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Transformation of Physics Learning: Integrating Virtual Laboratories to Improve Students' Scientific Literacy Skills

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Abstract

The literacy outcomes of the PISA 2022 test results show that Indonesian students are weak in literacy, suggesting a large gap between the current student performance and the needs of an autonomous curriculated framework. By focus on science literacy viewpoint attitude, this research uses R & D research model, 4D pattern is using to create and validate the module. The purpose of this study is to develop a physics module for teaching that combined with virtual laboratory, to enhance students' scientific literacy. This study aims to develop a virtual laboratory-based basic physics teaching module, to improve students' concepts in physics, science literacy of basic physics concepts, and skills. The implementation result support the effectiveness of the module to improve science literacy, and the validation indicates the feasibility of the module. Students' attitude towards science literacy pretest versus posttest assessment significantly different. Summary of this study comprises a more complete teaching tool that it includes modules, videos, and worksheets in a single platform to science literacy. Such findings emphasize that literal experiences need to be mapped on to abstract concepts if literacy is meaningful, and fit with accounts provided by cognitive theory. The pretest and posttest scores of the students produced significant (<0.05) influence on the student's attitude toward science literacy. According to cognitive theorizing, children must be able to link objects, events, and empirical experiences to develop abstract thinking.

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INTRODUCTION

Technology is developing rapidly, which has had a significant influence on education, providing new solutions to facilitate learning at all levels. In particular, physics education has seen the evolution of instructional designs, which seek to narrow the chasm between theoretical understanding and practical applications (Ridwanulloh et al., 2022). Notwithstanding these progresses, developing scientific literacy in students is still challenging, because it means not only having knowledge concepts, but also thinking critically and solving problems (Diani et al., 2019; Yasin et al., 2020), and an ability (Munifah et al., 2019) to connect the ideas in abstract ideas to real situations. Hence, customary teaching through a 4D model via virtual laboratory for children in

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Indonesian elementary school is not just an option but is a priority toward achieving better learning results, enhancing the required competences for the 21st century, and is tangential to the current digital learning challenges in the era of IR 4.0 (Fauza et al., 2025).

The importance of scientific literacy is well recognized as a foundation on which effective science education can be built. It includes the capability of critically thinking over scientific topics, relating phenomena to each other, and participation in making well-informed decisions over scientific issues(Eloranta et al., 2024; Gruber, 2024). Nevertheless, surveys like the PISA study have shown some weaknesses in students' scientific literacy in developing nations, particularly. These findings underscore the need for innovative and effective teaching strategies that can empower students to develop a deeper understanding of science and its applications (Picciano, 2017).

Literacy encompasses more than the ability to read and write; it also includes technological literacy, political awareness, critical thinking, and an understanding of the natural world. Literacy skills are broadly categorized into mathematics, reading, and science (Dewar & Walker, 1999; Nguyen, 2015). Students with scientific literacy possess the capability to make predictions, evaluate information and proof, and draw conclusions by combining relevant scientific theories and concepts, and apply the knowledge gained both within and beyond the school curriculum (Basar et al., 2021; Noesgaard & Ørngreen, 2015; Picciano, 2017). They also exhibit the capacity to assess intricate experimental plans, field research, or investigations in light of pertinent factors and scientific theory and evidence. Hendri & Hasriani, (2019) conducted on 138 students at a higher education institution in Indonesia, revealed that 53% of respondents either reiterated the discourse provided in the questions or left the answers blank. Furthermore, while 26% of students showed a multifaceted understanding of the ideas, student responses in the nominal, functional, and procedural categories stayed below 10%, indicating an inability to correctly apply scientific concepts or a deficiency in scientific literacy (Hendri & Hasriani, 2019). These findings suggest that structured and contextual learning modules can be a strategic tool in improving scientific literacy, especially in building conceptual understanding, science process skills, and critical, reflective, and responsible scientific attitudes. Therefore, the development of this module needs to be initiated systematically and sustainably as part of a contextual and adaptive science learning reform to address the challenges of the times (Atmojo & Wardana, 2025).

Previous studies have demonstrated that virtual laboratories can be used to improve some aspects of scientific instruction successfully. They have been proven particularly useful in promoting inquiry-based practices and enhancing conceptual understanding of light and optics (L. A. Putri et al., 2021). While some systematic reviews have concluded the pedagogical potential of virtual laboratories in science education, they also noted a dearth of systemic instructional designs with scientific literacy as the focal learning outcome (Rosli & Ishak, 2024). However, these developments notwithstanding, the vast majority of the research that exists centers on specific subject matter areas, age ranges, or short-term interventions. This void in the pursuit of a more holistic transformation of physics instruction. Thus, this study tries to fill this gap by incorporating virtual laboratories into an organized physics learning process, which can enhance students' scientific literacy.

One solution to improving the instruction of physics and addressing the discrepancies may be the incorporation of online virtual laboratories (Zhang et al., 2024). These labs provide students with a technology-mediated environment where they can interact and engage with science phenomena through simulations and guided activities (Basar et al., 2021; Noesgaard & Ørngreen, 2015; Reyes et al., 2024). Compared with traditional teaching methods, such as regular classroom instruction, virtual laboratory enables students to explore an experiment, get a sense of how a complex process works, and participate in learning more actively in cases where school resources are limited. This type of learning not only enhances scientific literacy, but studies also prove that it can increase students' interests in science (Eloranta et al., 2024; Oje et al., 2025; Wang et al., 2024). Even better, though numerous researches demonstrate how such virtual science practices can improve the way a student thinks and understand natural phenomena, none of them have been developed from a clear and systematic model like the 4D model (Define, Design, Develop, Disseminate) to make sure these tools are both valid and focused directly on certain science literacy skills. The 4D (Define, Design, Develop, Disseminate) model of development is the right method because it can generate feasible, practical, and effective learning products (Amri et al., 2024). This model provides a structured framework for analyzing learning needs, designing appropriate strategies and content, developing products that can be tested for effectiveness, and disseminating the results in a broader educational context. A comprehensive teaching module was designed to integrate a virtual laboratory into physics curricula effectively (Azisah et al., 2025). Some modules using the 4D model have been created in STEM topics, like environmental science, and show medium improvement (e.g., N-gain around 0.46), but similar tools in physics are still very limited. Also, most available virtual laboratories aren't directly tied to specific indicators of scientific literacy. This shows a clear gap that this study wants to fill by building and testing a virtual lab for physics learning using the 4D model, with a focus on helping students improve their scientific literacy in a measurable way. Previous studies have had models, methods, or tools that are carried out to improve scientific literacy; they are divided separately, for example, only methods, teaching modules only, or media only. In this study, researchers developed a package of teaching modules containing teaching modules, teaching media, evaluation instruments, and worksheets that are combined on one platform.

In this research, the focus is on the development and implementation of online virtual laboratories to improve students' scientific literacy skills. Using innovative frameworks, such as the 4D model. In previous research conducted by Atmojo & Wardana (2025), it was stated that virtual laboratories are effective for improving scientific literacy, but must be equipped with a set of learning materials. Through focusing on cognitive and attitudinal dimensions of scientific literacy, the study aims to investigate how VLABs can develop students' ability to transfer theoretical knowledge to practical situations and to develop positive attitudes towards science learning. This research contributes precious insights into the reasonableness, authenticity, and effectiveness of incorporating digital labs in physics teaching and learning. They stress that technology has a liberating power to deal with problems of scientific ignorance and provide evidence-based recommendations for teachers and policymakers. As the demand for scientifically literate graduates continues to rise, the present study has direct implications for the necessity of utilizing transformative pedagogy to guide students through the nuances of the modern scientific arena. How to set the virtual laboratory-based module with 4D mode? How about the perturbation of operability and practicability of the teaching model based on a virtual laboratory?

METHOD

Type of Research

This study proposed a virtual lab-based instruction to enhance students' scientific literacy. The module is designed to develop a learner's knowledge of scientific principles and their ability to apply these principles in a range of situations. Based on the Four-D model, the framework guides the development of the serious game through four core processes: Define, Design, Develop, and Disseminate (Thiagarajan & Semmel, 1976).

Research Subject

This research was conducted in 35 students who had reached the 4th semester in the Study Program Tadris IPA in one of the state universities in Indonesia. With ages ranging from 19 to 21, there were 15 males and 20 females. All participants received a thorough information sheet and an informed consent form before baseline testing and the start of the trial. The students received information about the aim of the study, the activities they would perform, the risks and benefits, as well as respecting privacy. Only those students who had consented to participate after seeking their signature were recruited for the study.

Research Procedure

The Four-D model of Thiagarajan's was employed as the base model of instruction for creating a scientific literacy–oriented instructional module (Thiagarajan & Semmel, 1976). This development approach includes four principal phases: definition (constraints), design (design), development, and distribution. The research model of the development is systematically depicted in Figure 1 (Sihombing et al., 2024).

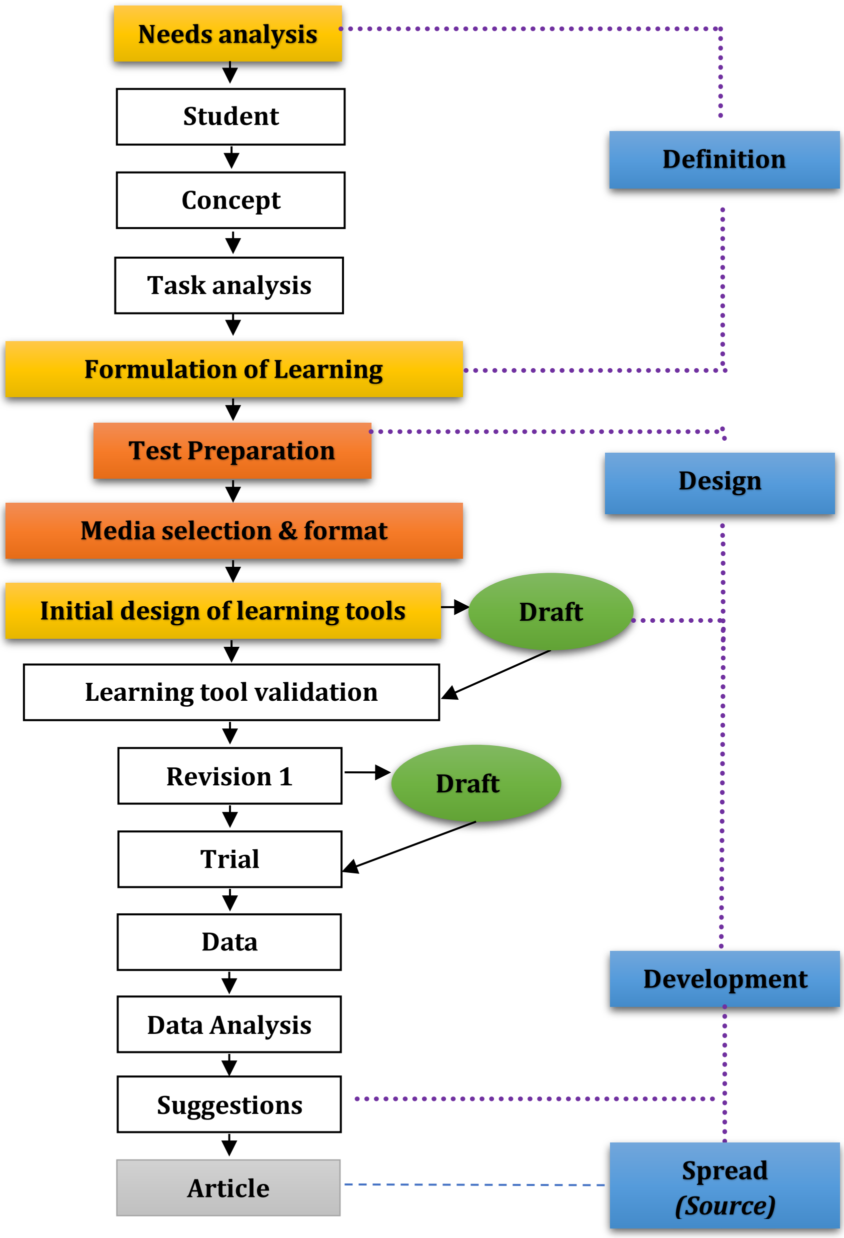

Figure 1. The Development Model of the Research Systematically

Trial Design

One group of students was evaluated both before and after the virtual laboratory-based physics module was implemented. The trial was designed as a quasi-experimental study using a one-group pretest-posttest design, with a pattern as illustrated in Figure 2.

Figure 2. The Trial was Designed as a Quasi-Experimental Study.

In this context, O1 represents the pretest, which assesses students' prior knowledge before any instructional intervention is applied. X denotes the treatment, which refers to the implementation of a science literacy–oriented teaching module supported by a virtual laboratory. The researchers developed and implemented this module for a specific period. Finally, O2 represents the posttest, which evaluates students' understanding after the intervention.

Data Analysis Techniques

Feasibility Analysis of Learning Tools

The feasibility analysis of the learning device includes expert validation after development is complete. Four validators were involved: two experts in learning quality and two in evaluation. The first learning quality expert is a professor of curriculum and learning at the State Islamic University of Syekh Wasil in Kediri. The second learning quality expert is a science education lecturer at the same university. The first evaluation expert is a learning evaluation professor at the State Islamic University of Syekh Wasil Kediri, and the second is a science education lecturer at the State Islamic University of Madura. Validators assessed the product in person using two instruments: the learning module validation sheet and the evaluation validation sheet. Scores from each aspect were averaged, and the results were interpreted using Table 1. The percentage of agreement formula by Borich was used to calculate agreement between validators and ensure consistency in their judgments.

Table 1. Average Score Interval and Validation Average Score Criteria (Yadlowsky et al., 2021)

Average Score Interval	Average Score Criteria
$1,0 \leq x < 1,6$	Invalid
$1,6 \leq x < 2,5$	Less valid
$2,6 \leq x < 3,5$	Valid
$3,6 \leq x \leq 4,0$	Highly Valid

Analysis of the Effectiveness of Learning Tools

The effectiveness of online virtual laboratories was analyzed by comparing the outcomes of students engaged in virtual lab activities with those participating in traditional, in-person laboratories. Key metrics such as pre-test and post-test results, student engagement levels, and qualitative feedback were utilized to assess the impact (Dewar & Walker, 1999; Nguyen, 2015). Students' responses to pretest and posttest items related to gas kinetic theory material were used to assess scientific literacy content. Table 2 outlines the specific indicators aligned with scientific literacy competencies.

Table 2. Indicators Used to Assess Students' Scientific Literacy Competencies (Rahayu & Setiana, 2024)

Competence	Code	Indicator
Explaining the phenomenon scientifically	K1	1. Remembering and applying appropriate scientific knowledge are both important. 2. Identify, use, and generate clear models and representations.
Designing and evaluating investigations scientific	K2	3. Propose a scientific method for exploring the given question. 4. Explain and assess the many methods that scientists employ to assess the objectivity and validity of evidence as well as the generality of theories.
Interpreting data and evidence scientifically	K3	5. Analyse and evaluate information to arrive at the appropriate conclusions.

To assess the effectiveness of the learning module, a two-sample paired t-test was conducted using the SPSS 17.0 software at a 95% significance level. The interpretation was carried out under the assumption that the data were normally distributed and homogeneous. If the significance value of the two-tailed test (sig) exceeded 0.05, there is a significant difference in students' scientific literacy, indicating no significant difference between the pretest scores and the posttest mean scores of the treatment group (Coletta, 2023; Coletta & Steinert, 2020). Conversely, if the significance value of the two-tailed test (sig) was less than 0.05, the null hypothesis (H_0) was rejected, signifying a significant difference between the pretest scores and the posttest mean scores of the treatment group. Additionally, to determine the magnitude of change, an N-Gain test was performed using Equation:

$$(N\ Gain) = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}}$$

Where: (g) Gain value; S_{post} is posttest value; S_{pre} is pretest value; S_{max} *the* maximum value. Furthermore, the N-Gain from the calculation results was changed to the, Coletta (2023), which is divided into three levels as shown in Table 3.

Table 3. Normalized Gain Criteria (Coletta, 2023)

N-gain Score	Normalized Gain Score
0.70 < N-gain	High
0,30 < N-gain < 0,70	Medium
N-gain < 0.30	Low

RESULTS AND DISCUSSION

Development of a virtual laboratory-based physics teaching module

A needs analysis initiated the development of the virtual laboratory-based physics teaching module. A review of the curriculum revealed that students' scientific literacy is suboptimal, especially when dealing with abstract topics. One such topic is the kinetic theory of gases, which is challenging because the particles involved are invisible and difficult to observe directly (Azura et al., 2021; Haili, 2022; Wartono et al., 2018). Students in the Tadris IPA study program are students who have diverse academic abilities but have something in common, namely weakness in analysis and science skills, which has an impact on their understanding of science, (Asshagab et al., 2023) as shown in Figure 8. A virtual, lab-based teaching module on gas kinetic theory was created in response to this demand in order to raise students' science literacy.

There will be both online and offline versions of the virtual laboratory-based physics training module on gas kinetic theory. Through the website, online education will be made easier https://modulgamifikasistem.my.canva.site/virlabfisikatkg and worksheet activities will be completed offline. The online platform offers students practical access, allowing them to engage with the material anytime, anywhere, and significantly enhancing their learning motivation and interest. Figure 3 presents screenshots of the web interface for the VL teaching module on ideal gas KT.

The need for students to increase their scientific literacy and the shortcomings of the traditional laboratory technique led to the development of the virtual laboratory-based physics education module. The process started by selecting physics key concepts according to the curriculum standards that could benefit from virtual simulations, such as mechanics, optics, and electromagnetism. These topics are chosen such that interactive visual representations are possible to a much larger extent than the traditional topics of organizers and sieves, resulting in better conceptual grasp.

The Module was intended to include virtual experiments, simulations, and interactive activities that focus on the inquiry approach and critical thinking. Cutting-edge software was employed to develop the realistic simulations, which enabled students to click on data points and see them change in response to their tweaks with freedom that was only possible in real-time hands-on experimentation. The module also contained scaffolding materials: instructional videos, step-by-step experimental protocols, and reflection questions for independent exploration and lasting learning gains. The interface of the virtual laboratory was designed in order to be easy to use, easy to access, and also to allow for the pace of learning.

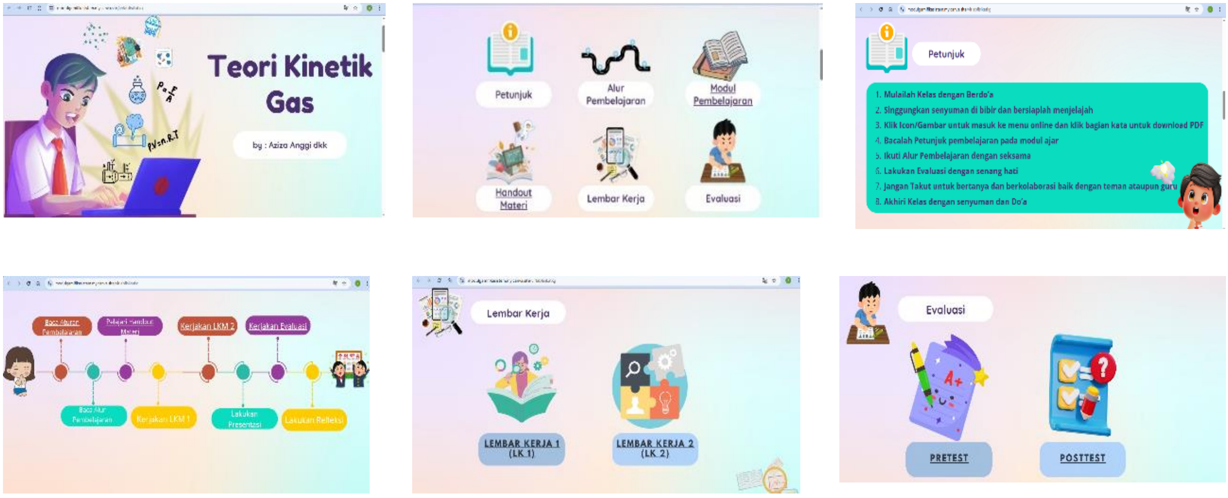

Figure 3. An Overview of the Web-Based Virtual Laboratory

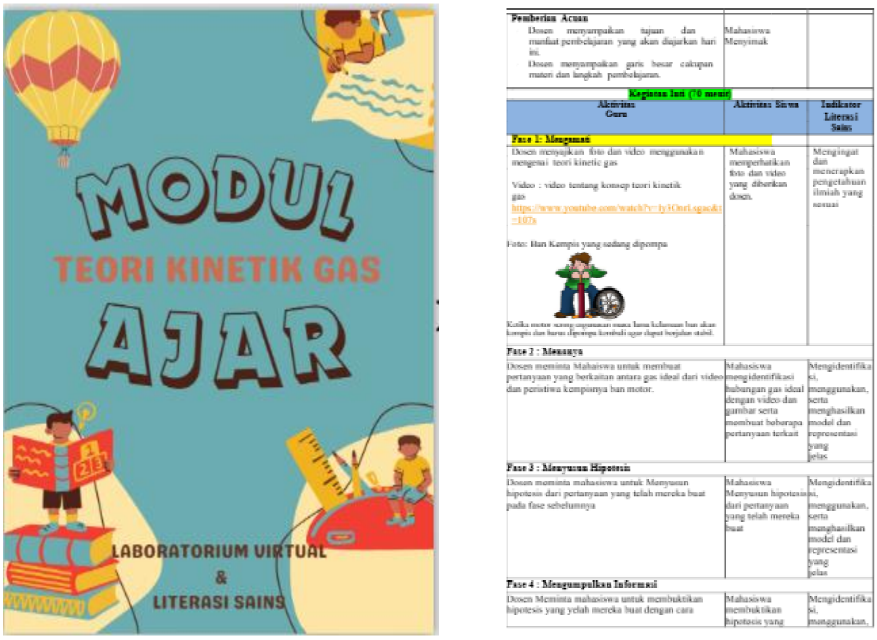

Figure 4. An Overview of Virtual Laboratory-Based Module in the Indonesian Language

The iterative design process involved collaboration with physics educators, software developers, and instructional design experts to ensure the module's pedagogical effectiveness and technical reliability. The module underwent rigorous testing and validation, which included feedback from educators and pilot studies with students. These evaluations helped refine the content and optimize the simulations to provide a stimulating and successful educational experience. Through its development, the virtual laboratory-based module aimed to close the gap between theoretical physics and practical application, fostering a transformative approach to modern physics education. The learning module is developed by following the inquiry learning steps with science literacy indicators. The module was presented in the form of a web-connected flipbook, as shown in Figure 4. The worksheets developed also contain science literacy indicators so that they can improve science literacy skills. The presentation of the worksheet is seen in Figure 5.

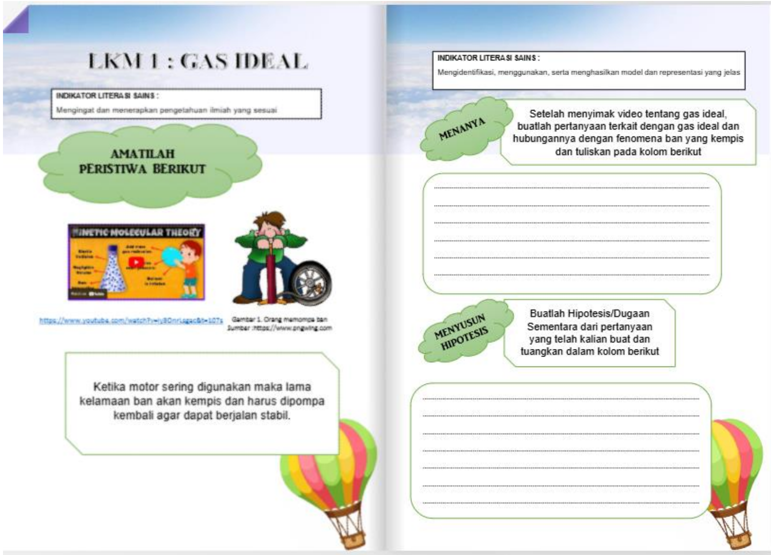

Figure 5. An Overview of Virtual Laboratory-Based Worksheets

Worksheet 1 and Worksheet 2 are the two pieces that comprise the student worksheet. Activities like watching real-life occurrences, coming up with questions, creating hypotheses, gathering data, analyzing it, and sharing the results are all included in each section. Worksheet 2 covers the kinetic theory of gases, whereas Worksheet 1 concentrates on ideal gases. Figure 5 illustrates the layout of the worksheets. A distinctive feature of the worksheets is that they encourage students to design their experimental procedures. This approach allows learners to engage in scientific literacy directly by independently constructing models and representations, which supports their ability to effectively obtain, interpret, and apply scientific information.

This study utilized the PhET simulation on gas properties (Figure 6) as an online virtual laboratory. This simulation was used to demonstrate Charles's Law, Boyle's Law, and Gay-Lussac's Law. Boyle's Law includes varying the pressure and volume while maintaining a constant temperature. The volume was kept constant while the temperature and pressure were changed in order to apply Gay-Lussac's Law. Charles' Law regulated temperature and volume while maintaining a steady pressure. After deployment, the designed teaching module's advantages and disadvantages were identified. Students reported that the module supported their learning by offering flexibility to access it anytime and anywhere, either individually or collaboratively. They also said that they could manage the learning process independently without needing direct assistance from instructors. However, one drawback was the module's reliance on a stable internet connection. The platform's performance was occasionally slow due to its use of a free domain hosted on Canva, which limited its accessibility and responsiveness.

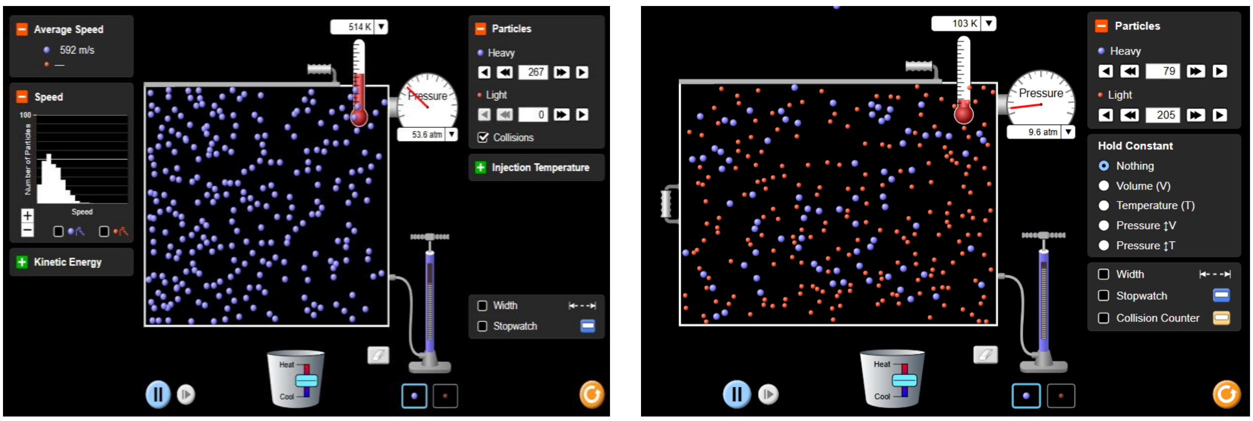

Figure 6. The Online Virtual Laboratory of PhET Simulation Gas Properties [https://phet.colorado.edu/en/simulations/gas-properties]

Feasibility of a Virtual Laboratory-Based Physics Teaching Module

Two expert reviewers conducted the validation of the teaching modules to evaluate their feasibility before implementation in the learning process. The evaluation aimed to provide constructive feedback and suggestions for refining the modules to ensure they meet quality and appropriateness criteria. A teaching module that is deemed good is expected to be suitable for use in the subsequent data collection phase within an educational institution. The validity of the modules is also assessed by experts before their implementation in schools. Tables 4 and 5 provide the results of the validation.

Table 4. Validation Result Data of the Worksheet

Assessed aspects	Validator Assessment		Average	Information	Percentage of Agreement
	V1	V2			
Format	3,3	3,3	3,3	Valid	98,5%
Fill	3,6	3,6	3,6	Valid	97,2%
Language	4,0	4,0	4,0	Valid	100%

Table 4 demonstrates that the worksheets created for the format aspect received an overall average evaluation of 3.3 from validators with a percentage of agreement of 98.5%, the content aspect is 3.6 with a percentage of agreement of 97.2%, and the language aspect is 4 with *a* percentage of agreement *of* 100%. The validation results indicate that the developed worksheet meets the validity criteria, rendering it appropriate for use in the implementation or research phase. Similar studies have found that digital learning tools, such as e-books in physics education, promote scientific literacy because they fulfill key feasibility criteria (Reyes et al., 2024). Other studies support the feasibility of using worksheets based on virtual laboratories. These studies highlight the potential of worksheets to enhance learning outcomes and strengthen students' scientific literacy skills (Basar et al., 2021). These studies reinforce that researchers developed worthy worksheets that can improve science literacy.

Table 5. Assessment Data for Module Quality Teaching

Assessed aspects	Validator Assessment		Average	Information	Percentage of Agreement
	V1	V2			
Format	4,0	4,0	4,0	Highly Valid	100%
Fill	3,3	3,3	3,3	Valid	98,5%
Language	3,0	3,0	3,0	Valid	100%

Teaching modules are learning tools that help students learn. The teaching module consists of learning objectives, learning steps, learning media, and assessment. Teaching modules can be applied to various subjects and levels of education (Nguyen, 2015). The average scores of the validity level given by two expert validators are presented in Table 5. The format aspect obtained an S-CVI of 4.0 and 100% agreement. Content used had a mean score of 3.3 with 98.5% agreement. Language scored 3.0 with full agreement. These findings support the validity and appropriateness of the teaching module for use or study. It's also critical to note that the module adheres to all required elements set by the Ministry of Education and Culture for a full unit of teaching the module (Oje et al., 2025). The following are components: learning phases, learning outcomes and objectives, use details, and teaching module details (Dewar & Walker, 1999; Picciano, 2017).

The average scores of the validity level given by two expert validators are presented in Table 5. The format aspect obtained an S-CVI of 4.0 and 100% agreement. Content used had a mean score of 3.3 with 98.5% agreement. Language scored 3.0 with full agreement. These findings support the validity and appropriateness of the teaching module for use or study. Also, it is important to mention that the module adheres to all required elements set by the Ministry of Education and Culture for a full unit of teaching the module (Oje et al., 2025). The following are components: learning phases, learning outcomes and objectives, use details, and teaching module details (Dewar & Walker, 1999; Picciano, 2017). Carefully constructed instructional units stimulate student participation in the learning of science. Students are taught to think critically, problem-solve, and communicate their knowledge through activities, research, and discussion. These items are necessary to develop scientific literacy (Febrianti et al., 2024). Well-designed teaching modules motivate students to actively engage in science learning. Through structured activities, research, and discussions, students are encouraged to think critically, solve problems, and share their ideas. These elements are essential to cultivating scientific literacy (Rahayu & Setiana, 2024).

Modules for teaching that include various formats of media (e.g., diagrams, infographics, simulations, videos) may display scientific concepts more interactively and visually comprehensible. These resources help all students develop critical thinking and interpretive skills. timeandspace for the way you teach students with a visual learning preference, benefit by including visual information that supplements the text. Analyzing data, interpreting graphs, solving problems in context, and writing experimental reports in themselves could be used as a basis for measuring scientific literacy (Malik et al., 2025). Assessment is central to the quality of educational modules, as it offers lectures and students insight into the understanding of subjects and the acquisition of scientific literacy. Selecting and implementing effective teaching strategies that not only stimulate and engage students in learning but also promote deep, active processing of information that will sustain learning and ensure that learned material is stored in long-term memory is essential. Clearly stated learning objectives should guide the creation of instructional modules. It is quite possible to include the phases of scientific literacy into module design, and doing so can have a big impact on student learning results. These modules are crucial resources for students during the learning process, whether it is carried out freely or under supervision, when they are created by instructors with explicit pedagogical goals. Furthermore, abstract physics ideas that are hard to witness directly using conventional techniques, including electricity, atomic theory, and other complicated subjects, may be explored or verified by students with the use of virtual laboratory-based teaching modules (A. Putri et al., 2025).

The Effectiveness of Virtual Laboratory-based Physics Learning Modules

Science Literacy Cognitive Aspects

Numerous pretests, educational exercises, and posttests are used to evaluate students' cognitive elements of scientific literacy. Before learning materials are delivered, the pretest is given during the first meeting, and the posttest is given after students have had a chance to interact with the updated course material. The first steps in data analysis are tests of normality and homogeneity, which assess students' knowledge of competencies, especially their conceptual comprehension. Tables 6 and 7 provide an overview of the outcomes of these examinations.

Table 6. The Results of the Normality Test of the Science Literacy Cognitive Aspect

One-sample Kolmogorov-smirnov test		Pre-test	Post-test
N		95	95
Normal Parameters [a,b]	Mean	52.8737	83.3895
	Std. Deviation	12.01262	9.97475
Most Extreme Differences	Absolute	.352	.273
	Positive	.352	.254
	Negative	-.216	-.273
Test Statistic		.352	.273
Asymp. Sig. (2-tailed)		.000[c]	.000[c]

Table 7. The Homogeneity Test of Science Literacy Cognitive Aspect Results

Test of homogeneity of variances		Levene Statistic	df1	df2	Sig.
PrePost	Based on Mean	2.985	1	188	.086
	Based on Median	.605	1	188	.438
	Based on Median and with adjusted df	.605	1	187.749	.438
	Based on trimmed mean	3.879	1	188	.050

The data are not regularly distributed, as shown by the normality test's significance value of less than 0.05, as seen in Table 6. The results of the homogeneity test, on the other hand, are shown in Table 7. A significance value larger than 0.05 indicates that the sample is homogeneously distributed. The Wilcoxon signed-rank test was used as a suitable non-parametric statistical technique because of the data's non-normal distribution. Table 8 provides a summary of the test's results.

Table 8. Results of the Wilcoxon Signed Rank Test

Test statiistics[a]	Posttest-Pretest
Z	-7.958[b]
Asymp. Sig. (2-tailed)	.000

At the 0.05 level of significance, the alternative hypothesis (H1) is accepted and the null hypothesis (H0) is rejected, according to the Wilcoxon signed-rank test findings. The two-tailed Sig value is below 0.05. This implies that students' scientific literacy scores before and after utilizing the virtual, lab-based physics learning module differed significantly. To measure progress in scientific literacy, particularly in this curricular area, an N-gain score was calculated. The results of the analysis are shown in Figure 7.

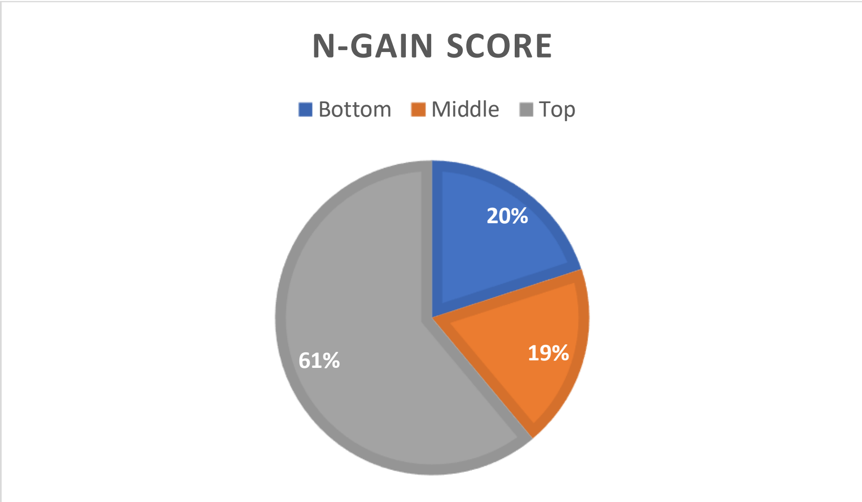

Figure 7. Category N-Gain Graph

Following therapy, 26% of students moved up to the medium group, while 74% moved up to the high category, as seen in Figure 7. Numerous learning theories and previous research may be used to evaluate the effectiveness of virtual laboratory-based physics learning modules that employ a cognitive scientific literacy approach. According to Piaget's theory of cognitive development, the formal operational stage generally emerges around age 12. At this stage, adolescents begin to think abstractly, reason logically, solve problems systematically, and engage in hypothetico-deductive reasoning. They also develop metacognitive skills (Cherry, 2024; Piaget, 1950). The efficacy of this module is supported by Bruner's cognitive theory. Students can better grasp complex physics concepts using the virtual laboratory's iconic and symbolic representation-based learning environment (Rozikin & Palas, 2021). According to knowledge processing theory, multimedia environments (e.g., virtual labs) may help to increase student attention, reduce forgetting less and promote problem solving by providing knowledge in a dynamic, graphical way.

Virtual labs are effective in enhancing the students' cognition of science. The study was conducted by Wongsa & Cojorn (2024) and Wang et al, (2024) compared to traditional methodologies, the study of virtual lab demonstrates to enhance understandings and interests about science ideas, particularly for material experiments which are impossible to expect in the real lab. A study by Dimov, (2021) highlighted that virtual labs may assist in the development of scientific literacy by offering more flexible and authentic learning environments. Such conditions encourage the development by students of independent critical thought and the detailed analysis of issues. In addition, research by Wongsa & Cojorn (2024) The researcher that the use of virtual laboratory experiments improves students' learning about physics. The main reason for this is that the students can experiment on difficult concepts without the need for having physical apparatus or materials (Rauf et al., 2021).

Virtual laboratory physics modules are an efficient way to improve science literacy in these times when scientific matters are particularly divisive at the level of culturally-based politics for students in cognitive domains. These modules are grounded in educational theory and previous research. These segments are an effective approach for today's physics classes by providing engaging experiences, increasing the accessibility of challenging ideas, and by students' thinking skills.

Science Literacy Aspects of Science Skills

Data on the Science Skills component was gathered by evaluating students' work on worksheets. Figure 8 displays the outcomes of the skills.

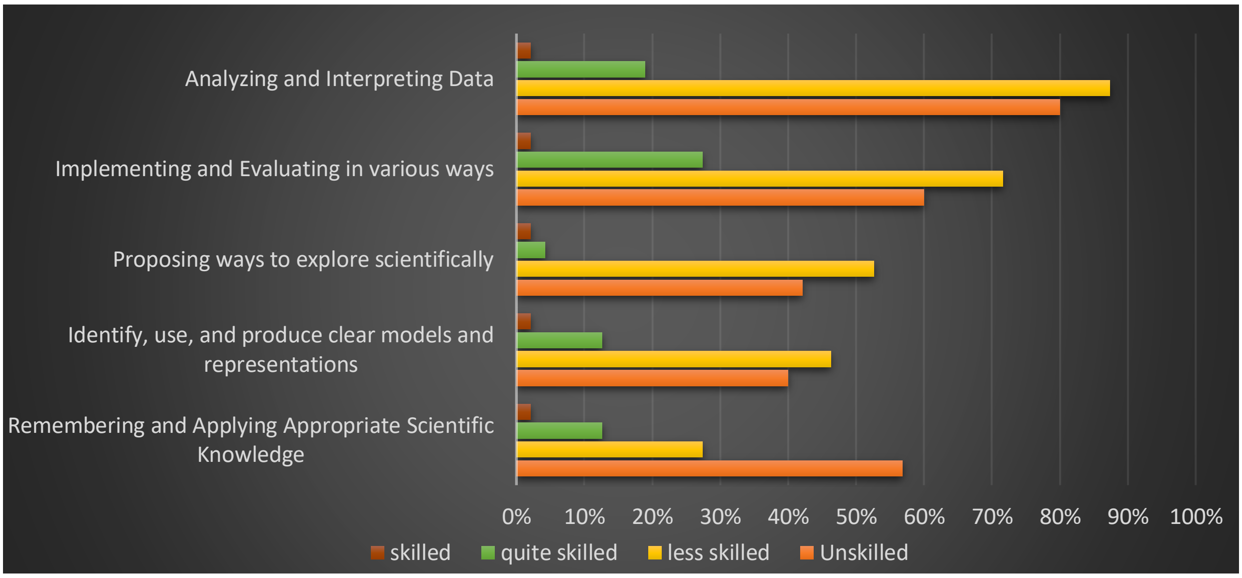

Figure 8. Pretest Result of the Science Skills Aspect Graph

Just 2% of students were classified as skilled before the therapy (pretest), as seen in Figure 8, with the remainder falling into the unskilled, under-skilled, or moderately skilled categories. All of the pupils were no longer classified as unskilled or under-skilled after the intervention, nevertheless. Every participant (100%) was categorized as proficient or somewhat talented. Figure 9 provides more information about the posttest findings according to the students' abilities.

Students' scientific abilities improved when the virtual laboratory-based fundamental physics education module was put into use. Over 50% of the students showed competency in every area of scientific skill, and none of them were classified as unskilled across all parameters, as seen in Figure 9. These findings unequivocally show that students' scientific skills significantly improved following the intervention as compared to their pre-intervention performance. The reason for this is that the virtual laboratory-based fundamental physics module has worksheets for students that meet their demands in terms of practicing the process of acquiring science abilities. The hypothesis that the development of positive scientific attitudes is responsible for the rise in students' scientific skills is supported by the findings of Wongsa & Cojorn, (2024), which highlight the effectiveness of virtual laboratory-based fundamental physics modules in developing students' scientific attitudes. Since a positive attitude towards science often encourages more active involvement and skill development, improved attitude and improved scientific skills are strongly related. The efficiency of the module based on a virtual laboratory was evaluated using normality and homogeneity tests, and the results are shown in Tables 9 and 10.

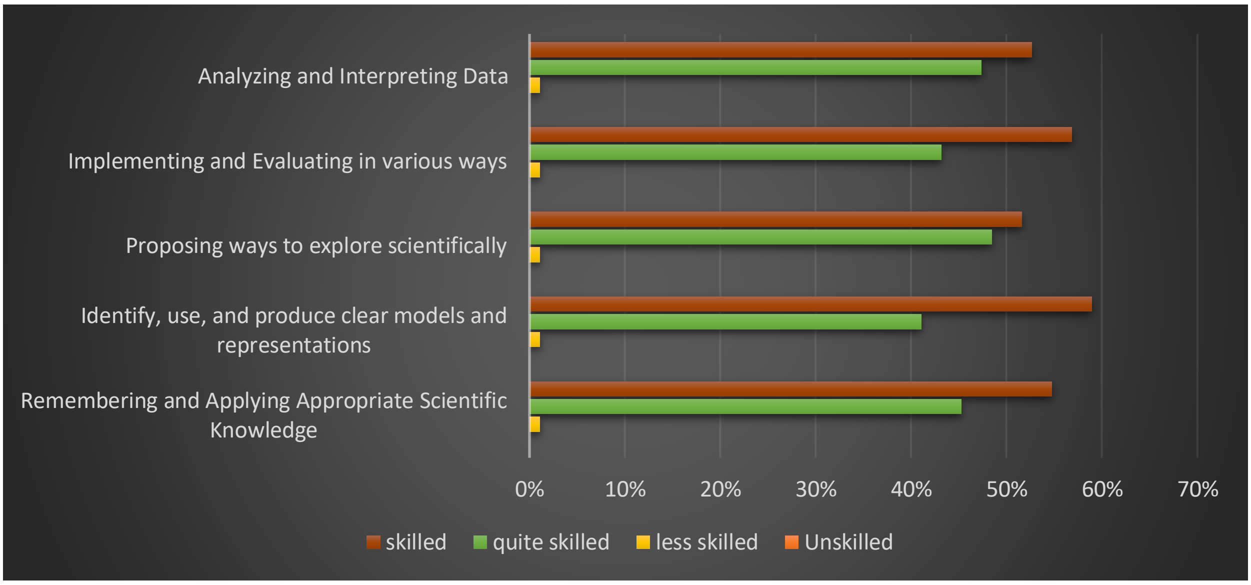

Figure 9. Post-test Result of the Science Skills Aspect Graph

Table 9. The Results of the Normality Test of the Science Skills Aspect

One-sample Kolmogorov-smirnov test		Pre-test	Post-test
N		95	95
Normal Parameters[a,b]	Mean	4.8842	10.6000
	Std. Deviation	1.60361	1.21515
Most Extreme Differences	Absolute	.283	.202
	Positive	.259	.195
	Negative	-.283	-.202
Test Statistic		.283	.202
Asymp. Sig. (2-tailed)		.000[c]	.000[c]

Table 10. The Homogeneity Test of the Science Skills Aspect Results

Test of homogeneity of variances		Levene Statistic	df1	df2	Sig.
PrePost	Based on Mean	15.623	1	188	.000
	Based on Median	3.233	1	188	.074
	Based on Median and with adjusted df	3.233	1	155.480	.074
	Based on trimmed mean	18.332	1	188	.000

Based on Table 9 and Table 10, to determine the significance, a non-parametric test was conducted using the Wilcoxon signed rank test, as it is evident that the data is not distributed normally or uniformly. The findings are shown in Table 11.

Table 11. The Results of the Wilcoxon Signed Rank Test

Test statiistics[a]	Posttest-Pretest
Z	-8.445[b]
Asymp. Sig. (2-tailed)	.000

The Wilcoxon signed rank test results are displayed in Table 11. We may infer that scientific skills changed significantly between before and after learning with virtual laboratory-based modules because the Asymp. Sig. (2-tailed) The value was less than 0.05. This is consistent with studies showing that science literacy attitudes may be enhanced via the use of instructional modules (Noura, 2024). The researcher's produced module, which includes a virtual laboratory, is an excellent way to enhance science literacy. Science literacy may be enhanced using virtual laboratory-based lessons, which are successful (Dimov, 2021; Rozikin & Palas, 2021). In order to lower the possibility of genuine laboratory equipment being damaged, the virtual laboratory may also be used as a trial platform for students to carry out experiments before they join the real one.

The levels of processing theory, which maintains that the more completely information is processed in the mind, the more likely it is to be stored in memory, is supported by these findings. Virtual laboratory-based learning enables students to engage in multi-stage information processing. Conventionally, students process information through visual, auditory, and reading activities; however, virtual laboratories facilitate a more profound level of information processing. Initially, students acquire information by listening to the researcher's explanation and observing the demonstrated phenomena. This information is then independently transformed into questions and hypotheses. Following the formulation of problems and hypotheses, students deepen their understanding by conducting experiments within the virtual laboratory environment. These experiments provide additional insights that build upon the previously acquired information. The newly obtained data from virtual laboratory experiments is further analyzed by students to address initial questions through group discussions, culminating in the establishment of conclusions.

After deriving conclusions through collaborative discussions supported by the teaching module, students are required to present their findings to the class. This presentation fosters classroom-wide discussions, facilitating information exchange among groups and leading to a consolidated class-wide conclusion, reaffirmed by the lecturer. This iterative process of information handling, spanning acquisition, experimentation, analysis, discussion, and presentation, is expected to enhance long-term retention and positively impact students' scientific literacy attitudes. This study's limitations include the fact that the instructional module was created solely to cover the kinetic theory of gases content; the worksheet also cannot be filled out directly on the web and still requires additional devices. It is hoped that further researchers can complete the virtual laboratory-based module for other teaching materials and develop the website to be more responsive and interactive.

These findings are consistent with other research showing how beneficial virtual laboratories are for promoting inquiry-based scientific education and enhancing students' conceptual knowledge (L. A. Putri et al., 2021; Basar et al., 2021). However, Rosli & Ishak, (2024) point out that many instructional designs incorporating virtual labs fall short in explicitly positioning scientific literacy as a core learning objective. Reyes et al (2024) also noted that many implementations lack instructional tools, such as structured modules or assessment instruments, that provide coherent guidance throughout the learning process. To address these gaps, the present study introduces a comprehensive virtual laboratory module developed using the 4D model. The module incorporates interactive media and integrates student worksheets and targeted assessment tools directly aligned with scientific literacy indicators. Unlike prior studies, which often isolate aspects of the learning experience by focusing solely on media, methodology, or content, this research offers a cohesive instructional package on a single platform. Thus, this study provides a structured, scalable, pedagogically sound model that enhances scientific literacy by integrating technology, learning strategies, and assessment tools into a unified educational ecosystem.

LIMITATION

This study still has several limitations. The learning module developed only covers the material of the kinetic theory of gases, so it cannot be used for other physics topics. In addition, the student worksheets are not fully interactive because they cannot be filled out directly through the web platform, so additional devices are needed. Another technical limitation is that access to the module still depends on a stable internet connection, considering that the platform used is not yet based on a paid domain and still relies on Canva, which can affect the smoothness of use by students.

CONCLUSION

The use of online virtual laboratories reflects a revolutionary method of physics education that does not have the limitations of instructional activities and serves to build the students' scientific literacy very effectively. This novel approach enables students to learn in-depth ideas of science while interacting with the simulations and in the process of developing critical thinking, problem-solving, and analytical skills. Boosting the learning outcome through multi-stage information processing and inquiry virtual laboratories provides a dynamic learning space in a way that caters to different preferences and contributes to long-term memory retention for students. The results of this study indicate that virtual laboratories provide an efficient learning alternative that connects theory with practice and offers opportunities for collaborative learning in terms of discussions and presentations.

The research conclusions show that the 4D model is very suitable for designing a physics teaching module on gas kinetic theory. The developed modules are available on the Web and have shown very high feasibility and high effectiveness in enhancing students' scientific literacy. The findings suggest that 26% of the trainees experienced improvement at a medium level, while 74% showed improvement at a higher level, especially in the content dimensions. For science skills, only 2% of students were roughly classified as skilled, while students were mostly classified as unskilled, underskilled, and quite skilled. However, following the intervention, no students remained in the unskilled or underskilled categories, with 100% achieving either the quite skilled or skilled classification. These results underscore the potential of virtual laboratories and well-designed modules to significantly enhance both the content knowledge and scientific skills of students.

This study implies that the integration of virtual laboratories in physics learning provides an innovative alternative that expands access to experimental experiences, especially in schools with limited laboratory facilities. Teachers can use virtual laboratories to accommodate students' Zone of Proximal Development (ZPD) through visual, interactive, and gradual guidance, thereby increasing the efficiency of education and scientific literacy. This study emphasizes how important it is to update the physics curriculum to emphasize more digital experimentation and simulation-driven learning, as they are crucial for developing scientific literacy, problem-solving, and critical thinking skills in the framework of education in the twenty-first century.

AUTHOR CONTRIBUTIONS

AAM conceptualized the study, led the development of the virtual laboratory-based module, and coordinated the implementation and data collection in the field. SH supervised the research methodology, contributed to the instructional design framework, and reviewed the manuscript critically for important intellectual content. AA assisted in designing the teaching materials and digital media content and participated in the instructional validation process. UFL performed the data analysis and statistical testing, including interpretation of the pretest-posttest results. LM contributed to the international literature synthesis and cross-referenced pedagogical frameworks related to virtual laboratories. RU provided theoretical and technical expertise in educational technology, reviewed the data analysis, and contributed to manuscript revision and final approval. All authors have read and agreed to the published version of the manuscript.

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