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Enhancing Junior High School Science Literacy through TPACK-Integrated Virtual Laboratory Modules

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Abstract: The persistently low level of science literacy among Indonesian students, as evidenced by stagnant PISA 2022 results remaining below the OECD average, underscores a critical need to transform teaching materials to be more adaptive to technological advances. This research addresses the lack of pedagogically integrated materials on technological aspects, which often hinders students' ability to interpret scientific phenomena. To bridge this gap, the study aimed to develop science learning modules based on the Technological Pedagogical Content Knowledge (TPACK) framework and to test their validity, practicality, and effectiveness in improving junior high school students' science literacy. Following the 4D developmental model, Define, Design, Develop, and Disseminate, the research involved 120 seventh-grade students from the former Besuki Residency and 25 teachers from the East Java Science Teacher Working Group. Data collection employed expert validation sheets, user-response questionnaires, and science literacy tests, which were analyzed using the Normalized Gain (N-gain) formula. The results indicated that the TPACK-based module demonstrated high validity, with a score of 88.97% from media and materials experts. In terms of practicality, the module earned an average of 90.9%, supported by a 91.55% positive student response rate. The effectiveness test demonstrated a significant increase in science literacy, with an average N-gain of 0.70 (high category), with the problem-solving indicator showing the most substantial growth. During the dissemination stage, the module was distributed digitally to the East Java Science Teacher Working Group, where validation by 25 practicing teachers yielded a 92.4% feasibility score. This study concludes that TPACK-based modules are highly effective modern instruments for enhancing scientific competence. By integrating interactive simulations and virtual laboratories, these modules overcome physical facility limitations, making them highly suitable for widespread adoption within the national science curriculum to foster a more technologically literate generation.

Keywords: science literacy, students, teaching module, TPACK, the development.

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INTRODUCTION

The implementation of science curricula at the junior high school level is currently facing fundamental challenges. Science education is not merely the transmission of factual knowledge, but rather a process of integrating attitudes, process skills, and deep conceptual understanding. The primary objective of science is the empirical examination of phenomena characterized by observable facts, conceptual frameworks, and established natural laws (Hover & Wise, 2022). Consequently, the optimal approach to science education would be to prioritize experiential learning, in which students are provided with direct experiences to facilitate their understanding of complex scientific phenomena (Kalogiannakis et al., 2021). However, in practice, a significant discrepancy exists between the demands of the ideal curriculum and the pedagogical reality in the field. Learning modules are an important tool in supporting the teaching and learning process in the classroom. However, several previous studies have shown that the modules currently in use do not fully integrate technology and pedagogical approaches. This has not maximized students' science literacy.

The science literacy crisis in Indonesia has attracted international attention, as seen in the results of large-scale studies. The latest data from the Programme for International Student Assessment (PISA) shows that Indonesia has remained at the bottom of the rankings for the past decade. In PISA 2022, the average science literacy score of Indonesian students was 383, significantly lower than the OECD average of 485 (OECD, 2023).

This data is certainly a serious concern, as it shows that most Indonesian students can only recognize basic scientific facts. Meanwhile, their ability to interpret data, explain phenomena scientifically, or evaluate the design of a scientific investigation is still underdeveloped. The results of the Trends in International Mathematics and Science Study (TIMSS) also reinforce these findings. Many students still struggle when faced with questions that require higher-level thinking skills, such as reasoning and applying concepts in real-world situations.

TPACK-based learning, when implemented, generally involves developing e-modules or interactive digital media, and the results show increased student motivation and cognitive scores. However, there are still modules that use technology solely as a visual aid and are not yet fully integrated with learning strategies that encourage students to think critically, analyze data, and construct scientific arguments (Zainuddin et al., 2023). Furthermore, the measurement of its effectiveness often does not fully reflect science literacy as a whole.

This dearth of science literacy is rooted in several interrelated systemic issues. Firstly, the learning approach in secondary schools remains dominated by conventional teacher-centered methods. In this paradigm, teachers are the sole repositories of knowledge and authority, while students are passive recipients of information. This has been shown to lead to low cognitive engagement among students when constructing scientific concepts independently. Secondly, a considerable disparity exists between the material taught and advances in digital technology. Although contemporary students are often referred to as "digital natives" who possess a high level of proficiency with gadgets, the utilization of these technologies for cognitive-scientific purposes remains in its infancy. Frequently, students' use of devices is confined to entertainment and social media rather than to exploring science simulations or conducting digital research (Almeida et al., 2023; Fortus et al., 2022).

In the contemporary digital age, educators are required to possess competencies that extend beyond conventional teaching skills. Pedagogical approaches must be adapted to align with the demands and expectations of contemporary students. The advent of the Fourth Industrial Revolution has precipitated a paradigm shift in which technology and scientific knowledge have become inextricably intertwined (Adel, 2024). Nevertheless, a significant number of teachers continue to experience difficulties in incorporating technology into their pedagogical practices. A recurrent phenomenon is the "technocentric gap," in which technology is used merely as a substitute for digital whiteboards, without concomitant modifications to pedagogical strategies. This underscores the pressing need to implement the Technological Pedagogical Content Knowledge (TPACK) framework.

TPACK is a framework that describes the knowledge required for teachers to integrate technology into their instruction (Muhammad, 2020). The framework under discussion consists of three main domains: content knowledge, pedagogical knowledge, and technological knowledge. The intersection of these three domains enables teachers to create transformative learning experiences. To illustrate this point, consider the potential for dynamically visualizing abstract scientific concepts, such as atomic structure or the solar system, using technological means. A comprehensive grasp of TPACK enables pedagogues to select the most suitable digital tools to support experimental and discovery methods, thereby markedly enhancing students' science literacy.

The TPACK approach combines knowledge of subject matter, teaching methods, and the use of technology in learning. These three aspects can support the development of students' science literacy (Zubaidah et al., 2023). Content knowledge helps students understand scientific concepts and theories correctly. Pedagogical knowledge relates to how teachers design learning activities so that students can analyze information, interpret results, and draw conclusions. Meanwhile, technological knowledge helps students visualize scientific phenomena through simulations or digital media, enabling them to more easily understand the impact of a discovery, solve problems, and apply scientific concepts in everyday life.

Despite the considerable potential of TPACK, the availability of teaching materials explicitly designed with this framework remains extremely limited. The majority of the modules available in the field remain textual and static. In addition, the use of technology remains limited to content delivery and has not yet been utilized for more interactive activities, such as simulations or exploratory exercises. The novelty of this research is evident in its exploration of these under-researched areas. The teaching modules developed for this program not only present science content in digital format, but also integrate interactive simulations with a problem-based learning approach linked to local socio-scientific issues in Indonesia. The modules have been meticulously designed to compel students to engage in active virtual investigations, analyze digital data, and formulate conclusions based on evidence, thus encapsulating the three fundamental pillars of science literacy. As a result, the newly developed module is expected to address the limitations of the previous module and provide a more interactive and contextual learning experience. The research's unique contribution lies in providing empirically tested learning instruments. These instruments bridge the limitations of physical laboratories in schools by integrating virtual laboratories into modules.

A discrepancy exists between the suboptimal PISA scores and the constraints imposed by technology-based teaching materials. This observation necessitates the initiation of a comprehensive research initiative on development. The objective of this study is to develop a product characterized by high feasibility and the ability to positively influence students' cognitive abilities. The research questions to be addressed in this study are as follows:

1. How is the development of a TPACK-based teaching module that is valid to enhance students' science literacy?
2. How is the development of a TPACK-based teaching module that is practical to enhance students' science literacy?
3. How is the development of a TPACK-based teaching module that is effective in enhancing students' science literacy?

METHOD

This study constitutes a form of research and development (R&D) aimed at producing TPACK-based science teaching modules and testing their feasibility for improving students' science literacy. The development procedure in this study systematically follows the 4D model framework (Define, Design, Develop, and Disseminate), adapted from Thiagarajan.

Participants

The study was conducted during the odd semester of the 2025/2026 academic year. The study subjects comprised 120 seventh-grade students and 4 science teachers from the Besuki Region, East Java. The Besuki Region was selected for this study because it is a geographical area characterized by diverse school digital infrastructure, ranging from institutions equipped with advanced technological facilities to those in the process of developing such infrastructure. The selection of the four schools was made based on the following criteria.

This research was conducted over two months during the odd semester of the 2025/2026 academic year. In the Develop stage, the product was tested on a limited basis in four schools in the Besuki region of East Java. The participants in this stage were 120 seventh-grade students selected through purposive sampling using the area technique. In addition to the students, four science teachers were also involved in the trial process. The schools were selected based on differences in digital infrastructure, so that the trial could illustrate the situation in schools with fully equipped technological facilities as well as those still in development.

The Disseminate stage involved 25 science teachers as practitioner teachers. The teachers provided assessments and input on the developed products, including their content, ease of use, and suitability for classroom learning needs.

Four schools were selected as samples based on several criteria. First, these schools had already implemented the Merdeka Curriculum in accordance with national education policy. Second, the schools had stable internet access, enabling the effective implementation of TPACK-based modules, especially those that used digital simulations and virtual laboratory activities. Third, these schools represent different levels of student science literacy, based on the results of the previous semester's assessments. Differences in students' science literacy levels are influenced by variations in facilities and technological readiness across schools, which can affect students' learning experiences in science education. The sample was selected using purposive area sampling to ensure the developed modules could be applied across various classroom conditions and levels of digital readiness.

Research Design and Procedures

This study used a research and development (R&D) design with a 4D model that includes the Define, Design, Develop, and Disseminate stages. The Define stage was conducted to formulate the basis for module development. At this stage, researchers conducted a needs analysis through literature studies, observations, and interviews to identify problems in science learning, particularly low science literacy and limited integration of technology in learning. In addition, an analysis of student characteristics was conducted to determine students' initial science literacy, digital readiness, and learning styles. In the Define stage, a concept analysis was also conducted to map science materials relevant to science literacy indicators. The results of this stage were used to formulate learning objectives aligned with the Merdeka Curriculum and TPACK principles, and to design the product.

The Design stage focused on designing the product to be developed based on the results of the analysis in the previous stage. The test instruments were developed based on science literacy indicators to serve as pre- and posttests. Researchers also determine which digital media to use, such as interactive simulations and virtual laboratories, and design module formats that include concept maps, problem-based activities, virtual experiments, reflections, and evaluations.

The output of this stage is a preliminary design of TPACK-based modules that systematically integrate Content Knowledge, Pedagogical Knowledge, and Technological Knowledge. This preliminary design is further developed and tested for feasibility in the Develop stage.

The Develop stage was carried out to test the feasibility and refine the designed modules. Draft I was first validated by subject matter experts, media experts, and education practitioners to assess the suitability of the content, language, appearance, and application of TPACK principles. The validation results were used as the basis for revision to produce Draft II. Next, a small-group trial is conducted to assess the module's readability, instructional clarity, and ease of use for students, and the results inform the revision to Draft III. After that, a limited field trial is conducted in four schools to assess practicality through observations of learning implementation and student response questionnaires, and to measure effectiveness by comparing pre-test and post-test results using N-gain analysis. The results of this series of processes produced Draft IV as the final revised product. The final product was then prepared for dissemination.

The Disseminate stage aimed to ensure that the module is ready for wider use. The revised module was repackaged with improved layout and easier access to digital features, making it more systematic and easier to use. Next, the modules were revalidated by 25 science teachers through the MGMP forum to assess their suitability with the curriculum, readability, and ease of implementation in the classroom. Once deemed suitable, the modules are disseminated online through digital platforms to support their wider application in science education.

Instruments

The data collection process used three instruments that had previously undergone validity and reliability testing by experts. These research instruments were adapted from the educational development research framework proposed by Plomp & Nieveen (2019). The first instrument is a validation sheet used to assess the quality of the developed modules through expert evaluations by media and subject matter experts. This validation aimed to ensure that the modules meet the established quality standards. The assessment indicators included the accuracy and suitability of the material content, the suitability of TPACK integration as a relevant learning framework, and the technical design's suitability for supporting the module's clarity and readability. The second instrument is a practicality questionnaire administered to teachers and students, the module's primary users. It aimed to obtain direct feedback on technical and operational aspects. The technical aspect assessed the extent to which the module supports the learning process. In contrast, the operational aspect evaluates the time efficiency of completing the material and the clarity of the module's language and instructions. The third instrument is a science literacy test administered as a pre-test and a post-test. This test consisted of 20 multiple-choice questions and 5 essay questions. Its composition referred to a science literacy framework that included seven indicators: understanding scientific concepts and theories, analyzing scientific knowledge, recognizing the impact of scientific findings, problem-solving, interpreting results, drawing conclusions, and applying science in everyday life. For example, to measure analytical skills, students were asked to examine how the positions of celestial bodies influence Earth's ocean tides. The reliability test results showed a Cronbach's alpha of 0.82, indicating high internal consistency for the instrument.

Data Analysis

Data analysis was conducted using quantitative and qualitative descriptive approaches to assess the quality of the developed modules in terms of validity, practicality, and effectiveness. Quantitative data were obtained from numerical scores on assessment instruments, while qualitative data were derived from suggestions, critiques, and feedback provided by validators and practitioners.

In addition to quantitative findings, qualitative data obtained from validators in the Develop stage and practicing teachers in the Disseminate stage were analyzed using a simple thematic approach. The results of the analysis showed four main themes, namely: clarity of concepts and depth of material, alignment of TPACK components, technical accessibility, and practicality in the classroom. Regarding conceptual clarity, subject-matter experts emphasized the importance of strengthening conceptual scaffolding so that students do not understand the material superficially. One validator said, "The material is actually good, but it would be more helpful if there were step-by-step explanations, so that students don't just memorize definitions but also understand the connections between concepts." This input was then followed up by expanding the material explanations and adding guiding questions to help students connect scientific ideas more coherently. Regarding TPACK integration, the validators emphasized that the technological element should not only serve as a visual complement but also have a clear pedagogical purpose. A media expert stated, "The simulation is already engaging, but it is best to include a prompt question. Otherwise, students tend to just experiment without really understanding the purpose of the activity." Based on this suggestion, inquiry-based questions and reflective tasks were added to each digital simulation to better align technology use with learning strategies. Feedback from practicing teachers during the dissemination stage emphasized ease of use and the feasibility of classroom application. Teachers highlighted the importance of easy access across various devices and clear instructions for use. One comment noted, "The module has actually been very helpful, but if the simulation link could be made lighter so it's easier to open on a smartphone, that would be great. Since most students use smartphones." In addition, time allocation was also a concern. One teacher said, "The discussion session was great, but maybe we should adjust the estimated time so it aligns better with class schedules." In response to this feedback, the final version of the module was equipped with simpler links, clearer instructions for use, and detailed time estimates for each activity. Overall, this thematic analysis shows that validators emphasize conceptual accuracy and theoretical consistency, while practicing teachers focus more on practical aspects and classroom management. Both perspectives contribute significantly to refining TPACK-based modules.

These analyses served as the primary reference point for refining the final product. The present study will commence with a validity analysis. An analysis was conducted to ascertain the extent to which the module met the standards of material and media feasibility. The data obtained from the subject experts was then calculated as percentages. Thereafter, the results were converted into qualitative categories based on specific criteria.

The product's validity level is determined using a range of values that reflect the criteria for converting the validity percentage, as outlined by Winarni (2018). A percentage of 85.01%–100.00% is categorized as highly valid; 70.01%–85.00% as moderately valid; 50.01%–70.00% as invalid and requiring major revision; and 01.00%–50.00% as invalid. These criteria serve as the basis for determining the feasibility of the developed TPACK-based modules.

The results of the calculations at this stage will determine whether the module is ready for testing or requires a thorough revision. If the validity percentage meets the minimum threshold for "Sufficiently Valid," development can proceed to the field-testing stage, with revisions made in accordance with the validator's recommendations. The results of the observation were scored on a 1–100 scale and subsequently categorized according to the criteria. The results of the learning observations were evaluated on a 1–100 scale and then categorized according to criteria from Winarni (2018). Scores of 0–39 are classified as poor, 40–59 as fair, 60–79 as good, and 80–100 as excellent. These categories are used to assess the level of learning implementation when applying TPACK-based modules.

The module's effectiveness was measured to assess the contribution of product use to improvements in students' science literacy. The researchers then compared pre-test and post-test scores using the Normalized Gain (N-gain) formula to obtain an objective measure of improvement. The instrument used to assess science literacy was developed by adapting a scientific competency framework relevant to the junior high school science curriculum. The instrument comprised 25 questions: 20 multiple-choice and 5 essay-format questions. The questions were designed to measure seven indicators of science literacy, namely: The following seven elements are to be considered: (1) understanding scientific concepts and theories; (2) analysis of scientific knowledge; (3) recognition of the impact of scientific findings; (4) problem solving; (5) interpretation of results; (6) drawing conclusions; and (7) application of science in everyday life (Fortus et al., 2022). Prior to data collection, the instruments underwent rigorous validity and reliability testing to ensure their integrity. The instrument's validity has been demonstrated through expert judgment. The aforementioned judgment concluded that all items met the criteria for content and construct validity. Empirically, the results of the instrument trial demonstrated that all items exhibited an adequate level of validity. This value indicates that the test exhibits high internal consistency (reliability) for measuring students' science literacy. The magnitude of the increase in science literacy was then interpreted using the criteria.

The criteria for learning effectiveness are determined by the N-gain value, as defined by Hake (1998). N-gain values ranging from 0.0 d" N-gain < 0.3 are classified as low, 0.3 d" N-gain < 0.7 as moderate, and 0.7 d" N-gain < 1 as high. These criteria are used to measure the level of improvement in students' science literacy after the implementation of the TPACK-based module.

The use of the N-gain formula is intended to mitigate potential bias arising from pretest disparities in students' initial capabilities. The module is declared effective if it provides a significant improvement that meets the minimum "Moderate" criterion for the majority of test subjects.

RESULT AND DISCUSSION

Define

The average pre-test scores in the four schools ranged from 31.8 to 34.1. This range indicates that students' initial science literacy skills across the four schools remained relatively low and similar. The problem of literacy was not limited to one school, but was common among students in science education. These scores also indicate that most students have not yet mastered science literacy skills to an optimal level.

The results of the needs analysis show that science learning in the classroom remains dominated by teacher explanations rather than by active student involvement in exploratory activities. This condition makes students less accustomed to thinking critically, asking questions, or testing ideas independently. In fact, in science learning, active student involvement is very important because understanding concepts occurs not only through teacher explanations but also through scientific investigation and discussion.

This aligns with the view of Wibowo et al. (2025), who argue that learning is more meaningful when students are directly involved in constructing their own knowledge through active learning experiences.

Design

At the design stage, researchers began developing the learning modules. The first stage was criterion-referenced test construction, which involved developing assessment instruments tailored to the learning objectives for Earth and Solar System material. These instruments were designed to assess students' understanding of concepts such as Earth's rotation, Earth's revolution, the structure of the solar system, and the characteristics of the planets. Evaluation questions are designed to measure students' understanding after using the learning module.

The next stage is media selection, which involves determining which media to use for learning. In this study, TPACK-based learning modules were selected as the learning media. These modules are equipped with images and illustrations related to Earth and the Solar System, which are expected to help students understand the material more easily and make learning more engaging.

The next step is the selection format, which is determining the arrangement or structure of the module to be created. The module is arranged systematically so that it is easy for students to use. The sections included in the module are the cover, introduction, learning materials, learning activities, exercises, evaluation, and bibliography. This arrangement is designed to help students easily follow the learning flow in the module.

The final stage is the initial design, which involves creating a preliminary design or prototype of the learning module. At this stage, a preliminary draft of the module is compiled, containing material on Earth and the Solar System, accompanied by images and learning activities to help students understand the concepts being studied. This prototype module will then be validated by experts before being used in the learning process. The prototype module is shown in Figure 1.

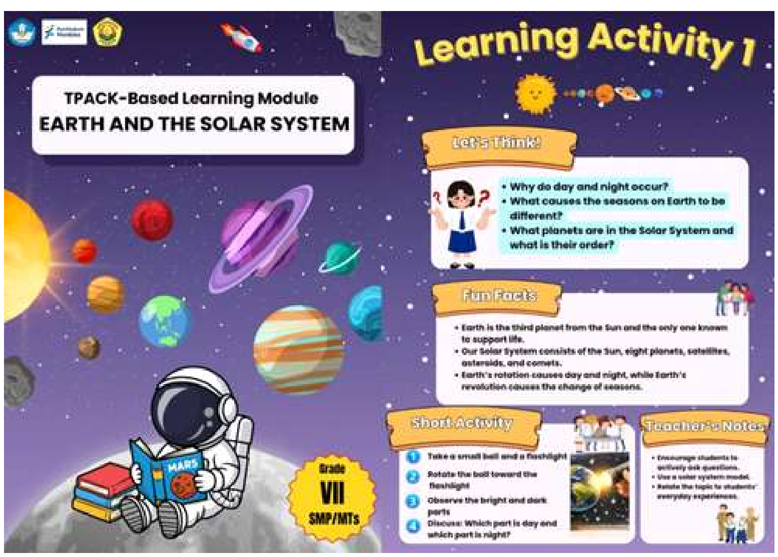

Figure 1. Module prototype

Develop

The present study developed a TPACK-based learning module utilizing the 4D development model. The results obtained include data on validity, practicality, and effectiveness as follows. The results of this study encompass three primary domains: namely, validity, practicality, and effectiveness. Collectively, these domains are designed to enhance junior high school students' science literacy within science learning contexts. One result is the module's validity data, derived from assessments conducted by media experts, as shown in Table 1.

The research instrument was validated by three validators: V1, a subject matter expert; V2, a media expert; and V3, an education practitioner.

Table 1. Validation of TPACK-based learning modules

Observed Aspects	Percentage of Each Validator (%)			Percentage (%)	Standard Deviation	Validity Criteria
	V1	V2	V3			
Approach	85.21	90.19	85	86.80	2.93	High
Format Language	76	93.75	93.75	87.83	10.24	High
Content	80.52	98.94	95	91.46	9.69	High
Practicality	85	89	96.53	90.18	5.85	High
Format Language	75.67	95	95	88.56	11.16	High
Average Score (%)	80.48	93.38	93.06	88.97	7.35	High

The assessment was carried out across five main aspects: approach, format, language, content, and practicality. Based on Table 1, the validation results show that, overall, each aspect received a high percentage. The average score given by Validator 1 was 80.48%, while Validator 2 and Validator 3 gave scores of 93.38% and 93.06%, respectively. When calculated as a whole, the average percentage across the three validators was 88.97%, with a standard deviation of 7.35. This relatively low standard deviation indicates that assessments between validators are consistent and do not show striking differences, and that the data is homogeneous, thus strengthening the validation results. In accordance with the established validity criteria, these results indicate that the TPACK-based learning module falls into the "Highly Valid" category. Specifically, the language aspect received the highest score of 91.49%, indicating that the module was well-structured and readable. The validator also noted that the language used in the module is clear and easy for students to understand, thereby supporting independent learning. "The language in the module is clear and unambiguous, so students can learn on their own without needing much additional explanation." These findings confirm that the research instrument meets the eligibility criteria and can be used to measure the research variables accurately and reliably in the next trial phase.

The module's high average validity score of 88.79% indicates that it meets the standards for instrument and material feasibility established by the TPACK framework. High validity indicates that a product exhibits consistent construction and robust content support, thereby ensuring the attainment of predetermined learning objectives. This finding aligns with the assertions by Daryono et al. (2021) and Arikunto (2010), which emphasize that the validity of a medium is contingent on its alignment with established criteria for teaching materials, namely its feasibility for implementation in the field. However, achieving a high validity score in theory does not necessarily guarantee success in practice. As asserted by Namayala et al. (2023), a discrepancy frequently exists between the conceptual evaluations of experts and the practical experiences of users (students) in real-world settings. This is further supported by feedback from the validators, who noted that while the module is sound in concept, its classroom implementation must still take into account students' circumstances and school facilities. "Conceptually, this module is excellent, but its implementation must still be adapted to classroom conditions and student readiness." A high validity score indicates structural quality; however, it does not guarantee readability or learning motivation unless it is tested empirically through direct interaction. Moreover, the inherent complexity of the TPACK framework further complicates implementation. Tseng et al. (2022) emphasize that TPACK-based design is highly contextual. This suggests that, despite a module being regarded as highly valid in technical and content terms, its efficacy in the classroom is frequently impeded by external variables, such as the readiness of school infrastructure and teachers' self-efficacy. These dynamic factors cannot be fully captured by expert validation instruments alone.

The overall standard deviation value of 7.35 indicates that the assessments of the three validators are not significantly different. This means that the three validators have relatively similar views on the quality of the developed module. In other words, the assessment results are consistent enough to reinforce the module validation results. This finding is also in line with the study by Daryanes et al. (2023), in which the teaching materials developed obtained high validity scores from each validator, demonstrating consistency in assessment across validators. This shows that the developed modules were not only deemed suitable by one expert but also received similar assessments from other validators. In addition, the validators also provided suggestions for improvements, particularly regarding the layout and user instructions, to make them clearer for users. "User instructions are already in place, but they should be made simpler and more systematic so that teachers and students can easily follow them." A series of practical tests was conducted in order to evaluate the extent to which TPACK-based learning modules could be used effectively and efficiently by educators and students. The practicality of these modules was assessed through their implementation in science learning. The assessment was conducted by observers, who completed an implementation sheet encompassing nine primary indicators. The results of the practicality analysis conducted in four pilot schools are presented in Figure 2.

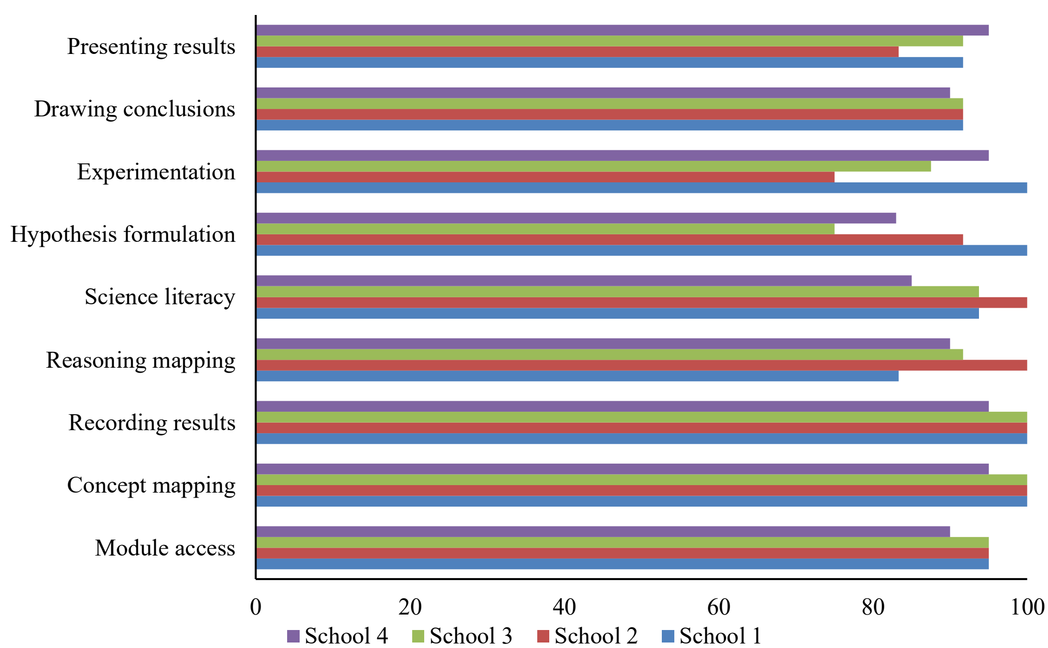

Figure 2. The ensuing discourse will present the findings of the practicality analysis of the TPACK-based learning module

The implementation of TPACK-based learning, as measured by nine indicators across four schools, exhibited remarkably consistent and favorable outcomes, as depicted in Figure 2. All aspects of the evaluation scored above 80%, with an overall average of 90.9%, placing it in the "Very Practical" category. The teacher also noted that the module is easy to use in the classroom because of its clear instructions and simple interface, so students have no trouble accessing it. "The module is easy to use, and students aren't confused because the steps are clear and can be followed right away." Indicators such as access to modules, preparation of concept maps, practical implementation, and group work presentation showed noticeable variation in assessment results across Schools 1, 2, 3, and 4. This finding aligns with the developmental trajectory depicted in Figure 1, wherein the 'Develop' stage, encompassing small-group and limited trials, culminated in the generation of a preliminary module (Draft 4) deemed suitable for dissemination. The findings demonstrate the efficacy of TPACK-based learning methodologies in facilitating active student participation in the learning process.

The module's high average validity score of 90.9% indicates that it meets the standards for instrument and material feasibility established by the TPACK framework. Selain itu, guru juga menilai bahwa akses melalui perangkat seperti smartphone membuat modul lebih praktis digunakan dalam berbagai kondisi pembelajaran. "*Karena bisa dibuka lewat HP, siswa jadi lebih mudah mengakses modul kapan saja*." The concept of 'high validity' in the context of educational products refers to the product's consistent structural framework and robust content support, thereby facilitating the achievement of the stipulated learning objectives. The pivotal factor in this practical aspect's success is the user-centered design of the module interface and the provision of clear operational guidelines for students. The use of a digital platform that seventh-grade students are already familiar with (e.g., via personal devices) helps minimize technical barriers to accessing TPACK links and virtual laboratory simulations. This finding aligns with the assertions of Daryono et al. (2021), who emphasized that the validation of a medium is contingent on the congruence of its outcomes with the established criteria for teaching materials deemed suitable for implementation in the field. However, adopting a more critical stance, Pattinson et al. (2023) observe that elevated validity scores often reflect experts' perceptions of theoretical feasibility, rather than the instrument's capacity to adapt to the evolving dynamics of a genuine classroom environment. In line with this, Tseng et al. (2022) emphasize that TPACK-based designs are highly contextual, meaning that the effectiveness of technically valid modules remains vulnerable to external variables such as school infrastructure readiness and teacher self-efficacy, which are not always fully captured by validation sheets alone.

Consistent with the validation results, the module's practicality, which achieved a score of 90.9%, indicates that this medium can be used effectively and efficiently by students in science learning. Easy access to the module and clear instructions for practical activities are the main factors supporting students' active involvement in the classroom. As stated by Tamrongkunanan & Tanitteerapan (2020) and Suryani et al. (2020), a systematically structured module not only makes learning easier for users but also facilitates the development of new ideas among students. However, this high level of practicality still requires careful attention. Rahmadani & Sunarmi (2023) note that practicality is strongly influenced by students' science literacy; therefore, the modules' efficiency can vary significantly when implemented with students of different characteristics. Furthermore, Kirschner & Hendrick (2024) note that instructions that are "too easy" risk reducing the cognitive load required for deep understanding. Therefore, the 90.9% practicality percentage in this study must be maintained to ensure a balanced intellectual challenge for students and to achieve optimal science competency.

Table 2. Kruskal-Wallis test result

	Value
Kruskal-Wallis H	3.126
Df	3
Asymp. Sig.	0.020

The Kruskal-Wallis test yielded a p-value of 0.020, which exceeds the 0.05 significance threshold. This value indicates that the differences in scores obtained from the four schools are not statistically significant, meaning there is no meaningful difference among the groups. Therefore, it can be concluded that the effectiveness of the TPACK-based module in improving students' scientific literacy is consistent and does not differ significantly across schools.

The effectiveness of the TPACK-based learning module was evaluated by analyzing pre- and post-test results from 120 participants across 4 schools. The purpose of the effectiveness test is to determine the extent to which the product enhances learning outcomes and scientific literacy in the TPACK-based learning module. The data will serve as foundational evidence for assessing the validity of TPACK-based learning media in enhancing the scientific literacy of junior secondary school students. Table 6 presents the pre-test and post-test outcomes, calculated using the N-gain formula.

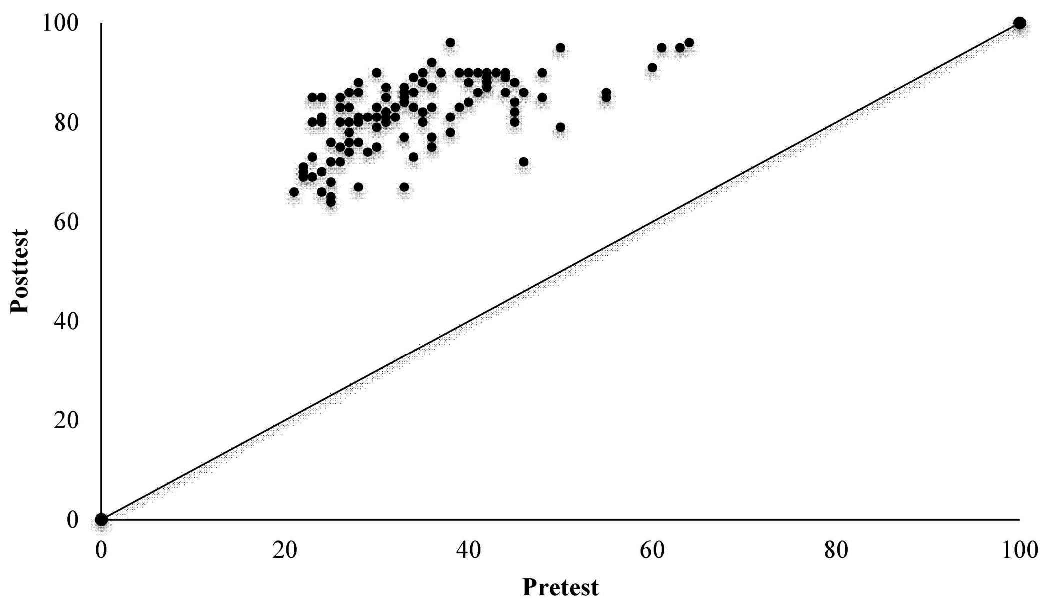

Figure 3. Pre-test post-test science literacy scores

As shown in Figure 3, there is a marked upward trend in pupils' scores across all participating schools. The mean pre-test scores, which ranged from 26 to 43, increased substantially to post-test scores ranging from 77 to 88. This outcome serves as a testament to the efficacy of the developed learning module in enhancing students' conceptual understanding, thereby fulfilling the established criteria for effectiveness. This success is consistent with the Develop stage delineated in Figure 1, in which a series of revisions from "Draft 1" to "Draft 4" (through small-group and limited trials) optimized the quality of the module's materials and instructions before the commencement of the Disseminate stage. This enhancement was not only cumulative but also encompassed a range of dimensions of scientific competence cultivated within the module. To provide a more detailed picture of which aspects of science literacy showed the greatest improvement, an N-gain analysis was conducted for each question indicator. The N-gain results for each science literacy indicator across the four schools are summarised in Table 3.

As demonstrated in Table 3, the "problem solving" indicator showed the largest increase (N-gain of 0.75–0.80). This success was attributed to the integration of virtual laboratories into the module, which enabled students to conduct independent, systematic investigations of variables. The teacher also noted that the use of virtual labs encourages students to be more active in exploring solutions because they can experiment and observe phenomena firsthand. "With virtual labs, students can experiment on their own and be more proactive in finding solutions, rather than just waiting for the teacher's explanation." The substantial increase in the "drawing conclusions" indicator (0.70–0.80) is also a direct result of the interactive simulation feature, which helps students make logical connections between visual data and scientific theory. In line with this, teachers also reported that the simulation feature helps students connect experimental results with scientific concepts, thereby supporting their ability to draw conclusions. "Simulations help students understand the relationship between experiments and theory, making it easier for them to draw conclusions." Concurrently, the "understanding concepts" and "interpreting results" indicators fall within the moderate-to-high category, attributable to TPACK digital visualization's efficacy in simplifying abstract material. The "application of science in life" indicator, which falls in the moderate category (0.50–0.68), indicates that the module's function is more pronounced in enhancing scientific process skills than in internalizing social contexts. The integration of interactive components in TPACK-based modules has a significant impact on improving

Table 3. Score of each science literacy indicator

Science literacy indicators	School 1 (N-gain)	Criteria	School 2 (N-gain)	Criteria	School 3 (N-gain)	Criteria	School 4 (N-gain)	Criteria
Understand valid scientific concepts and theories	0.78	High	0.65	Medium	0.72	High	0.60	Medium
Analyze scientific knowledge	0.65	Medium	0.58	Medium	0.70	High	0.55	Medium
Knowing the impact of something found	0.56	Medium	0.50	Medium	0.68	Medium	0.60	Medium
Problem Solving	0.75	High	0.85	High	0.90	High	0.75	High
Interpret the results	0.65	Medium	0.60	Medium	0.70	High	0.58	Medium
Draw conclusions	0.80	High	0.75	High	0.78	High	0.70	High
Applying science in everyday life	0.6s3	Medium	0.55	Medium	0.68	Medium	0.60	Medium

students' critical thinking and problem-solving skills.

The improvement in students' science literacy, with an average N-gain of 0.78 in the high category, indicates that this module effectively enhances knowledge acquisition among junior high school students. This success is driven primarily by the integration of virtual laboratory features and interactive simulations, which enable students to independently explore variables. These digital activities provide hands-on learning experiences that help students construct abstract concepts into more concrete ones, thereby improving their critical thinking skills. The focus on problem-solving and conclusion-drawing indicators has a significant impact on students' critical thinking skills compared to conventional methods. This is in line with the findings of Delita et al. (2022) and Sofyan et al. (2023), which confirms that the use of modules based on everyday phenomena has a positive influence on students' science literacy experiences.

The results of the study on problem-solving indicators showed the greatest improvement. These findings align with Mitra (2022), which indicates that integrating virtual laboratories and interactive simulations into the module not only helps students understand concepts but also encourages them to conduct investigations and think systematically. This means that the improvement in problem-solving skills is due not only to the use of digital technology but also to the module's simulations, which are designed to train students' thinking and problem-solving skills rather than simply serve as additional visual aids.

However, the effectiveness of these achievements warrants further critique, particularly regarding the sustainability of learning outcomes. Lin et al. (2024) warn of the potential for a novelty effect, in which a spike in cognitive scores is often triggered by students' enthusiasm for new technological formats (TPACK), thereby requiring long-term testing to ensure that such science literacy is sustained. Furthermore, quantitative success, as measured by N-gain, does not necessarily reflect comprehensive mastery of science literacy in real-world contexts. Hadjichambi et al. (2023) emphasize that true science literacy requires behavioral transformation and environmental responsibility, not just the ability to draw conclusions in practice questions. On the other hand, Diah et al. (2022) also highlight that the effectiveness of digital media depends heavily on the quality of scaffolding or teacher guidance in the classroom. This implies that the figure of 0.70 reflects synergy between the module and the teacher's role as a technology facilitator. To reinforce the results of the analysis, a Wilcoxon signed-rank test was conducted to compare students' science literacy scores before and after using the TPACK-based module. The results of Wilcoxon test are presented in Table 4.

Table 4. Wilcoxon test result

School	Asymp. Sig (2-tailed)
School 1	< 0.01
School 2	< 0.01
School 3	< 0.01
School 4	< 0.01

The statistical test results show that the Asymp. Sig (2-tailed) value in all four schools is < 0.01. The Wilcoxon Signed-Rank Test value is smaller than the significance threshold of 0.05, indicating a significant difference between students' pretest and posttest scores within each school. This indicates that the use of the developed module contributed to an increase in students' science literacy after the learning process. These findings are in line with research by Pratumsala & Nuangchalerm (2023), which states that learning that integrates TPACK can help improve students' understanding of science concepts and their ability to analyze and use scientific knowledge in various learning situations. However, to determine whether the increases differed across the four schools, a Kruskal-Wallis test was conducted. The results of the test are presented on page 5.

Table 5. Kruskal-Wallis test result

	Value
Kruskal-Wallis H	41.331
Df	3
Asymp. Sig.	0.000

Based on Table 5, the significance value (Asymp. Sig.) of 0.000 ($p < 0.05$) indicates a statistically significant difference among the four schools. This suggests that the improvement in student learning outcomes following the use of TPACK-based modules was not uniform but varied across schools. These differences indicate that module effectiveness is influenced not only by instructional design quality but also by contextual factors such as technological facilities, internet access, and digital literacy. Additionally, teachers' role in implementing the modules affects outcomes, with greater readiness leading to greater improvements. The effectiveness of TPACK-based learning modules is assessed not only through tests but also through student response questionnaires about the products produced after their use in science learning. To facilitate a comprehensive understanding of the products in question, students are invited to provide responses that address specific aspects of interest, material, and language. The results of the analysis of the student response questionnaire data are presented in Figure 4.

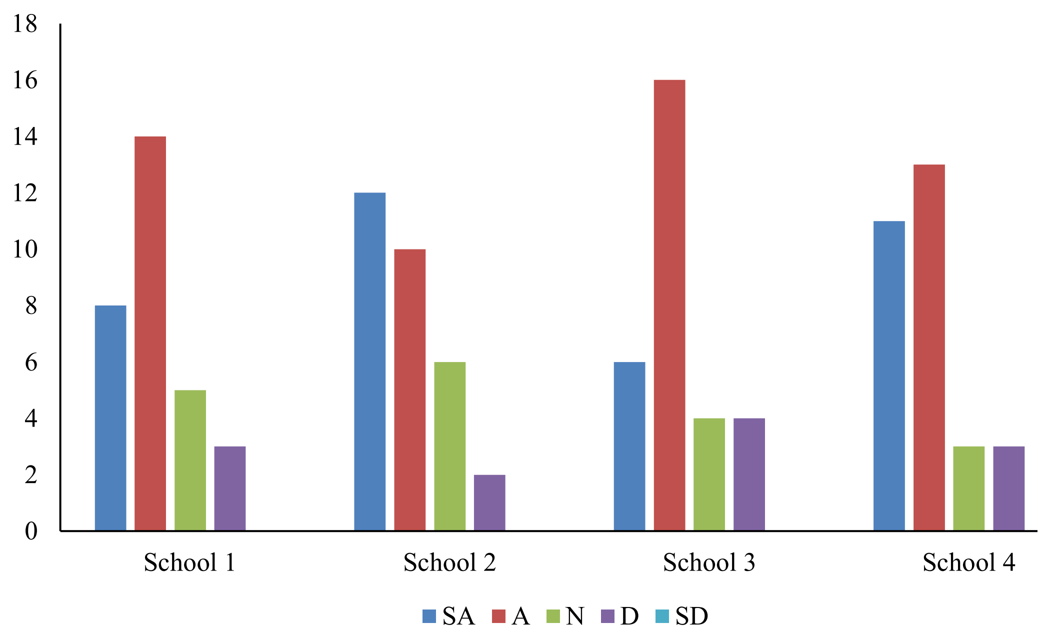

Figure 4. Student response questionnaire result

The results of the student response survey on the use of TPACK-based learning modules in four schools show a positive response trend. At School 1 and School 2, most students responded in the agree and strongly agree categories, indicating that the modules used were considered helpful in understanding the learning material. Students also noted that the module's visualizations helped them understand concepts that are difficult to visualize, such as the movement of the Earth and the planets. "Thanks to the simulations of the Earth's and planets' movements, I now better understand why day and night occur and why the seasons change." These positive responses show that TPACK-based learning modules are able to attract students' interest in learning and make it easier for them to follow the science learning process. However, a small number of students gave neutral or disagree responses, which was relatively small compared to the positive responses.

The same was observed in Schools 3 and 4, where the majority of students responded with “agree” or “strongly agree” regarding the use of the module. This response shows that the TPACK-based learning module is considered quite interesting and easy to understand, and that it can help students understand the material being studied. In addition, some students also said that the simulation helped them understand phenomena like eclipses, which had previously been hard to imagine. “Before, I had a hard time imagining how an eclipse works, but the simulation made it much clearer.” Overall, student responses across the four schools indicate that the developed module received positive feedback and can support more effective science learning. These findings are in line with a study by Ginting et al. (2022), which shows that applying TPACK in learning can increase student engagement and help students understand the material better.

The utilization of TPACK-based learning modules averaged 91.6% (SD = 0.82), placing students in the “Very Good” category. The standard deviation value is smaller than the average, indicating that the variation in student responses is very low. This means that the four schools gave assessments around the average, so the data can be considered homogeneous.

Student responses to the module were rated excellent, with an average of 91.6%, covering the aspects of interest, material, and language. The attractive visual design and the use of communicative language fostered interest in learning and made it easier for students to understand scientific concepts independently. This aligns with the views of Andalib & Monsur (2024) and Serevina et al. (2022), who argue that aesthetically designed, age-tailored teaching materials foster a positive learning environment, thereby maximizing learning effectiveness. However, this high satisfaction rating should not obscure the analysis of the actual cognitive challenges students face. Garzón & Lampropoulos (2024), in their study on digital learning media, note that students’ positive perceptions, or “interest,” are often superficial; students may like attractive visual designs, but this does not necessarily correlate with the depth of cognitive processing. Additionally, Li et al. (2023) highlight that, in technology-based learning environments, positive student responses may be triggered by gamification or aesthetic elements that risk producing the seductive details effect. This effect occurs when students focus too much on attractive visual elements and ignore the more complex substance of the core material. Therefore, it is necessary to ensure that this average response of 91.55% reflects ease of understanding the content, not merely visual distractions. Furthermore, Cheng et al. (2025) emphasize that student responses to independent modules are greatly influenced by self-regulated learning. This means that, for students with low motivation, even highly engaging modules still require teacher intervention to prevent initial enthusiasm from declining when students encounter science concepts that require advanced reasoning.

Disseminate

The dissemination stage was initiated to distribute the TPACK-based learning modules that had undergone rigorous testing to assess their effectiveness. Given the study’s extensive coverage area, materials were distributed online via digital platforms (e.g., WhatsApp Groups, Google Drive, and Google Forms) to ensure timely, efficient access for educators. In this stage of the research, the TPACK-based learning modules were validated by 25 science teachers from the East Java Science Teacher Working

Group. In contrast to the preliminary stage of expert validation, the objective of this validation testing was to evaluate the appropriateness of the modules from the perspective of practitioners who interact directly with students in the classroom.

Table 6. Validating testing results

Validator	Number of Participants	Aspects Assessed	Average Score (%)	Standard Deviation	Criteria
East Java Science Teacher Working Group	25 Teachers	Curriculum suitability, readability, ease of use (tpack), and material relevance	92.4%	1.21	Highly Suitable

The validation results showed a value of 92.4% with a "very good" rating and a standard deviation of 1.21. This standard deviation value indicates that most teachers gave almost the same assessment of the module's quality. Teachers also said that the use of technology in the module was very helpful for presenting scientific phenomena that are usually difficult to explain through ordinary classroom explanations. Therefore, input from teachers is an important consideration in determining whether this module is sufficiently appropriate for the learning needs and conditions of schools in East Java.

Based on suggestions from teachers, several improvements were made in the final stage. These improvements mainly concerned the layout of the instructions for use, to make them easier to understand during classroom activities. In addition, the technology links in the module (TPACK feature) were also ensured to be accessible via various devices, including laptops and smartphones. After the revision process was completed, the module was distributed to 25 teacher representatives involved in this activity. Through the East Java Science Teacher Working Group (MGMP IPA Jawa Timur), this module is expected to serve as a reference for teachers in developing more engaging teaching materials and helping to improve students' science literacy.

The dissemination stage in the development of this TPACK-based module provides a distinct dimension of validation relative to the initial stage, namely through the direct involvement of 25 science teachers in East Java. The average score of 92.4% in the "Very Appropriate" category indicates that this module is not only theoretically sound in the eyes of experts but also highly practical from the perspective of teachers in the field. In line with the views of Takalao et al. (2024), dissemination through professional communities such as MGMP is highly effective in ensuring that the learning innovations developed align with curriculum requirements and real classroom conditions.

The high appreciation among teachers for the module's visualization of scientific phenomena reflects the successful integration of TPACK features. As Pamintuan (2024) states, the main strength of TPACK lies in technology's ability to represent abstract concepts in a more digestible form. Practitioners' recognition that this module helps visualize conventional material provides evidence that this product can bridge the pedagogical barriers often faced by science teachers. However, the success of online dissemination via digital platforms (WhatsApp and Google Drive) also presents challenges. Although accessibility has increased, the effectiveness of teachers' independent adoption across regions depends heavily on each individual's digital literacy (Su, 2023).

Furthermore, the packaging phase, informed by teachers' input, particularly regarding the flexibility of access on smartphone devices, demonstrates the importance of user experience (UX) in learning media. This aligns with research by Taghizadeh et al. (2022), which emphasizes that perceived ease of use is a key predictor of teachers' sustained adoption of new technologies. Thus, this dissemination stage is not merely a process of disseminating information but a stage of synchronizing innovative products with the broader educational ecosystem in East Java to overcome low science literacy in an integrated manner.

Limitations and Future Research

This study still has several limitations. During the learning process, not all students are accustomed to independent learning through modules, so some still need direct explanations from teachers. In addition, students' varying academic abilities also affect how they understand the material in the modules. There are also other obstacles, such as incomplete student attendance, which can make students' focus on learning in some meetings less than optimal.

Further research could apply this module over a longer period to see how students' science literacy develops in greater depth. In addition, the module could be improved by incorporating interactive technologies, such as Augmented Reality (AR) or other forms of digital visualization, to increase students' interest and make it easier for them to understand the scientific concepts being studied.

CONCLUSION

This study developed a TPACK-based science learning module that meets high-quality standards and improves junior high school students' science literacy. Following analysis of the test results, the module in question was deemed highly valid, with an average score of 88.97% from both experts and practitioners. In terms of practicality, the module achieved an average of 90.9% (very practical) and was supported by 91.55% of students. Empirical investigation demonstrated that implementing the module substantially enhanced science literacy, as evidenced by an average N-gain of 0.70, categorized as 'high'. The most notable advancements were observed in problem-solving and the formulation of conclusions. The success of this module is predicated on integrating virtual laboratories and interactive simulations that transcend the limitations of physical school facilities, thereby facilitating the transformation of abstract scientific concepts into more concrete ones for students. Consequently, the present study posits that the TPACK-based module under discussion warrants widespread adoption as a contemporary pedagogical tool, commensurate with the demands of education in the digital age.

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DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the authors employed Grammarly to assist with language refinement/proofreading. The authors have reviewed and edited the content generated by this tool and assume full responsibility for the content of the published article.

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