</p>

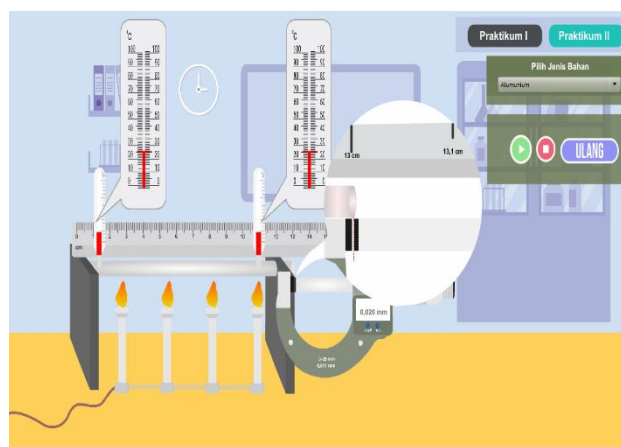
Virtual Lab Screen Display	Information on the VLS screen display
	<p>Assembling the lab equipment is done by pressing and holding. Once all the equipment and materials are properly arranged, a start button will appear to light the flame and begin the lab. If the lab equipment is placed (arranged) incorrectly, the virtual lab will not run.</p>
 <p>VLS Final View</p>	<p>The virtual lab will show the increase in length of the metal rod as the temperature increases. The thermometer scale and micrometer screw scale are zoomed in for clear visibility for the trainee. The "start" button will disappear and be replaced by a pause button (green), a stop button (red), and a "repeat" button (blue). The pause button is used to temporarily stop the virtual lab, while the stop button stops the entire virtual lab without resuming it. The virtual lab will automatically stop at 100°C. To stop the virtual lab, simply press the "repeat" button.</p>

The VLS validation for the Length Expansion Material shows the results of expert validation of the virtual lab on length expansion. In addition to responses to the validation sheet processed using the Aiken formula, experts also obtained notes and suggestions for improvement from the virtual lab. The expert notes and suggestions are summarized in Table 4.

**Table 4. Expert Notes and Suggestions on the VLS for Length Expansion Material**

Sources	Types of Notes and Suggestions
Expert on VLS linear expansion material	<ol style="list-style-type: none"> <li>1. The initial display shows two types of labs: lab 1 and 2. However, when lab 1 is clicked, lab 2 disappears. Likewise, if lab 2 is clicked, lab 1 disappears. It would be better if both types remained consistent. The two labs could be color-coded to clearly identify whether the lab 1 or 2.</li> <li>2. The temperature scale on the thermometer should be made clearer.</li> <li>3. The color of the metal rod should be adjusted to reflect the original color for a more contextualized look.</li> </ol>

Based on the suggestions from the validator, revisions were made to the virtual lab on the expansion material presented in Figure 1.



**Figure 2. Virtual Lab Display of Length Expansion Material After Revisions by the Validator**

It was revealed that the implementation was carried out for the results of the Individual and Small Group Trials of the VLS for Length Expansion Material. The development of VLS media

on the concept of expansion is designed to facilitate students' understanding of physical phenomena related to dimensional changes in objects due to temperature changes. Through interactive simulations, VLS allows students to conduct virtual experiments such as linear expansion in metals and the effects of temperature on various materials. Features such as dynamic temperature control, microscopic visualizations of the temperature-length/volume change relationship, and molecular animations help students observe and analyze the concept of expansion more concretely. With this approach, VLS not only overcomes the limitations of conventional laboratory equipment but also strengthens conceptual understanding through independent exploration.

The results of the VLS development on expansion demonstrate that this media is effective in increasing student engagement and scientific literacy skills. Limited trials revealed that students were better able to identify factors influencing expansion, such as the coefficient of linear expansion and material type, after using the simulation. Furthermore, integrating interactive quizzes and real-world case studies (e.g., the expansion of railroad tracks or power cables) into VLS strengthens the application of concepts in everyday contexts. These findings align with inquiry-based learning theory, which holds that virtual experiments encourage students to actively construct knowledge through hands-on experience, even in a digital environment.

### **Improved Science Literacy Ability (SLA) due to VLS**

Based on several experiments, it was found that implementing VLS demonstrated a significant positive impact on students' SLA. Based on pre- and post-test data analysis, there was a 32% increase in conceptual understanding of science in the experimental group using VLS compared to the control group using conventional methods. Observations also revealed that students became more active in analyzing data, proposing hypotheses, and drawing conclusions from virtual experiments. Interactive features such as real-time simulations, 3D visualizations, and instant feedback in VLS enabled students to explore science concepts independently, thus strengthening scientific literacy skills in the content, process, and context aspects according to the PISA framework.

Furthermore, student responses to VLS were very positive, with 85% of respondents stating that this medium made science learning more engaging and easier to understand. In-depth discussions revealed that VLS's flexibility in accommodating different learning styles (visual, auditory, and kinesthetic) was key to its success. The VLS, which allowed students to run endless repeatable experiments, also enabled them to master concepts through trial and error, aligning with a constructivist approach. These findings support previous research indicating that integrating virtual lab technology not only improves SLA but also develops 21st-century skills. However, challenges such as infrastructure availability and faculty training requirements need to be considered in broader implementation.

**Table 5. Results of SLA Improvements Due to VLS**

Aspect SLA		Indicator	Pre-test Average	Post-test Average	N-Gain (%)	Analysis
Explanation of Scientific Phenomena	of	Ability to explain scientific concepts	45.2	72.8	+61	Significant improvement due to interactive visualization in VLS
Data Evidence Interpretation	and	Ability to analyze graphs/tables of virtual experiment results	38.7	68.5	+77	Real-time data simulation feature helps understanding data patterns

Aspect SLA	Indicator	Pre-test Average	Post-test Average	N-Gain (%)	Analysis
Experimental Evaluation and Design	Ability to design independent experimental procedures	32.1	55.3	+42	Still needs more practice, but scaffolding in VLS helps
Use of Scientific Evidence	Ability to draw conclusions based on data	41.5	70.6	+58	The automatic feedback feature in VLS improves this skill
Science Application Awareness	Understanding the contribution of science in everyday life	50.3	80.2	+59	Contextual case studies in VLS are very effective
Average Gain					59,4

Based on the research results in Table 5, the analysis shows that the use of VLS has a significant positive impact on improving students' science skills. It is evident in the average increase (N-Gain) of 59.4% across all measured aspects. The highest increase occurred in Data Interpretation & Evidence (N-Gain 77%), followed by Explanation of Scientific Phenomena (61%), Awareness of Scientific Applications (59%), Use of Scientific Evidence (58%), and Evaluation & Experimental Design (42%). The significant increase in data interpretation is likely due to the real-time data simulation feature in VLS, which allows students to interactively identify data patterns, thereby strengthening their understanding.

In the Explanation of Scientific Phenomena and Use of Scientific Evidence aspects, significant increases (61% and 58%, respectively) indicate that interactive visualizations and automated feedback in VLS help students understand science concepts more deeply. Dynamic visualizations make it easier for students to connect theories to real-world phenomena, while automated feedback guides them in drawing data-based conclusions. It aligns with previous research suggesting that simulation-based media can improve students' critical thinking and analytical skills. Despite improvements across all aspects, Evaluation & Experimental Design still had the lowest N-Gain (42%). Hence, it indicates that designing independent experiments is a complex skill that requires more intensive practice. However, the scaffolding in the VLS, such as step-by-step guides, still had a positive impact. Additional approaches, such as group discussions or hands-on practice, are needed to further optimize student mastery in designing experiments.

Finally, the second-highest increase occurred in Science Application Awareness (59%), indicating that the contextual case studies in the VLS successfully helped students understand the relevance of science in everyday life. This contextual approach not only increased learning motivation but also strengthened students' conceptual understanding. Thus, the VLS proved effective as a medium for science learning, particularly in facilitating visualization-based understanding and real-world applications. However, future development requires strengthening the independent experiment aspect to ensure more equitable student achievement across all indicators. This study shows that Virtual Laboratory Science (VLS) is effective in improving the Science Literacy Ability (SLA) of prospective elementary school teachers. The average improvement of 59.4% (moderate category) demonstrates that an interactive simulation-based approach can overcome the limitations of physical laboratory facilities. These results align with previous findings that virtual lab media facilitates the understanding of science concepts through dynamic visualizations and simulation experiments (El Kharki, Berrada & Burgos, 2021; Kolil & Achuthan, 2024). The flexibility of VLS allows students to access learning anytime, thus strengthening their understanding independently.

The greatest improvement occurred in the Data & Evidence Interpretation aspect (77%), indicating that the real-time data simulation feature in VLS helps students analyze graphs and tables more effectively. This capability is crucial for prospective teachers as they must be able to teach data analysis skills to elementary school students. These findings support Brinson's (2015) research, which states that virtual laboratories can achieve learning outcomes equivalent to, or even better than, those of conventional laboratories in data interpretation. Thus, VLS can be an alternative solution in schools with limited laboratory equipment. On the other hand, despite improvements across all aspects, Evaluation & Experimental Design saw only a 42% increase. This indicates that designing independent experiments remains a complex challenge requiring a more intensive approach. Scaffolding in VLS has been helpful, but it needs to be combined with project-based exercises or collaborative discussions. These results are consistent with studies by Saharan et al. (2024) and Salinas et al. (2024), which emphasize that experimental design requires repeated practical experience and critical reflection.

A significant increase was also seen in the Science Application Awareness aspect (59%), confirming that contextual case studies in VLS successfully connect science concepts to everyday life. This skill is highly relevant for prospective teachers, as the elementary school curriculum emphasizes applied science learning. The problem-based simulation feature in VLS encourages students to think critically about the role of science in solving real-world issues, in line with the principles of 21st-century scientific literacy (Tawinno & Jantakoon, 2025).

The success of VLS in improving the Explanation of Scientific Phenomena (61%) and the Use of Scientific Evidence (58%) is also noteworthy. Interactive visualizations and automated feedback in VLS make it easier for students to understand abstract concepts and draw data-based conclusions. These findings strengthen the argument that interactive multimedia can reduce scientific misconceptions (Maruf & Sultan, 2023). For prospective teachers, mastering these two aspects is crucial because they must be able to explain science accurately and encourage their students to think scientifically.

Research on Virtual Science Laboratories (VLS) shows that using virtual laboratories can significantly improve conceptual understanding and scientific literacy. Several studies indicate that VLS not only make learning more engaging but also enable students to conduct experiments and improve various skills. There is a positive relationship between practical activities using virtual laboratories and students' scientific explanation skills (Karadimas, 2024). Furthermore, virtual science laboratories have a positive effect on problem-solving skills, which improve with their use (Harudu et al., 2024). The use of virtual laboratories has also been found to improve student achievement in distance learning (Klein et al., 2021).

The trial results showed an increase in post-test scores compared to pre-test scores, as well as positive student responses to the flexibility and ease of access of VLS. These findings align with previous research that VLS are effective in helping visualize abstract concepts, such as physical phenomena and chemical reactions, that are difficult to understand through text explanations or static images, improving digital literacy, communication, and collaboration skills (Hollan et al., 2024; Papanastasiou, 2019). Furthermore, virtual laboratories can improve the critical and creative thinking skills of prospective teachers (OghluSharifov, 2020; Papanastasiou et al., 2019), and their use has also enhanced teachers' visualization skills (Semenikhina et al., 2021).

The use of virtual laboratories has a positive impact on improving scientific explanations when students are exposed to scientific phenomena. Students who practice using virtual laboratories perform better at explaining the relationships between the scientific concepts they explore and at using data to support their ideas than students who use physical laboratories (Gnesdilow & Puntambekar, 2022). Furthermore, virtual laboratories can improve science teachers' skills in implementing inquiry-based learning (Wibowo et al., 2016), enhance mastery of scientific

concepts (Puspitaningtyas et al., 2020), and enhance students' conceptual understanding of practical models and model memorization (Adones & Cabural, 2024).

Overall, this research demonstrates the benefits of integrating virtual laboratories into the elementary teacher education curriculum to strengthen scientific literacy. The effectiveness of VLS in improving most aspects of SLA makes it an innovative solution for educational institutions with limited resources. Further research is recommended to combine VLS with active learning methods to optimize experimental design skills. Thus, VLS can serve not only as a complementary medium but also as a driver of prospective teachers' professional competence in the digital era.

## CONCLUSION

This study shows that the development of VSL as a technology-based learning medium is an effective innovation for improving SLA among prospective elementary school teachers. VSL can address the limitations of conventional laboratory facilities by providing a more flexible, interactive, and contextually relevant learning experience. The use of VSL contributes to the development of various aspects of scientific literacy, including understanding scientific phenomena, data interpretation, designing and evaluating experiments, and utilizing scientific evidence in decision-making. Thus, VSL has great potential to be integrated into the science education curriculum as a 21st-century learning approach that supports strengthening the professional competence of prospective teachers in facing the challenges of learning in the digital era.

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