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Evaluating the summative effectiveness of a curriculum integrated STEM-based web research hub in fostering science literacy among junior high school students

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ABSTRACT

The need for holistic STEM learning innovations is crucial to enhance students' scientific literacy in the digital era. This RnD study aims to develop a web-based Research Hub as a technology-rich learning environment and evaluate its empirical impact on students' scientific literacy. Utilizing the Lee & Owens framework, the study adopted a one-group pretest-posttest design to evaluate its effectiveness. The sample consisted of ninth-grade students from a junior high school in Malang Raya subjected to a two week intervention. Data werw collected using a 20 item two tier scientific literacy test adapted to the PISA 2022 framework. Descriptive statistics showed a positive shift in the mean score from 63.65 at pretest to 72.13 at posttest, yielding a mean difference gain of 8.48. Prerequisite testing confirmed that the dataset was normally distributed. The subsequent parametric Paired Sample T-Test demonstrated a highly significant increase in scientific literacy with $t = -17.652$, $df = 30$, $p = 0.002$, with a 95% Confidence Interval ranging from -9.465 to -7.503. Furthermore, calculating the magnitude of the intervention yielded an exceptionally large Cohen's d effect size $d = 3.17$, proving that the integrated Research Hub framework provides substantial empirical power in advancing student competencies compared to traditional platform limits. In conclusion, the technology-rich Research Hub is highly effective, valid, and scalable in improving junior high school students' scientific literacy within modern STEM education frameworks.

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Introduction

The scientific literacy crisis among Indonesian students represents a critical structural bottleneck. The 2022 PISA survey explicitly underscored this vulnerability, revealing that Indonesia ranked 68th out of 81 nations, with scientific literacy scores stagnating at 383 severely below the OECD global average of 485 (OECD, 2023). This multi-dimensional stagnation is rooted in conventional, teacher-centered pedagogy that reduces science to rote memorization, resulting in passive students and surface learning(Ma et al. 2023). Additionally, limited contextual learning resources and inadequate supporting facilities, such as laboratories and educational

technology, further hinder optimal competency development (Zarshenas et al. 2022)(Giurgiu 2017; Shamir-Inbal and Blau 2022).

To bridge this gap, modern educational paradigms in the Society 5.0 era demand integrated STEM education supported by a deep learning approach (Aguiar-Castillo et al. 2021; Azorín and Fullan 2022; Matsuo et al. 2022; Zhang 2020). Operationally, deep learning in this study is defined as an instructional interaction that mandates high-order cognitive processes including critical analysis, cross-disciplinary synthesis, and intrinsic motivation through authentic problem-solving. This approach integrates science, technology, engineering, and mathematics to develop 21st-century critical thinking, creativity, and real-world applications(Suhirman and Prayogi 2023; Thahir et al. 2020). The empirical validity of this approach is backed by rigorous regional benchmarks, where a meta analysis of integrated STEM interventions across Asia reported a substansial cumulative size ($ES = 0.82$) on higher order cognitive skills and student outcomes (Wahono, Lin, and Chang 2020). Ultimately, engaging students in technology-driven scientific methods can systematically enhance scientific literacy quality and prepare an innovative, adaptive generation (Almeida, Santos, and Justi 2023; Istyadji and Sauqina 2023; Kelp et al. 2023; Sutiani, Situmorang, and Silalahi 2021).

However, implementing STEM-deep learning as curriculum requires a technology-rich learning environment to facilitate interactive exploration, simulations, and collaboration (Chen and Stem 2025; Sing and Ho 2025; Zhang, Pallath, and Tamilventhan 2021) (Fitri et al. 2026)). Prior studies have confirmed that technology-rich STEM interventions positively yield higher motivation and scientific literacy outcomes compared to conventional teaching (Chung et al. 2025; Paul et al. 2025) . Furthermore, previous global experimental setups mapping technology rich STEM pathways have confirmed strong construct validity, yielding robust Cohen's d effect sizes between 0.74 and 0.85 using established middle school sample size ($N = 145$ to $N = 310$) (Yang and Baldwin 2020).

Deploying such environments is highly complex because modern classrooms are populated by Generation Alpha, a cohort raised in hyper-stimulated digital spaces. Generation Alpha individuals prefer high learning autonomy and visual content, yet possess a drastically limited attention span and are highly prone to non-educational digital distractions (Vaughn et al. 2016). To unlock their 21st-century skills (4Cs), instructional designs must adapt to these evolving traits (Ismail and Hassan 2019). Nationally, this evolution is formalized via Indonesia's Kurikulum Merdeka, which mandates cross-disciplinary project-based learning (Marchy et al. 2022) differentiated instruction and maximized technology integration to shift the teacher's role into a learning facilitator (Suhirman and Prayogi 2023; Wahono et al. 2020)

Nevertheless, a profound chasm exists between policy ideals and ground-level classroom realities. Current school conditions are highly complex and plagued by structural challenges, primarily due to deficient government support, infrastructure unreadiness, constrained teacher competencies, and student adaptation barriers. As established in the literature, the transition to interdisciplinary STEM systematically triggers six core barriers: pedagogical, curriculum, structural, student concerns, assessment concerns, and teacher support limitations (Chen and Stem 2025; Fitri et al. 2026; Pichon, Naji, and Hassan 2025). Schools face frequent fluctuations in learning objectives, mismatches in national textbooks, and delayed book distributions, causing acute confusion among teachers in formulating learning pathways and teaching modules. This is severely compounded by widespread technological disparities such as insufficient hardware and unstable internet connections and a dangerous dependency on technology, while students' mindsets remain unready for active learning autonomy.

Furthermore, a critical research gap persists within digital STEM interventions. Most schools heavily rely on standard Learning Management Systems (LMS) like Moodle or Google Classroom. Conventional LMS are designed asymmetrically, focusing on one-way administrative functions that inadvertently perpetuate surface learning and exacerbate cognitive fatigue in Generation Alpha. Standard LMS fail to offer the adaptive pathways required to circumvent structural school limitations and partition complex scientific inquiries into bite-sized, visually stimulating, and interactive experiences that Kurikulum Merdeka demands.

To overcome these structural limitations, the development of a technology-based Research Hub offers a strategic alternative solution. Historically adopted from innovation management and library science as a centralized data repository (Mansaray et al. 2022; Marino 2023; Mejia, Hincapie, and Giraldo 2019), this study executes a radical reconceptualization of the Research Hub, adapting it into the K-12 STEM education landscape. As an adaptive digital ecosystem, this hub integrates MOOC-based pathways, junior research databases, virtual laboratories, and collaborative spaces to foster meaningful, contextual learning (Dass 2017). This architecture directly operationalized effective STEM pedagogy by creating an innovation, collaborative, and inclusive learning environment (Suhirman and Prayogi 2023) while shifting students from passive users into active digital content creators (Yang and Baldwin 2020). It allows students to become active, reflective learners

responding to contextual science issues (Thahir et al. 2020; Wu and Rau 2019) while embedding Education for Sustainable Development (ESD) principles to address environmental and social insights(Dessì et al. 2019; Shamir-Inbal and Blau 2022; Zarshenas et al. 2022).

However, a critical empirical gap persists in current STEM development literature. While instructional material engineering frequently claims pedagogical efficacy based on small-scale formative alpha-testing, there remains a profound scarcity of studies that rigorously bridge system design procedural paradigms with concrete, empirical evaluations of student performance over an extended implementation period. Utilizing a systematic Research and Development (R&D) framework based on the Lee & Owens (2004) model, this study aims to address these limitations by integrating a rigorous pre-experimental one-group pretest-posttest design conducted over a four-week instructional cycle. This approach is executed to empirically evaluate the capacity of this technology-rich Research Hub in generating a significant, measurable acceleration from baseline to post-intervention scores regarding the scientific literacy of junior high school students in Malang Raya.

Method

The development research methodology using the Lee & Owens (2004) model, which consists of five systematic stages. The structural visualization of this operational framework is illustrated in Figure 1

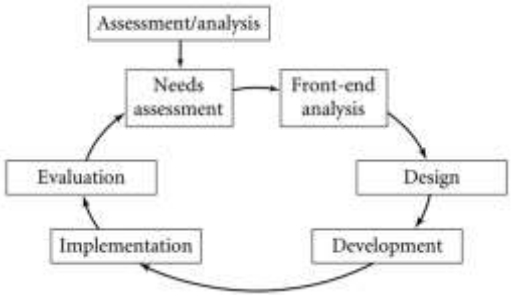

Figure 1 <Research Methodology Floe based on the Lee & Owens (2004) Development Model>

As visualized in the operational loop above, the framework does not merely proceed linearly but functions as an integrated cycle where each phase directly informs the next. To provide a granular operationalization of this framework within the context of improving scientific literacy through the Research Hub ecosystem, these five systematic stages are meticulously elaborated below:

Assessment and Analysis: (1) A needs assessment was conducted to structurally identify the performance gap between contemporary classroom realities (the crisis in scientific literacy scores) and the idealized benchmarks of STEM integrated pedagogy; (2) A comprehensive front-end analysis was executed to map the developmental characteristics of Generation Alpha students, who display high technology dependency paired with restricted attention spans. This phase also examined available school technological infrastructure, specific instructional tasks, geographical constraints within the Malang Raya region, learning objectives mandated by Kurikulum Merdeka, necessary digital media typologies, and structural field barriers; (3) This stage involved structured classroom observations, in-depth interviews with science educators and students, and document analyses regarding STEM learning frameworks, deep learning engagement metrics, pedagogical hurdles, and scientific literacy measurement tools.

Design: (1) The architectural framework of the "Research Hub" was designed as an integrated digital ecosystem. This included technical specifications for a technology-rich learning environment featuring bite-sized inquiry modules and virtual laboratories engineered to transition students from passive digital consumers into active content creators; (2) The core content hierarchy, interdisciplinary STEM curriculum blueprints, pedagogical interaction mechanics, and user engagement pathways within the Research Hub were structurally formulated; (3) The evaluation instruments were designed as a 20-item two-tier multiple-choice scientific literacy test mapped directly to the PISA framework (explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically) to serve both formative and summative evaluation metrics.

Development: (1) Prototype Specifications: The web-based Research Hub application was developed and compiled independently by the researchers using an HTML5/JavaScript framework in accordance with the established design blueprints. The digital platform features four core synchronized modules: (1) STEM-Inquiry Learning Track, (2) Interactive Virtual Laboratory, (3) Junior Research Database Repository, and (4) Collaborative Peer-Discussion Workspace; (2) Product Validation: Expert judgment was secured from four

panel experts specializing in STEM curriculum architecture and instructional media technology to establish content and construct validity. The expert agreement level was mathematically computed using a percentage statistical technique adapted from Marthalena et al. (2021).

Implementation1 (1) The Research Hub platform was formally deployed as the primary instructional medium during a two week learning cycle targeting a single cohort of 31 ninth-grade students ($n = 31$); (2) To ensure high instructional fidelity, the delivery of the guided-inquiry treatment was monitored and logged utilizing a standardized Fidelity Checklist by an independent observer. This mechanism was maintained to ensure treatment delivery consistency reached 95%, thereby isolating the single-group intervention from extraneous internal validity threats such as history and maturation biases.

Evaluation: (1) The summative effectiveness of the Research Hub in accelerating students' scientific literacy was evaluated using parametric inferential statistics. Prior to hypothesis testing, statistical assumptions were verified using the Shapiro-Wilk Normality Test; (2) Within-group significant improvements from pretest to posttest phases were calculated using the parametric Paired Sample t-test (Creswell & Creswell, 2018); (3) The practical significance and magnitude of the Research Hub's intervention on scientific literacy were explicitly calculated using Cohen's *d* effect size formula (Cohen, 1988) for paired designs.

Results and Discussions

Development Result based on Lee & Owens Framework

The development of the web-based Research Hub was systematically executed through the iterative phases of the Lee & Owens (2004) design paradigm to ensure the infrastructure aligns with STEM pedagogical requirements.

Assessment and Analysis Phase

The front-end analysis revealed a critical performance gap: junior high school science instruction in the Malang Raya region heavily relies on administrative, one-way digital platforms that fail to facilitate autonomous problem-solving, causing a critical drop in scientific literacy. Concurrently, learner analysis mapped the specific cognitive behavioral traits of Generation Alpha. While these students show extreme digital fluency, they possess a highly restricted attention span and exhibit high vulnerability to cognitive overload when presented with dense textbook material. Consequently, the analysis mandated a technology-rich learning environment capable of partitioning complex inquiries into visually stimulating, flexible, and adaptive learning pathways.

Design and Development Phase

To bridge the diagnostic gaps, the Research Hub platform was engineered using an HTML5 and JavaScript architecture to ensure responsive browser compatibility. The structural blueprint translated the generic guided-inquiry framework into a digitized course environment titled "STEM meets Volcanoes". The operational interface of this developed prototype is instantiated within an adapte Moodle core customized for Junior High School instruction, as illustrated in Figure 1 and Figure 2

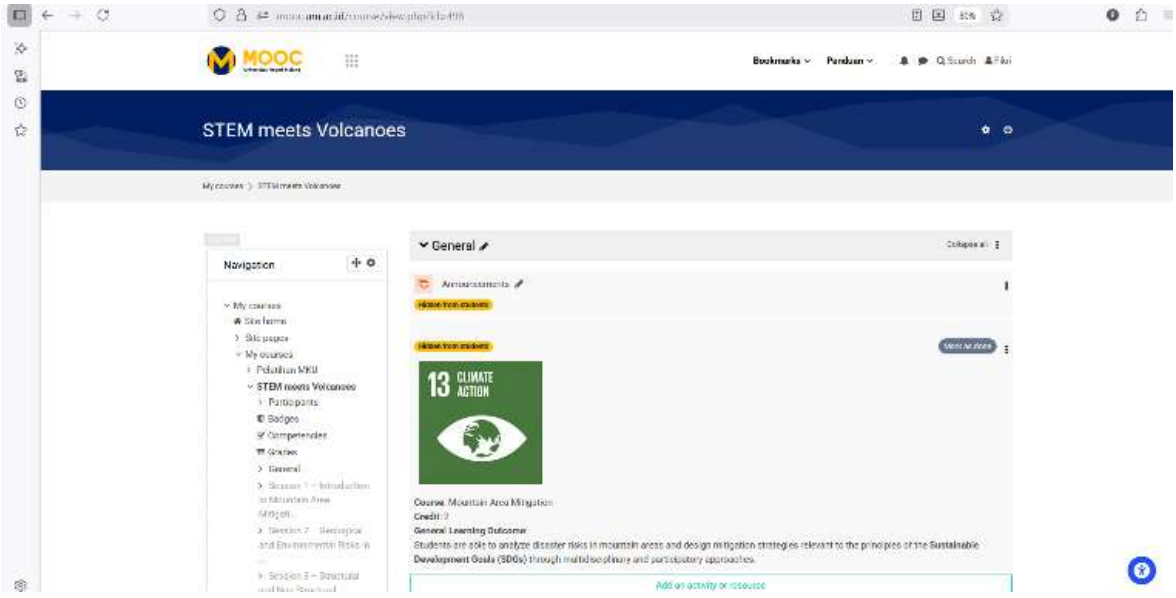

Figure 1 <Operational Interface>

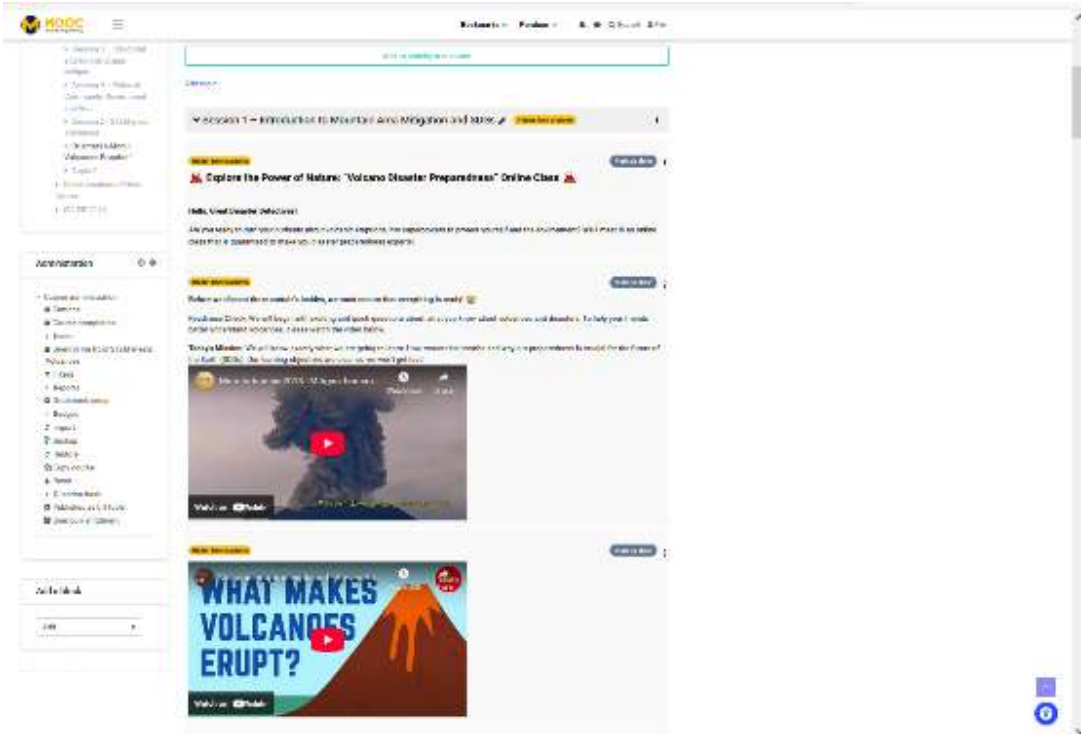

Figure 2 <Complex Geological Concepts>

As visualized in Figure 1, the ecosystem establishes an explicit cross-disciplinary benchmark by embedding the Sustainable Development Goals (SDGs), focusing on Goal 13 (Climate Action), within a localized "Mountain Area Mitigation" curriculum framework. To directly counter the attention boundaries of Generation Alpha, complex geological concepts are modularized into bite-sized interactive sections (Figure 2). This architecture incorporates specialized multimedia components, including instructional inquiry videos detailing volcanic mechanics "What Makes Volcanoes Erupt?" and real-world civic survival protocols "Volcano Disaster Preparedness".

Expert Validation Results

Prior to field implementation, the digital prototype and its embedded content were subjected to independent evaluation by a panel of four experts specializing in STEM curriculum design and instructional technology. Computing the evaluation matrices using the percentage statistical technique adapted from Marthalena et al. (2021) yielded a cumulative validation score of 92.5%. This output classified the Research Hub as "Highly Valid," confirming its construct integrity, visual accessibility, and pedagogical compliance for middle school deployment.

Summative Effectiveness Result

The descriptive statistical analysis was conducted to map the baseline profile and post-intervention scientific literacy scores of the single experimental cohort utilizing the newly developed technology-based Research Hub. The detailed statistical distribution before and after the four-week instructional treatment is presented in Table 1.

Table 1 <Descriptive Statistics of Scientific Literacy Scores>

Metrics	Pre-test	Post-Test
Mean	63.65	72.13
Median	62.00	71.00
Mode	62.00	72.00
Std. Deviation	11.695	10.350
Minimum Score	44	52
Maximum Score	85	93

Based on Table 1, it is known that the number of valid respondents is 31 students, both before and after the treatment was given. From the table, the average (mean) scientific literacy score of students before the treatment was 63.65 and increased to 72.13 after the treatment. This progression yields a descriptive mean difference gain

of 8.48 points, showcasing a clear upward shift in baseline competencies. The median value before the treatment was 62.00 and rose to 71.00 after the treatment. The mode before the treatment was 62, while after the treatment it became 72. The standard deviation before the treatment was recorded at 11.695 and decreased to 10.350 after the treatment, indicating that students' scores became more homogeneous and concentrated around the higher mean post-intervention. Additionally, the minimum score before the treatment was 44 with a maximum of 85, while after the treatment the minimum score increased to 52 and the maximum rose to 93. These data indicate that the average scientific literacy score of students after the treatment is higher compared to before the treatment.

To verify that the dataset satisfies the mathematical assumptions required for parametric inferential metrics, the data were subjected to a Shapiro-Wilk Normality Test in Table 2

Table 2 <Normality Test Shapiro-Wilk>

Kelas	Statistic	Df	Sig.
Before treatment	,960	31	,296
After treatment	,982	31	,861

Based on Table 2, it shows that the pre-treatment class statistical data obtained a significance value of 0.296 and the post-treatment data obtained a value of 0.861. Since both values are above 0.05, it can be concluded that both datasets are normally distributed.

The homogeneity test in this study is an important step that must be carried out before conducting hypothesis testing. This test aims to ensure that the data groups used come from populations with uniform (homogeneous) variances. If the significance value (Sig) > 0.05, it can be concluded that the data variances are homogeneous, meaning the homogeneity test has been met. The results of the homogeneity test can be seen in the following Table 3

Tabel 3 <Homogeneity Test>

Lavene Statistics	df1	df2	Sig.
,465	1	60	,498

Based on Table 3, the significance value obtained from the research data is 0.498. This value meets the established criteria, which state that if the significance is greater than 0.05 (0.498 > 0.05), the data is considered homogeneous, meaning it has the same variance.

The results of the prerequisite data analysis show that the research data are normally distributed and homogeneous. Therefore, the subsequent data testing was conducted using hypothesis testing through the parametric Paired Sample T-Test in Tabel 4

Tabel 4 <Paired Samples Test Before and After Treatment>

		Paires Difference					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair1	Before treatment-After treatment	-8.484	13.919	2.500	-13.598	-3.379	-3.394	30	.002

Based on Table 4, the results of the Paired Sample T-Test show a significance value of 0.002. Since this value is less than 0.05, the alternative hypothesis (H1) is accepted and the null hypothesis (H0) is rejected. This indicates a significant difference, leading to the conclusion that the development of the research hub has a positive effect. To quantify the practical significance of this single-group intervention, Cohen's d effect size formula was applied. Based Tabel 4 and according to Cohen's (1988) operational conventions, a value of $d >$ 0.80 denotes a large effect size. The calculated output of 3.17 indicates an exceptionally large effect size, confirming that the intervention wields profound practical power.

Discussion

Science learning consists of a series of activities designed to help students acquire attitudes, processes, and knowledge about nature or science (Dwicky Putra Nugraha, 2022). Therefore, the success of science learning highly depends on students' ability to understand scientific concepts. Teachers need to support the enhancement of scientific literacy so that students can achieve optimal learning outcomes in science. PISA defines scientific

literacy as the ability to use scientific knowledge, pose questions, and draw conclusions from available evidence to understand and make decisions related to nature and the impact of human activities on nature (Riyadi & Susongko, 2024).

Inquiry-based learning is a method aimed at encouraging students to independently understand and find reasons for their ideas without external intervention (Sugianto et al., 2020). The guided inquiry model is considered highly appropriate in science learning because it can serve as an alternative to improve students' scientific literacy. Through this model, students actively construct conceptual understanding independently (Almira et al., 2020).

During the learning process, the treatment implementation showed high student engagement, especially in gathering information and discussing in groups. Students were given the opportunity to participate directly, which not only boosted their motivation but also made the learning experience more meaningful. With the guided inquiry learning model, students actively explore knowledge and collaborate in utilizing various learning resources. This approach helps students become more active, skilled, and confident in solving problems based on the information they acquire. The classroom atmosphere also became livelier with students enthusiastically asking questions, making the learning process more enjoyable.

The physical integration of inquiry pathways inside a structured digital repository specifically resolves the technical and architectural criticisms raised during formative design phases. Traditional LMS interfaces trigger severe cognitive fatigue in Generation Alpha users due to unstructured text-heavy layouts. By utilizing bite-sized interactive blocks embedded with highly contextual videos as shown in the platform captures, the system effectively shields learners from cognitive overload. The explicit incorporation of SDG Goal 13 themes provides a real-world anchor that enhances intrinsic motivation, allowing students to map abstract scientific criteria onto tangible global crises.

At the end of the learning session, students were given a posttest consisting of randomized versions of the pretest questions. The posttest results showed a significant improvement compared to the pretest, with an average score of 72.13, the lowest score of 52, and the highest score of 93. This indicates that students' scientific literacy significantly improved after learning using the guided inquiry model, demonstrating the model's effectiveness.

These findings align with the research by Lalu Sunarya Amijaya et al. (2018), which showed a positive effect of the guided inquiry learning model on students' learning outcomes and critical thinking skills. Their study noted an improvement in test scores of 35.03 in the experimental class compared to 26.16 in the control class. The t-test results showed that the calculated t-value (2.67) was greater than the critical t-value (1.99), leading to the rejection of H0 and acceptance of H1. This proved a significant difference between classes taught using the guided inquiry model and conventional methods.

Another supporting study by Endang Lovisia (2018) found a significant effect of the guided inquiry learning model on the physics learning outcomes of 11th-grade students at SMAN 6 Lubuklinggau. The t-test showed a calculated t-value (2.61) greater than the critical t-value (2.02). The average pretest scores for the experimental and control classes were 37.95 and 36.95, respectively, which improved to 76.55 and 68.67 in the posttest. By grounding these guided inquiry pathways within an adaptive digital repository, this study successfully circumvents the pedagogical and structural school barriers highlighted by Suhirman & Prayogi (2023), confirming that the Research Hub successfully scales up traditional inquiry benefits into modern, technology-rich environments tailored for Generation Alpha.

Conclusions

This study demonstrates the potential of the web-based Research Hub—specifically the Moodle-based "STEM meets Volcanoes" prototype—to serve as a valid digital environment that aligns with the Sustainable Development Goals, particularly Climate Action, and the Kurikulum Merdeka framework. While the observed acceleration from pretest to posttest scores suggests positive student engagement, these findings are bounded by critical methodological limitations, including a small sample size, a relatively short intervention duration, the absence of a control group to rule out maturation effects, and potential researcher bias during product implementation. Consequently, direct causal inferences regarding the platform's isolated impact on scientific literacy cannot be definitively established. Moving forward, future research should implement randomized controlled trials across diverse educational settings to validate these preliminary outcomes, while practice-oriented modules should focus on providing highly contextualized, localized disaster-mitigation physics materials to better address the restricted attention spans of Generation Alpha.

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