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Enhancing Primary Students Scientific Literacy Through Virtual Laboratory-Based Digital Learning Packages to Support Sustainable Development Goals (SDGs)

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Abstract: This study aims to develop and evaluate a virtual laboratory–based digital learning package to enhance scientific literacy among elementary school students. The study employed a Research and Development (R&D) approach using the ADDIE model, which includes analysis, design, development, implementation, and evaluation. The product was validated by experts in science education, media, and language, and then implemented with fourth-grade students. Data were collected through validation sheets, practicality questionnaires, and pretest–posttest instruments. The findings show that the developed learning package is both valid and practical for classroom use. Students demonstrated a significant improvement in scientific literacy, with an N-gain score of 0.65 (moderate category), particularly in understanding concepts, interpreting data, and relating science to everyday phenomena. The integration of interactive simulations and multimedia elements supported active engagement and meaningful learning experiences. Overall, the virtual laboratory–based digital learning package is effective in improving students' scientific literacy and shows strong potential to enhance the quality of science instruction in primary education in line with 21st-century learning demands.

Keywords: ADDIE; Digital Learning Tools; Scientific Literacy; Virtual Laboratory

Introduction

In recent decades, the world of education has undergone significant changes along with the development of digital technology. This innovation has not only transformed the way teachers teach but also how students learn—from conventional methods that emphasize memorization to more interactive, conceptually based approaches that integrate technology (Sarwar et al., 2024). Amid this progress, science education at the elementary school level faces major challenges in adapting to these changes. Science learning, which has long focused on memorizing theoretical concepts, is now expected to equip students with scientific thinking skills and science literacy from an early age (Purnawati & Yakin, 2025). The results of PISA 2022 show that the science literacy score of Indonesian students remains relatively low, at around 383, a decline from 396 in PISA 2018. Although Indonesia's relative ranking shows a slight shift compared to other countries, this change should be interpreted cautiously, as the overall score indicates a statistically significant decline in students' science literacy achievement.

The implementation of science literacy in elementary school science learning is essential, as it serves as the foundation for developing scientific thinking skills from an early age (Dewantari & Singgih, 2020; Dewi & Fauziati, 2021). Elementary school students are at the concrete operational stage of cognitive development, during which they learn most effectively through direct experiences and environmental exploration. Thus, teaching science alongside science literacy enables learners to relate and

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integrate scientific concepts with daily occurrences, stimulates interest, and strengthens reasoning and problem-solving abilities. Moreover, science literacy prepares learners with 21st-century skills, including critical thinking, creativity, collaboration, and communication (4C) (Kembara et al., 2019).

The incorporation of virtual laboratories into digital learning resources is one way to address these challenges. However, rather than replacing concrete experiences, virtual laboratories in this study function as a representational bridge that helps visualize phenomena that are difficult, dangerous, or impossible to observe directly, such as microscopic processes or abstract interactions. In this sense, virtual laboratories complement hands-on learning by providing meaningful representations that support conceptual understanding. A virtual laboratory is a computer-based simulation that allows students to perform science experiments without relying entirely on physical laboratory availability (Fitri et al., 2025). More recent research indicates that virtual laboratories not only support learning but also deepen students' understanding of complex and abstract scientific concepts (Lestari & Supahar, 2020; Alhashem & Alfailakawi, 2023; Dodevska et al., 2025).

On the other hand, the Representation Construction Approach (RCA) is positioned as the key conceptual foundation of this study and constitutes its primary novelty. RCA emphasizes the use of multiple representations—such as graphs, images, simulations, and symbolic forms—as a means for students to construct scientific understanding. By engaging in constructing, evaluating, and coordinating these representations, students are able to develop deeper science literacy and critical thinking skills (Cirkony et al., 2022). In this study, RCA is explicitly integrated into the design of virtual laboratory–based digital learning resources, enabling students to connect abstract concepts with meaningful learning experiences.

In addition, the development of digital learning tools in this study is guided by the TPACK (Technological Pedagogical Content Knowledge) framework. In this context, TPACK is not only viewed as a teacher competency but also as a design framework for developing digital learning resources that integrate science content, inquiry-based pedagogy, and virtual simulation technology. Through this integration, the developed learning tools are expected to present science concepts in a more interactive, contextual, and meaningful way, thereby supporting the improvement of students' science literacy (Koehler et al., 2013; Schmid et al., 2024).

These gaps are the core reason this study was designed to develop validated and practical digital learning resources based on virtual laboratories and the Representation Construction Approach (RCA) to support science learning in primary education. This study ensures that both the content and media design are systematically developed, validated by experts, and tested in real classroom settings. Therefore, this research contributes not only by providing empirically tested digital learning tools but also by offering a novel integration of RCA and virtual laboratory within elementary science education, particularly in enhancing students' science literacy in line with current technological advancements.

Method

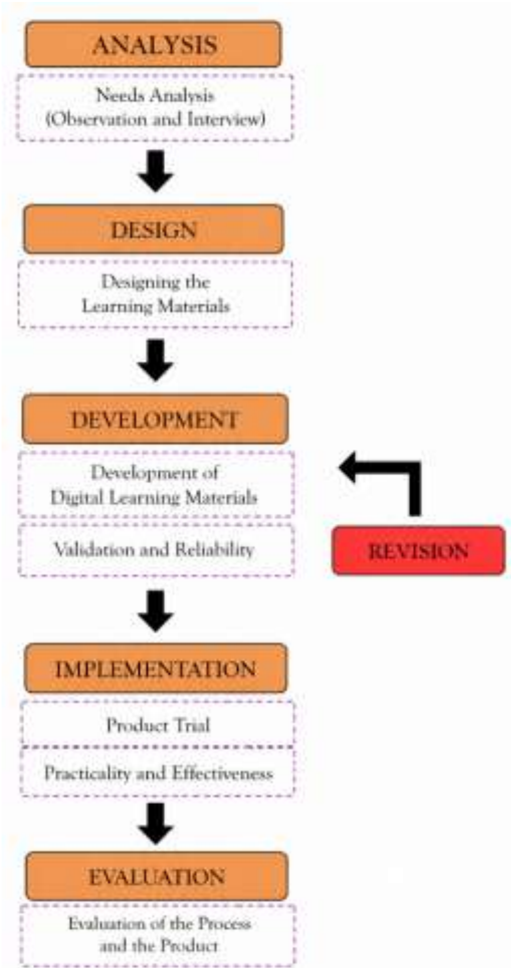

Figure 1. Flowchart

This work constitutes a research and development (R&D) study based on the model proposed by Robert Maribe Branch. According to Yu et al. (2021). R&D research is a method carried out to generate a specific product while assessing and testing its practicality and viability. The study develops a digital learning tool in the form of a virtual laboratory aimed at improving elementary learners' science literacy. This study's development model is grounded on the ADDIE model proposed by Branch & Varank (2009) with the research stages: Analysis: In this phase, the study evaluates the learning needs, the science literacy needs for the learner, and the appropriateness of the virtual lab features for the elementary science education, through observation and interviews, Design: In this phase, the structure, content, and interactivity of the digital learning tool is designed, Development: In this phase, the initial product is created and is validated by content, media, and language experts. The language validator is a lecturer with language expertise, the media validator is a digital learning design expert, and the content validator is a lecturer in science education, Implementation: In this phase, a limited-scale trial is conducted and the tool is integrated into science learning in the classroom. Afterward, the researchers gather feedback from the teacher and the learners, Evaluation: In this phase, the revised product is tested in classroom learning, and evaluation stage is both a formative and summative evaluation of the entire development process.

This research employed a mixed-method data collection approach by combining observation, questionnaires, and interviews to obtain comprehensive data (Maxwell, 2013; Silverman, 2021). The use of multiple data sources was intended to support the validation of instruments and strengthen the empirical findings. Quantitative data were primarily obtained through validation sheets and test instruments to measure validity using Aiken's V and effectiveness using N-Gain, while qualitative data from observations and interviews were used to support the interpretation of results (Rahmi, 2019).

Figure 2. ADDIE model

The research data were obtained through several instruments used to assess the feasibility of digital learning tools based on virtual laboratories. These instruments include: A needs analysis questionnaire administered to students and teachers to determine the extent to which virtual laboratory-based tools are needed to support science learning and the development of science literacy. A content expert validation sheet used to assess the completeness, conceptual accuracy, alignment with the curriculum, and integration of science content presented in the digital learning tool. A media expert validation sheet focused on the quality of visual design, interactivity, ease of navigation, and the suitability of virtual laboratory features in supporting elementary science learning. A language expert validation sheet used to evaluate the linguistic aspects of the developed product to ensure compliance with scientific language conventions, communicativeness, and ease of understanding for both teachers and students. Student and teacher response questionnaires administered after the implementation of the tool in science learning, using a 4-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = agree, 4 = strongly agree) to assess the practicality, attractiveness, and usefulness of the tool in enhancing science literacy. Pre-test and post-test items, used to measure the achievement of students' science literacy indicators.

The instruments used for validation consisted of questionnaire sheets with a 4-point Likert scale, according to Likert (1932) with the following score categories: 4 = very good, 3 = good, 2 = fair, and 1 = poor. Furthermore, Yang & Yagi (2024) emphasize that the Likert scale is useful for quantifying subjective data into measurable numerical scores that can be analysed statistically. The validation data were analysed descriptively and quantitatively by calculating the average score for each assessment item using Aiken's V formula. According to Aiken (1985), the Aiken's V coefficient is used to measure the content validity of items based on expert judgment, where values range from 0 (invalid) to 1 (highly valid).

$$V = \frac{\sum s}{n\,(c-1)} \tag{1}$$

With the following criteria:
V > 0.80 = Highly valid
0.60 – 0.79 = valid
< 0.60 = Needs revision
(Riduwan, 2022)

When developing the educational resource, the reviewers' suggestions, comments, and validation excerpts were incorporated. This included revisions on the substance of the educational resource, improvements on the media added, enhancement of the resource's interactivity, and language refinements. These modifications were then assessed for practicality through teaching fifth graders, a class of 12 girls and 10 boys (limited implementation). Both teachers and students were asked to complete a practicality questionnaire, also using a 4-point Likert scale. Teacher assessments focused on the ease of using the tool for teaching, its alignment with learning objectives, and time efficiency. Meanwhile, the student questionnaire evaluated the attractiveness of the interface, readability, clarity of instructions, and ease of use.

The practicality data analysis process began by accumulating scores from all respondents for each item, including both teachers and students. The total score for each item was then summed and divided by the number of respondents to obtain the average score per item. Subsequently, all item average scores were compiled and averaged again to determine the overall practicality score of the learning tool. This score served as the primary indicator in categorizing the tool as highly practical, practical, less practical, or not practical.

The formula used to calculate the average practicality score is as follows. This formula comes from classical descriptive statistics, which was first formalized by Pearson (1895) and later standardized in the statistical works of Fisher (1925).

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (2)$$

After obtaining the average scores, interpretation was carried out based on the predefined rating scale categories. For example, if a 4-point Likert scale is used (1 = not practical, 2 = less practical, 3 = practical, 4 = highly practical), the interpretation of the practicality categories can be described as follows:

3.25 ≤ X¯\bar{X}X¯ ≤ 4.00 = Highly Practical
2.50 ≤ X¯\bar{X}X¯ < 3.25 = Practical
1.75 ≤ X¯\bar{X}X¯ < 2.50 = Less Practical
1.00 ≤ X¯\bar{X}X¯ < 1.75 = Not Practical
(Riduwan, 2022)

All data obtained from teachers and students were then systematically tabulated, both in tables and graphs, to provide a more comprehensive overview. These results were further analysed to examine the consistency between teacher and student perceptions, as well as to evaluate which aspects of the tool were already optimal and which aspects still needed improvement.

The effectiveness of the digital learning tool based on virtual laboratories developed in this study was determined by the improvement in the average science literacy test scores of the students. This improvement was demonstrated through the calculation of N-Gain scores between the pre-test and post-test results, According to Hake (1998) and Meltzer (2002), N-Gain provides a standardized way to quantify learning improvement, where values are interpreted as follows: high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$) (Wijaya & Astuti, 2022).

$$g = Gmax-T1T2-T1 \quad (3)$$

Where T2 = post-test, T1 = pre-test

The N-Gain score helps assess the improvement in learners' science literacy after interacting with the digital learning tool centred on virtual laboratories. N-Gain also helps determine the degree of improvement in students' conceptual understandings by evaluating the difference between the assigned pre- and post- tests. N-Gain values can also be classified as high, medium, or low to show the degree of effectiveness of the intervention. Thus, N-Gain analysis not only communicates the degree improvement in the learning outcomes, but also illustrates the degree to which the designed learning tool can markedly improve learners' science literacy.

Result and Discussion

Result

In this research, the development of digital learning tools that integrate virtual laboratories utilized the ADDIE model. This model is selected because it is commonly utilized in the research and development of learning tools and it is considered efficient in the design of the educational systems across different environments. As cited in Branch & Varank (2009), the ADDIE model is a systematic approach to the instructional design which is composed of five fundamental components: Analysis, Design, Development, Implementation, and Evaluation.

Analysis

This study's needs analysis employed observations, surveys, and interviews with elementary school teachers and students. Conversations with teachers and on-site observations revealed that the instructional materials and media employed in the science lessons were quite restricted and infrequently changed, causing the students to miss out on many valuable experiential learning opportunities, particularly learning through hands-on experiments. Teacher interviews furthermore revealed that the implementation of science practicums at the schools was also limited due to a lack of equipment for the practical lessons and insufficient materials for the experiments. Furthermore, the digital media used in learning were still conventional, such as simple slide presentations or videos, and therefore were not yet capable of training students to achieve science literacy indicators. These findings reinforce the need to develop a digital learning tool based on virtual laboratories as an alternative to overcome resource limitations while providing more interactive learning experiences that align with the demands of 21st-century science education. To clarify the existing conditions, a SWOT according to Puyt et al. (2023), the SWOT analysis is a strategic planning tool used to identify internal and external factors that influence the success of a project or organization. Analysis was conducted and is presented in Table 1.

Table 1. SWOT analysis of digital learning tools

Strengths	Weaknesses	Opportunities	Threats
Teachers demonstrate an awareness of the importance of scientific literacy in primary science education.	Limited availability of equipment and materials for hands-on science practicum in schools.	Rapid advancement of digital technology supports the development of interactive and innovative learning media.	Not all schools are equipped with adequate ICT infrastructure (e.g., stable internet, computers, or mobile devices).
Students show high interest in science learning when digital or animated media are utilized.	Some teachers lack confidence in integrating digital tools into classroom instruction.	Integration of virtual laboratories aligned with the elementary science curriculum.	Some teachers remain accustomed to conventional, teacher-centered instructional methods.
Teachers and students exhibit enthusiasm in using virtual laboratory-based learning.	Students experience difficulty in understanding abstract science concepts without adequate scaffolding.	Availability of open-source and accessible digital learning platforms that can support virtual experimentation.	Without proper guidance, the use of digital media may lead to confusion or increased cognitive load among students.
Teachers possess basic experience in using digital tools for instruction.	Unequal access to digital devices (laptops, smartphones, internet) among students.	Support from educational policies promoting digital transformation in education (Education 4.0).	Rapid technological changes may render digital tools obsolete if not continuously updated.

Design

The development of the digital learning tool based on virtual laboratories in this study considered several important aspects, including content, media, virtual laboratories, and evaluation instruments. These considerations were made to ensure that the developed tool is fully aligned with the needs of elementary school students and capable of supporting the mastery of science literacy. According to Bybee & McCrae (2011), science literacy refers to the ability of learners to apply scientific knowledge, skills, and reasoning to make informed decisions in real-life contexts.

The content was developed with reference to the most recent elementary school science curriculum. Specifically, the basic competencies and achievement indicators were considered. The content was shaped to the characteristics of elementary school learners, that is, it was made simple, contextual, and closely tied to everyday life. Furthermore, the selected content aimed to facilitate the development of some dimensions of science literacy, particularly the abilities to understand scientific concepts, identify science-related issues, and situate knowledge within real-world phenomena.

The design of the digital media presentation employed the chunking strategy, which entails breaking down the information into smaller, more digestible pieces. To promote engagement and comprehension, the presentation integrated text, images, animations, and videos. The design was kept simple and user-friendly to minimize the interface and allow students to engage with the presentation without excessive technical challenges.

The developed learning tool's centrepiece is the virtual laboratory feature. The purpose of the virtual laboratory is to provide students with simulations of uncomplicated science experiments which, due to the lack of tools and materials, difficult to implement in elementary schools. Students can observe, experiment, and analyse data in simulations as if they were actually in a laboratory. Consequently, this helps to develop students' science process skills, conceptual understanding, and science literacy.

The developed evaluation instruments were centred on assessing science literacy with a focus on High Order Thinking Skills (HOTS). The indicators included understanding scientific phenomena, designing and interpreting experiments, and evaluating scientific data. These instruments included written tests along with context-based questions which included reflective questions that aimed to assess the extent to which students can apply the science concepts in everyday life.

These four aspects aim to improve the quality of elementary science education in light of the shortcomings surrounding the conventional teaching of science education and the expected potential of the virtual laboratory-based digital learning tool.

Development

The design and construction of digital learning tools, particularly for virtual laboratories, unfold with the collaboration of content, media, and language experts who serve as validators, as illustrated by Borg & Gall (1983). They define expert validation as an indispensable step in the R&D process aimed at ensuring the product achieves defined quality standards addressing content validity and instructional design and delivery. The content for the digital tools under development incorporated the most recent elementary science curriculum, digital technology integration, and other current references in science. The media design focused on elementary science content and included teaching modules, instructional materials, instructional media, student worksheets (LKPD), and various evaluation tools. Development discussions with science education experts were undertaken to maximize alignment and integration with quality science literacy indicators and in the development of the evaluation instruments for higher order thinking skills (HOTS) focused on measuring students' understanding of scientific concepts, experimentation, and evaluation of scientific evidence. Expert validation indicated the developed instrument was appropriate and ready for implementation in elementary science.

Content experts confirmed that the developed material is curriculum-compatible, addresses fundamental scientific principles, and possesses scientific validity. Furthermore, it confirmed that the material aids the strengthening of the students' science literacy, and is applicable to everyday situations. A language expert evaluated the communication used in the digital learning tool for virtual laboratories to verify that it employs the language of communication, is suitable for the elementary learners' level of cognitive development, and is understandable. Elements assessed included clarity of the sentences, suitability of words, readability, and uniformity in the use of terminology (Pires et al., 2017). Clarity and appropriateness of language are essential to ensure that instructional materials are easily understood by learners at the intended level. Media expert validation was carried out to assess whether the digital learning tool met the criteria for visual presentation, interactive navigation, and the relevance of illustrations to the science content. An attractive design, organized layout, and harmonious colours make the media easy to understand and engaging for students. The validation results for these three aspects can be seen in the figure below. Validity of Digital Learning Tools Based on Virtual Laboratory.

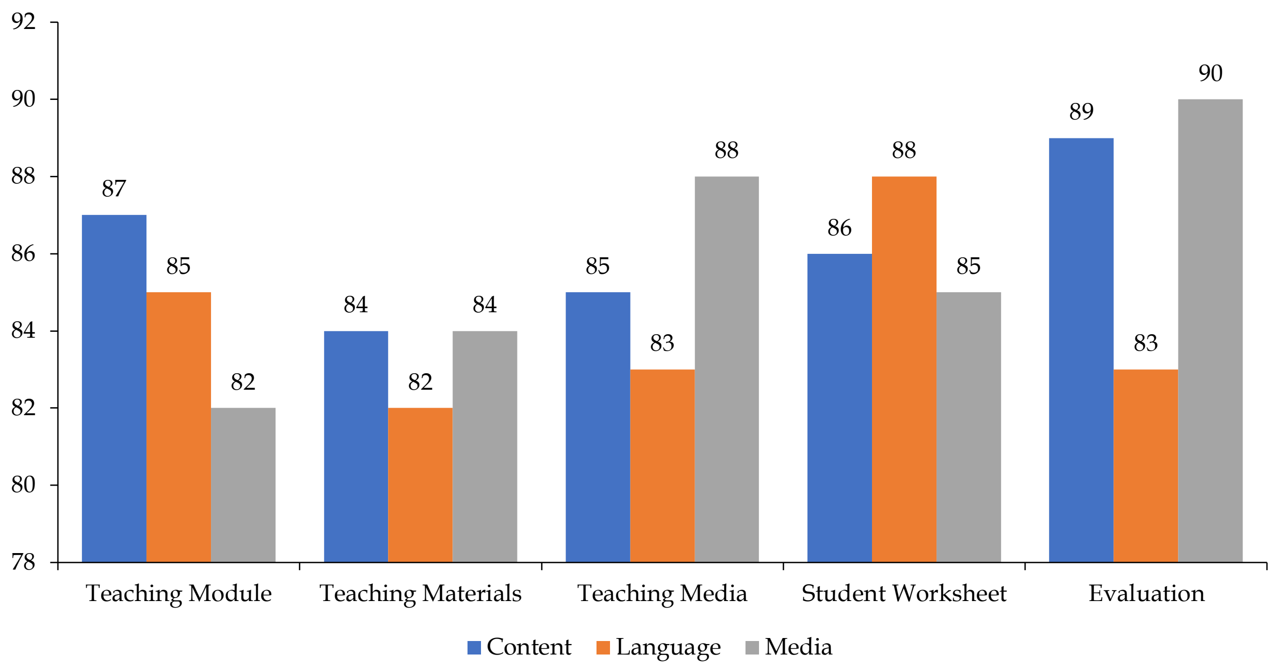

Figure 3. Validity of Digital Learning Tools Based on Virtual Laboratory

Implementation

After the digital learning tools based on the virtual laboratory were declared valid by experts (language experts, subject matter experts, and media experts), the next stage is the practicality test. This test is conducted by involving education practitioners, namely elementary school science teachers and students who serve as the users of the tools. The results of the practicality test are presented in Table 2.

Based on the calculation results, out of 18 questionnaire statements, 13 statements were categorized as "Very Practical" and 5 statements fell into the "Practical" category. The overall average score was 3.52, which still falls within the Very Practical category. This indicates that, in general, the digital learning tool based on the virtual laboratory is highly practical to use, both in terms of appearance, ease of navigation, and its usefulness in enhancing science understanding. This finding is in line with Dahal et al. (2023) who states that practicality reflects the extent to which a developed learning product can be easily used and effectively implemented in real educational settings, with positive responses from users and suitability for classroom application.

Table 2. Results of the practicality test of the tools by students

Statement	Average	Category
I enjoy learning science using this digital learning tool	3.70	Highly Practical
The colours, images, and videos are attractive	3.80	Highly Practical
I have no difficulty in opening and using the tool	3.60	Highly Practical
The wording and explanations are clear and easy to understand	3.10	Practical
Videos and animations make it easier for me to understand science lessons	3.70	Highly Practical
I enjoy conducting experiments within the tool	3.80	Highly Practical
It does not contain too much text and keeps me interested	3.00	Practical
I can follow the instruction easily	3.20	Practical
I can work on the questions and understand my results	3.10	Practical
I understand science better after using this tool	3.60	Highly Practical
Learning is more engaging with activities or games	3.70	Highly Practical
I am able to go back and study the parts I haven't understood	3.50	Highly Practical
Learning is more enjoyable with fun games or activities	3.70	Highly Practical
Using this tool is not confusing for me	3.20	Practical
I am able to learn whit this tool at home	3.80	Highly Practical
I am able to learn science on my own with this tool	3.60	Highly Practical
I am able to learn science on my own with this tool	3.80	Highly Practical
I would like to use this digital tool for other science topics	3.90	Highly Practical
Overall average	3.52	Highly Practical

However, there are some aspects that remain in the "Practical" category, such as clarity of language, text density, ease of following instructions, feedback on exercises, and reducing potential confusion. This means that, although the tool is already feasible and effective, minor improvements are needed to make it even more optimal in supporting science learning in elementary schools.

Table 3. Teachers' practicality test results of the tool

Evaluation Aspects	Mean Score	Category
Content aligned with the Science Curriculum and learning outcomes	3.20	Highly Practical
The learning objectives are achieved systematically	3.30	Highly Practical
Language and visuals are appropriate for elementary school students' characteristics	3.10	Practical
Information is concise, clear, and not confusing	3.00	Practical
The interface is attractive and support students' learning focus	3.40	Highly Practical
Images, videos, or animations support the understanding of science concept	3.30	Highly Practical
Experiments in the virtual lab are easy to understand and relevant to science topics	3.20	Highly Practical
The tool's navigation is easy to use for both students and teachers	3.10	Practical
Student interaction promotes engagement and active learning	3.00	Practical
Automatic and informative feedback is provided for each exercise	3.20	Highly Practical
Activities help students develop scientific literacy	3.40	Highly Practical
The tool can be used by teacher without complicated training	3.30	Highly Practical
The tool is flexible for use in both classroom-based and independent learning by students	3.20	Highly Practical
Compatible with various devices (laptops, tablets, smartphones)	3.30	Highly Practical
Enhances students' scientific literacy and learning interest	3.40	Highly Practical
Overall average	3.25	Highly Practical

Based on the evaluation results from two teachers, the digital learning tool based on the virtual laboratory received an average score of 3.25, falling into the Very Practical category. Out of a total of 15 assessed aspects, 11 aspects (73%) were categorized as Very Practical, while only 4 aspects (27%) remained in the Practical category. These findings indicate that the tool is already feasible and effective for use in science learning in elementary schools.

Teachers assessed the tool as having an attractive interface, being easy to use, relevant to the curriculum, and capable of enhancing students' scientific literacy. However, several aspects, such as language, clarity of information, navigation, and student interaction, still need improvement to make the tool more optimal and achieve the Very Practical category across all aspects.

Evaluation

The effectiveness of the developed digital learning tool based on the virtual laboratory was determined by the increase in students' average science literacy test scores. This improvement was demonstrated through the calculation of the N-Gain score between the pretest and post-test results. The descriptive analysis of students' science literacy test results is presented in Table 4.

Table 4. Descriptive analysis of students' science literacy assessment

Category	Pretest	Post-test
A large number of students	22	22
Maximum Score	85	100
Minimum Score	15	30
Total Score	1180	1710
Average	53.60	77.70
Standard Deviation	19.80	23.50
Variance	392	552
N-Gain		0.65
Pretest–Post-test		(Medium Category)

Based on the analysis of pretest and post-test data, there was an improvement in students' science literacy skills after using the digital learning tool based on the virtual laboratory. The average pretest score was 53.6, while the average post-test score increased to 77.7. This improvement is also reflected in the maximum and minimum scores, with the highest score rising from 85.0 in the pretest to 100.0 in the post-test, and the lowest score increasing from 15.0 to 30.0. In addition, the total sum of students' scores significantly increased from 1,180.0 in the pretest to 1,710.0 in the post-test.

From the perspective of data distribution, the standard deviation and variance in the post-test (23.5 and 552.0, respectively) were higher than those in the pretest (19.8 and 392.0). This indicates greater variation in students' abilities after the intervention, although the overall average learning outcomes increased. The N-Gain calculation yielded an average score of 0.65, which falls into the medium category. These findings indicate that the digital learning tool based on the virtual laboratory is effective in improving students' science literacy, although the improvement has not yet reached the high category. Thus, the results reinforce that the integration of interactive technology-based media can serve as an innovative alternative to support science learning in elementary schools, particularly in enhancing students' understanding of scientific concepts through more contextual and engaging learning experiences.

Discussion

The results of the study indicate that the development of a digital learning tool based on the virtual laboratory—which includes a teaching module, learning materials, instructional media, student worksheets, and evaluation instruments—can enhance the science literacy of elementary school students. The average pretest score of 53.6 increased to 77.7 in the posttest, with an average N-Gain of 0.65 (medium category).

This improvement confirms that integrating digital tools into learning not only provides interactive media but also establishes a more structured learning system through the combination of content, experimental simulations, and assessments that align with the characteristics of elementary students. This improvement indicates that virtual laboratory-based intervention could overcome the challenges in conventional learning process such as limited access to physical laboratory and could positively contribute to achieve science education goals in primary school. These findings are consistent with Abdjul et al. (2024), who stated that digital interactive media are effective in improving science learning outcomes, although this study further contributes by developing the tools comprehensively, rather than focusing solely on the media aspect.

In addition to the improvement in learning outcomes, the developed tool was also found to be valid and practical by both experts and users. Content validation by subject matter experts indicated alignment with the curriculum and relevance to daily life, while language validation emphasized clarity of instructions and readability, and media validation demonstrated an attractive and interactive design. The practicality test also showed that both students and teachers responded positively, with average scores of 3.52 for students and 3.25 for teachers, both falling into the "Very Practical" category.

This shows that the virtual laboratory-based digital learning tool is positively valued in an elementary school context which is consistent with the findings of Delita et al. (2022), who stated that digital tools in the form of e-modules increase motivation and help students grasp the subject matter. Moreover, Yuniarti et al. (2023), Hinostroza et al. (2024), and Januar et al. (2025) stated that learning with digital tools is better than using textbooks or other traditional learning methods. Therefore, the results from the practicality test reinforce that the digital learning tool developed from the virtual laboratory is not only valid from a theoretical standpoint, but also very practical in real classroom situations in elementary schools. Compared with traditional methods, digital tools provide a more flexible, interactive, and accessible learning environment. The enthusiastic reception of digital tools in elementary educational settings also suggests that these tools can be widely implemented, especially in under-resourced areas, which can help close the infrastructural gaps related to access to quality science education.

That said, the impact of the tool in this study was still in the medium range. Because of the greater standard deviation and variance in the post-test, in comparison to the pretest, there was greater distribution in the range of student learning outcomes after the intervention. Some students gained a lot more from the digital tool while others still struggled with the instructions and content. This condition is also noted in research by O'Connor et al. (2014), which highlights that digital tools require adaptive scaffolding design to accommodate students with heterogeneous abilities. Therefore, although the developed tool is generally effective, improvements are still needed in aspects such as navigation, clarity of instructions, and content differentiation.

A further finding that needs to be addressed is the limitation of digital tools in the face of the need for real, hands-on, experimental learning. Some studies, such as Rodríguez-Ardura & Meseguer-Artola (2020), have shown that the use of digital resources without the right pedagogical techniques may lead to cognitive overload. This is also relevant to the present study, where several indicators related to language and tool navigation were still categorized as "Practical" rather than "Very Practical." Thus, although the virtual laboratory–based digital tool offers a solution to the limitations of laboratory facilities, its development should be accompanied by a systematic learning approach to minimize students' cognitive load.

Overall, this study reinforces the evidence that the development of a virtual laboratory–based digital learning tool can serve as an innovative alternative for science learning in elementary schools. The advantage of this study compared to previous research lies in the comprehensive scope of the tool, including the module, student worksheets (LKPD), media, and evaluation instruments, which enables a more systematic implementation in the classroom. However, the findings also underscore the need for continuous improvement, both in pedagogical and technical aspects, to ensure that the tool can enhance students' science literacy more evenly (Snow & Dibner, 2016; Vieira & Tenreiro-Vieira, 2016; Virtič, 2022). For future research, it is recommended to expand implementation to a larger number of schools, compare the effectiveness of the digital tool with conventional learning methods, and explore the integration of adaptive, AI-based features to tailor learning to individual student needs.

Conclusion

This study demonstrates that the implementation of a virtual laboratory–based digital learning instrument effectively enhances students' understanding of the concept of force while simultaneously fostering scientific literacy through structured virtual experimentation. The findings indicate that students not only improved in conceptual comprehension and data interpretation but also showed increased confidence and enthusiasm during the learning process. Notably, many students expressed a preference for continuing science lessons using this approach, suggesting that the instrument supports both cognitive and affective dimensions of learning. Despite these positive outcomes, several challenges were identified during implementation. Variations in students' digital competencies, the presence of techno-becoming gaps, and the continued need for guided teacher supervision highlight important pedagogical considerations. In addition, limitations related to time allocation, availability of technological resources, and teacher readiness emerged as critical factors influencing the effectiveness of the intervention. These findings suggest that the success of virtual laboratory integration depends not merely on its use, but on the proper management of instructional design, technological infrastructure, and teacher capacity. In conclusion, the virtual laboratory–based digital learning instrument is effective in improving students' mastery of force concepts and advancing their scientific literacy, while also strengthening learning confidence. Future research is recommended to explore its application across different science topics, investigate long-term impacts on self-regulated learning, and examine strategies to reduce digital skill disparities among students.

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Author Contributions

Conceptualization, U.F.; methodology, U.F.; validation, A.P.Z.; formal analysis, U.F.; investigation, U.F.; data curation, G.R.; writing—original draft preparation, U.F., A.P.Z., G.R.; writing—review and editing, U.F., A.P.Z., G.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest in this research.

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