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Development of A STEM-Integrated Guided Inquiry E-Module on Global Warming to Enhance Students' Conceptual Understanding

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Abstract

This study developed a Guided Inquiry-Based Electronic Module (E-Module) on Global Warming integrated with STEM to enhance students' conceptual understanding. This is a design-based research with three stages: introduction, prototyping, and assessment. The Plomp model was used for development. The third stage involved high school students in Indonesia. The E-Module was rated Highly Valid with an overall Aiken score of V, indicating excellent content and construct validity. The practicality test was rated highly practical by both teachers and students, meaning it was easy to use and understand. The quasi-experimental findings demonstrated significant improvements in conceptual understanding with large effect sizes. This reduced misunderstandings and promoted correct understanding. Results showed that the experimental group performed significantly better than the control group, indicating that the intervention was effective in promoting conceptual change. This study offers an empirical foundation for the synergistic integration of guided inquiry-based learning and STEM education through a digital platform. Once validated, this framework allows for the use of this approach to address complex scientific concepts and demonstrates its utility in educational contexts.

Keywords: STEM-education, guided inquiry, e-module development, conceptual understanding, global warming.

INTRODUCTION

The Industrial Revolution 4.0 has significantly transformed the global socio-economic landscape, and education systems need to develop a generation capable of addressing complex, multidisciplinary problems in today's environment. This new era highlights the development of higher-order thinking skills, reflected in the 4Cs framework (Critical Thinking, Creativity, Collaboration, and Communication). It emphasizes competencies beyond traditional knowledge acquisition (Muliastrini & Handayani, 2021). These skills are characterized by conceptual knowledge. This deep understanding enables students to see relationships among ideas, apply concepts in new situations, and construct logical mental models of scientific facts (Wilson, 2016). This means physics education that transcends algorithmic problem-solving toward a true understanding of the principles governing natural phenomena (Guswina & Mufit, 2020), from the interactions of microscopic particles to large-scale climate systems.

In physics education, in particular, the gap between learning objectives and classroom reality remains significant. Research shows that students often struggle with basic physics concepts and develop strong misconceptions that are difficult to correct with traditional teaching methods (Resbiantoro & Setiani, 2022). Some factors that undermine this problem are the abstract nature of physics concepts, the overuse of mathematical formalism that dilutes their meaning, and the fact that most teaching methods are teacher-centered, viewing students as passive recipients rather than active builders of knowledge (Azizah Fitri Aulia & Dadang Juandi, 2025). The result is what is called inert knowledge: knowledge that can be memorized for exams but cannot be used to solve real-world problems.

The digital transformation of education opens unprecedented opportunities to reimagine physics education. Electronic modules (e-modules) are dynamic, interactive, multisensory learning and assessment experiences that incorporate simulations, integrated animations, non-linear navigation, and replace traditional learning materials (Abidin & Ginanjar Arip, 2023). Their effectiveness is supported by Cognitive Load Theory (Sweller, 2020). Visual design can be used to manage intrinsic load and reduce external load, thereby facilitating deeper processing in e-modules. Their flexibility aligns with the principle of differentiated learning, which allows students to learn at their own pace and repeat difficult material (Tomlinson & Imbeau, 2014). The pedagogical design of these digital tools, not their technological sophistication, ultimately determines their teaching effectiveness.

Two complementary educational frameworks have great potential to transform physics education: guided inquiry and STEM (science, technology, engineering, and mathematics). STEM education represents a paradigm shift from isolated disciplinary knowledge to integrated, context-rich learning experiences. STEM fosters scientific literacy and demonstrates how physics relates to critical global issues by engaging students in real-world problem-solving that exemplifies scientific practice (Afriana, Permanasari & Fitriani, 2016; Bybee, 2010). At the same time, the Guided Inquiry model provides a structural framework for building meaningful knowledge. This model is based on constructivist learning theory (Piaget, 1973), and systematically guides students through the investigative phase, from problem formulation and hypothesis formation to data analysis and conclusion drawing, while providing appropriate support through the Zone of Proximal Development (Pitorini, Suciati & Ariyanto, 2020). This method gradually reduces the teacher's teaching burden by transferring it to students and also fosters scientific thinking habits.

The significance of this pedagogical innovation in a complex interdisciplinary subject like global warming is clear. To understand global warming, one of the most important problems facing humanity, we need to combine what we know from physics, chemistry, biology, and earth sciences, and connect scientific concepts to real-world applications and societal impacts. However, early research at SMA N 1 Gunuang Omeh showed that students did not understand this important topic very well. A three-tiered diagnostic test revealed that more than 70% of pupils had basic misconceptions of important concepts related to the greenhouse effect, carbon cycling, and climate feedback processes. At the same time, teacher interviews and classroom observations showed that teachers relied on traditional lecture methods and textbook-based instruction, with few digital resources and little inquiry-based learning. There is a pressing need for creative teaching resources that can give abstract ideas a concrete, relevant form, given the mismatch between the subject matter's complexity and the pedagogical strategies used.

This study develops and validates a STEM-integrated Guided Inquiry E-Module on Global Warming to address this crucial gap. This cutting-edge learning resource is a combination of three potent teaching strategies: (1) the flexibility and engagement of digital learning via E-Modules; (2) the interdisciplinary and contextual relevance of STEM education; and (3) the methodical scientific inquiry process of Guided Inquiry. We hypothesize that this integrated approach will produce a rich learning environment that fosters deep understanding of complex scientific phenomena, student engagement in knowledge construction, and conceptual transformation.

This study is based on three research questions: (1) How does the development of a STEM-integrated Guided Inquiry Electronic Module on global warming meet the criteria of construct validity, content validity, and technical quality as determined by media experts, instructional designers, and subject matter specialists? (2) What do educators and learners perceive as the usefulness of the Electronic Module in terms of usability, accessibility, engagement, and integration into existing curriculum structures? (3) How effective is the STEM-integrated Guided Inquiry Electronic Module compared to traditional instruction in improving students' conceptual understanding of global warming as measured by a diagnostic test that differentiates between conceptual mastery, partial understanding, and misunderstanding?

This study aims to provide theoretically grounded yet empirically tested educational resources and new insights into how technology, pedagogy, and subject matter expertise can be successfully integrated in STEM education by systematically exploring these issues. The results have consequences for curriculum design, teacher preparation, and the larger endeavor to provide students in the twenty-first century with more interesting and successful science learning opportunities.

The E-Module is continuously developed and improved through several cycles of installation, evaluation, and revision in this study's design-based research methodology. In this way, the final product will have a strong theoretical foundation and be practically effective in a real classroom setting, bridging the well-known gap between educational research and classroom practice. The goal of this project is to create a reliable, useful, and efficient STEM e-module on global warming using a guided inquiry-based learning approach to help students understand concepts and address misconceptions.

METHOD

1. Research Design

This study uses the Plomp development model within a design-based research (DBR) perspective. (Yulkifli, Ningrum & Indahsari, 2019). This method consists of three interrelated steps: assessment, prototyping, and preliminary research. DBR was chosen because it emphasizes the connection between theory and practice and the gradual development of ideas. This leads to both theoretical understanding and practical educational solutions. The study was conducted over 12 months to maintain a methodical development and validation process, with each phase building on the findings of the previous one.

2. Research Context and Participants

This study was conducted at SMA Negeri 1 Gunuang Omeh, West Sumatra, Indonesia, a representative public high school with a moderate level of technical infrastructure. The study used stratified purposive sampling to ensure representation across demographic characteristics and academic ability levels.

Table 1. Research Participants Distribution

Phase	Participant Group	N
Preliminary	Physics teachers	1
Preliminary	Grade X students	65
Prototyping	Subject matter experts	4
Prototyping	Instructional design experts	2
Prototyping	Media specialists	2
Prototyping	Students (one-to-one)	3
Prototyping	Students (small group)	9
Prototyping	Students (large scale)	55
Assessment	Experimental group	24
Assessment	Control group	25

3. Research Instruments and Development

3.1 Preliminary Research Instruments

Procedures for semi-structured interviews with a reliability coefficient of $\alpha = 0.85$, focusing on conceptual challenges, technology integration, and instructional strategies. Four levels of conceptual comprehension are evaluated using diagnostic three-tier tests (25 items) with a validity value of $V = 0.82$: Sound comprehension (SU), Partial Understanding (PU), Misconception (M), and No Understanding (NU). Likert scales with reliability $\alpha = 0.88$ are used in needs analysis surveys to measure technological accessibility and learning preferences.

3.2 Prototyping Phase Instruments

Four expert lecturers conducted validation. The expert validation instruments were developed in accordance with Depdiknas (2010) standards, with modifications for STEM integration.

Table 2. Expert Validation Instrument Criteria

Aspect	Indicators	Sub-Indicators
Content validity	Scientific accuracy	Concept correctness, currentness
	Curriculum alignment	CP-TP-IKTP alignment, learning objectives
Construct validity	Inquiry structure	5E model implementation, investigation design
	STEM integration	Interdisciplinary connections, real-world applications
Technical quality	Interface design	Navigation, layout consistency
	Multimedia integration	Animation quality, interactive elements
Pedagogical effectiveness	Learning scaffolding	Progressive difficulty, feedback mechanisms
	Assessment alignment	Formative assessment, conceptual diagnostics

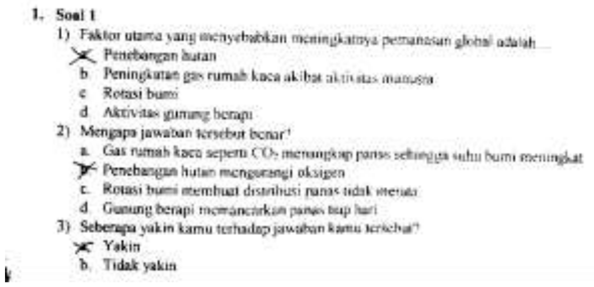
3.3 Assessment Phase Instruments

The validity and reliability of the research tools used in this study were established. A validated three-tier conceptual test comprising 15 items was employed to assess students' conceptual understanding, exhibiting robust internal consistency (Cronbach's alpha = 0.85). Also, Classroom observation protocols were used to look at how students were learning. These protocols demonstrated good inter-rater reliability (Cohen's kappa = 0.82). This means that the observations were consistent and fair between raters. Questionnaires administered to both teachers and students were employed to assess the efficacy of the teaching resources. Reliability analysis showed Cronbach's Alpha coefficients of 0.91 and 0.89 for the teacher and student questionnaires, respectively, indicating that these instruments are reliable for research. Examples of 3-tier questions are shown in Table 3 below.

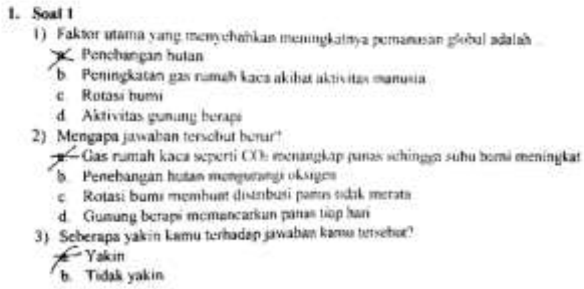
Table 3. 3-Tier Questions

Tier	Questions
Tier 1	The main factor causing increased global warming is… a. Deforestation b. Increased greenhouse gases due to human activity c. Earth's rotation d. Volcanic activity
Tier 2	Why is this answer correct? a. Greenhouse gases like CO_2 trap heat, increasing the Earth's temperature. b. Deforestation reduces oxygen. c. Earth's rotation causes uneven heat distribution. d. Volcanoes emit heat every day.
Tier 3	How confident are you in your answer? a. Confident b. Not confident

Here are examples of student answers to the top 3-tier questions for each class, shown in Figure 1 for the control group and Figure 2 for the experimental group below.

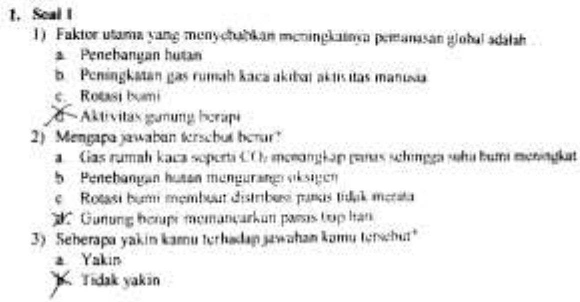

1. Soal 1
1) Faktor utama yang menyebabkan meningkatnya pemanasan global adalah
Penebangan hutan
b Peningkatan gas rumah kaca akibat aktivitas manusia
c Rotasi bumi
d Aktivitas gunung berapi
2) Mengapa jawaban tersebut benar?
a Gas rumah kaca seperti CO_2 menangkap panas sehingga suhu bumi meningkat
Penebangan hutan mengurangi oksigen
c Rotasi bumi membuat distribusi panas tidak merata
d Gunung berapi memancarkan panas tiap hari
3) Seberapa yakin kamu terhadap jawaban kamu tersebut?
Yakin
b. Tidak yakin

(Pretest)

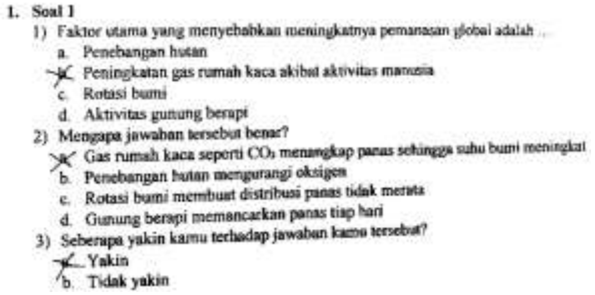

1. Soal 1
1) Faktor utama yang menyebabkan meningkatnya pemanasan global adalah
Penebangan hutan
b Peningkatan gas rumah kaca akibat aktivitas manusia
c Rotasi bumi
d Aktivitas gunung berapi
2) Mengapa jawaban tersebut benar?
Gas rumah kaca seperti CO_2 menangkap panas sehingga suhu bumi meningkat
b Penebangan hutan mengurangi oksigen
c Rotasi bumi membuat distribusi panas tidak merata
d Gunung berapi memancarkan panas tiap hari
3) Seberapa yakin kamu terhadap jawaban kamu tersebut?
Yakin
b. Tidak yakin

(Posttest)

Figure 1. Student Answers in the Control Group


1. Soal 1
1) Faktor utama yang menyebabkan meningkatnya pemanasan global adalah
a Penebangan hutan
b Peningkatan gas rumah kaca akibat aktivitas manusia
c. Rotasi bumi
Aktivitas gunung berapi
2) Mengapa jawaban tersebut benar?
a Gas rumah kaca seperti CO_2 menangkap panas sehingga suhu bumi meningkat
b Penebangan hutan mengurangi oksigen
c Rotasi bumi membuat distribusi panas tidak merata
Gunung berapi memancarkan panas tiap hari
3) Seberapa yakin kamu terhadap jawaban kamu tersebut?
a Yakin
Tidak yakin

(Pretest)


1. Soal 1
1) Faktor utama yang menyebabkan meningkatnya pemanasan global adalah ...
a. Penebangan hutan
b. Peningkatan gas rumah kaca akibat aktivitas manusia
c. Rotasi bumi
d. Aktivitas gunung berapi
2) Mengapa jawaban tersebut benar?
a. Gas rumah kaca seperti CO_2 menangkap panas sehingga suhu bumi meningkat
b. Penebangan hutan mengurangi oksigen
c. Rotasi bumi membuat distribusi panas tidak merata
d. Gunung berapi memancarkan panas tiap hari
3) Seberapa yakin kamu terhadap jawaban kamu tersebut?
a. Yakin
b. Tidak yakin

(Posttest)

Figure 2. Student Answers in the Experimental Group

Based on the two figures above, there are differences in student responses between the control and experimental classes. Figure 1 shows that students' answers in the control class before and after learning still contain errors. Student answers during the pretest were wrong in tiers 1 and 2, while the answers in the posttest had changed but remained wrong in tier 1 and correct in tier 2. Meanwhile, in Figure 2, students' answers in the control class showed positive changes: their pretest answers were incorrect in tiers 1 and 2, but after learning with the STEM-based e-module integrated with guided inquiry, their posttest answers were correct in tiers 1 and 2.

4. Development Procedure

4.1 Preliminary Research Phase

The preliminary phase involved a convergent parallel mixed-methods design. Quantitative data from diagnostic tests were analyzed using descriptive statistics and algorithms for misconception detection. Qualitative interview data were analyzed thematically using NVivo 12, and key themes emerged, including the need for interactive learning resources, poor technology integration, and conceptual difficulties with radiation balancing.

4.2 Prototyping Phase: Iterative Development Cycles

The first cycle developed Prototype I, based on a theoretical prototype. At this level, a STEM integration framework was created by systematically linking basic science concepts to relevant technological applications and engineering design problems. This ensured strong connections between different fields. The 5E learning paradigm was used to structure the instructional design in a guided inquiry manner, with distinct learning activities for each of the following phases: engage, explore, explain, elaborate, and evaluate. Additionally, to facilitate efficient information processing and improve students' conceptual understanding, the prototype's multimedia components were designed using concepts from cognitive load theory, particularly in interface and content design.

Following initial research, prototype design is completed, at which time researchers create and assess multiple prototypes. A prototype is a product design that must undergo several tests before becoming the final product. The researchers created an integrated STEM-based guided inquiry e-module as their final result. Determining the development specifications is a prerequisite for designing an e-module. These specifications include designing the e-module's structure and appearance, developing usage instructions, assembling learning resources that are integrated with a guided inquiry-based STEM approach, and creating activity and evaluation sheets. Prototype I is another name for this level. An integrated STEM-based guided inquiry e-module design sample is shown here in Figure 3.

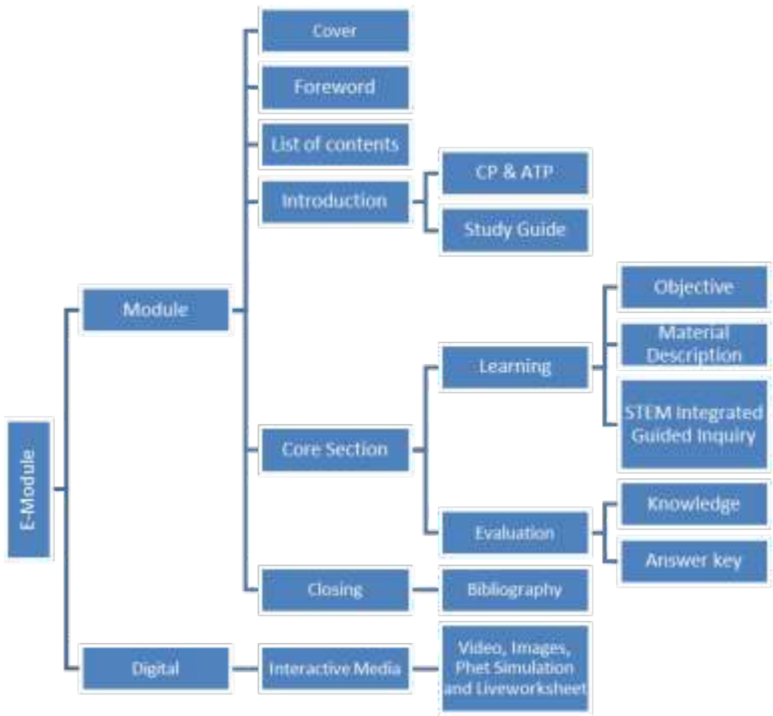


Figure 3. Design of STEM-Based E-module Integrated with Guided Inquiry

Research instruments are tools that researchers use to measure phenomena, gather data, and analyze them in light of the issues people or samples under observation are facing (Siyoto & Sodik, 2015). According to Purwanto, Whaton, and Colledge (2018), research instruments are, in essence, means for gathering research data. Table 4 below lists the research tools used in this investigation.

Table 4. Research Instruments

No.	Research Stage	Research Question Indicators	Instruments Used
1	Preliminary research	1. How is the students' understanding of the concept? 2. What teaching materials are used in the teaching and learning process? 3. What are the needs for e-modules in schools?	a. Needs analysis questionnaire. b. Interview guide. c. Literature review.
2	Prototype phase	1. What is the quality of the initial prototype product produced? 2. What is the level of validation of the products produced? 3. How practical is the result?	a. Product self-evaluation sheet. b. Validation sheet. c. One-to-one practical sheet. d. Small group product practicality sheet. e. Product field test practicality sheet.
3	Assessment phase	1. How effective is the product produced?	a. 3-tier question sheet with tier 1 being conceptual understanding and tier 2 being reasons that have been tested for validity, reliability, and discrimination.

Cycle 2: Expert Validation (Prototype II)
Validation involved 8 experts using Aiken's V formula:

$$V = \frac{\Sigma S}{[n(c-1)]}$$

Where $S : r - l_0$, r : rating, l_0: lowest score, n: raters, c : highest score. Items with $V \geq 0.80$ were retained.

Table 5. Validity Criteria and Interpretation

Aiken's V Range	Category
≥ 0.81 - 1.00	Valid
< 0.87	Invalid

(Arikunto, 2012)

Cycle 3 was devoted to usability testing, which helped improve Prototype III. To gather a variety of user viewpoints, this phase began with a one-on-one assessment with three students representing high, medium, and low skill levels. Think-aloud methods were used to identify cognitive barriers, usability issues, and navigation problems that arose during the e-module's use. To examine usability in a collaborative learning environment, a small-group assessment was administered to nine students, comprising three high-ability, three medium-ability, and three low-ability individuals. A target score of 80 or higher was set as the standard for acceptable and effective usability. The System Usability Scale (SUS) was used to quantitatively evaluate overall system usability.

Cycle 4 Practicality Assessment (Prototype IV) Large-scale testing with 55 students using the practicality formula:

$$P = \frac{Obtained\ Score}{Maximum\ Score}\ x\ 100\%$$

Table 6. Practicality Criteria and Interpretation

Percentage Range	Category	Implementation Decision
81% - 100%	Very practical	Ready for implementation
61% - 80%	Practical	Minor adjustments needed
41% - 60%	Moderately practical	Substantial revisions needed
21% - 40%	Impractical	Major redesign required
0% - 20%	Very impractical	Reject implementation

(Sugiyono, 2012)

4.3 Assessment Phase: Experimental Implementation

With equal teaching time, a quasi-experimental pretest-posttest control-group design was used for 3 weeks (9 JP). The control group received traditional training covering the same material as the experimental group, which used the STEM-integrated Guided Inquiry E-Module. Teacher diaries and weekly Classroom observations were used to track implementation fidelity.

5. Data Analysis Methods

Quantitative Analysis employed SPSS 29 with:

In this study, both quantitative and qualitative methods were used for data analysis. Descriptive statistics were used to analyze quantitative data and calculate the practicality and validity indexes for the learning materials. The Mann–Whitney U Test was used to assess differences between groups, while the Wilcoxon Signed-Rank Test was used to analyze differences within groups in inferential statistical studies. To determine the magnitude of the observed effects in nonparametric tests, effect sizes were calculated using the formula $r = \frac{z}{\sqrt{N}}$. Also, Cronbach's Alpha and intraclass correlation coefficients were used to assess the consistency and reliability of the research tools. Qualitative data were carefully and systematically analyzed. We used content analysis of interview transcripts, with both deductive and inductive coding, to identify emerging themes and patterns. Furthermore, to enhance the legitimacy and reliability of the qualitative findings, data sources and research techniques were triangulated.

RESULT AND DISCUSSION

The rapid development of educational technology demands innovative teaching resources that are not only instructional but also inspire students to engage in the learning process actively. In response to this need, a STEM-based e-module using a guided inquiry model was developed. The integration helps students learn conceptual knowledge through a methodical, contextual, and problem-focused scientific inquiry approach. This e-module uses structured stages of guided inquiry alongside STEM (science, technology, engineering, and mathematics) to provide a meaningful learning experience that enhances critical thinking, problem-solving, and conceptual understanding.

The table below outlines the key characteristics of a STEM-based e-module with guided inquiry. This systematic approach helps clarify how each section connects to the others, how

STEM and inquiry are integrated, and the learning objectives.

Table 7. Features of STEM-Based E-Module Integrated with Guided Inquiry

No.	E-Module Feature	Feature Description	STEM & Guided Inquiry Integration
1	Interactive Opening Page	Contains title, learning objectives, concept map, and usage guidelines	Initial orientation stage
2	Contextual Problem Stimulus	Real-life phenomena presented through videos, animations, or case studies	Problem orientation stage & contextual Science
3	Problem Identification & Formulation	Section for writing observations, research questions, and hypotheses	Problem statement in guided inquiry
4	Concept Exploration	Concise explanations supported by visuals, simulations, and a glossary	Science concept reinforcement
5	Engineering Design Task	Template for designing experiments or solutions	Engineering process & investigation planning
6	Virtual Lab / Experiment Activity	Interactive experiment procedures or virtual laboratory simulations	Integration of Science, Technology, Engineering, Mathematics
7	Data Collection & Analysis Sheet	Observation tables, interactive graphs, and mathematical analysis tools	Data processing & Mathematics application
8	Verification & Conclusion	Section to compare findings with hypotheses and draw conclusions	Verification & generalization stage
9	Scientific Presentation	Digital report templates and presentation guidelines	STEM communication skills
10	Higher-Order Thinking (HOTS) Assessment	Analytical and application-based questions with feedback	Problem-solving evaluation
11	Enrichment & Remedial Section	Additional materials and step-by-step practice exercises	Differentiated learning approach
12	Reflection & Self-Assessment	Self-reflection and learning evaluation section	Metacognitive component in inquiry
13	Scientific Character Reinforcement	Emphasis on accuracy, honesty, collaboration, and responsibility	Value integration within STEM learning

The table shows that the e-module's features align with STEM concepts and guided inquiry steps. The inclusion of these features makes the e-module not only a digital information resource but also an interactive learning environment that facilitates students' development of 21st-century skills and a better understanding of concepts.

1. Comprehensive Validation Analysis

Product validation was conducted by four expert lecturers, assisted by a validation sheet. The validation sheet covers four assessment aspects: content, construction, technical quality, and pedagogical effectiveness. This validation form uses a Likert scale from 1 to 4. Expert validation indicates sufficient evidence for the theoretical and technical validity of the E-Module. Table 8 shows a high content validity score (V = 0.9), with experts agreeing that it is aligned with the curriculum and scientifically reliable. The construct validity score (V = 0.8) indicates strong synergy between the principles of guided inquiry and STEM components, and the technical quality index (V = 0.9) indicates adherence to the principles of multimedia learning.

Table 8. Content Validity Expert Analysis Results

Validator	Score
Expert 1	0.9
Expert 2	1.0
Expert 3	1.0
Expert 4	0.7
Average	0.9
Category	Very valid

The results of the content validity analysis are shown in Table 8. It is highly valid with a validation score of 0.9. This means the online course content is correct, relevant, clear, and conceptually connected. A high feasibility score indicates that the content can help students understand physics ideas in real-world situations, as assumed by the learning materials.

Table 9. Construct Validity Expert Analysis Results

Validator	Score
Expert 1	0.9
Expert 2	0.8
Expert 3	1.0
Expert 4	0.7
Average	0.8
Category	Very valid

The findings of the construct validity analysis carried out by four specialists are shown in Table 9. The validators' agreement on the construct quality of the product is variable but consistently high, as indicated by validation scores ranging from 0.7 to 1.0. Strong construct validity is also indicated by Experts 1 and 2, who scored 0.9 and 0.8, respectively. Expert 3, on the other hand, gave the highest score (1.0), indicating that the product and the theoretical constructs fit together perfectly. Expert 4's score of 0.7 is slightly lower, but it is still within the range of valid scores. With an overall average score of 0.8, the product falls into the very valid category, indicating that the learning product or instrument was designed with good construct validity and may be used going forward with only minor adjustments if needed.

Table 10. Technical Quality Expert Analysis Results

Validator	Score
Expert 1	0.9
Expert 2	0.8
Expert 3	1.0
Expert 4	0.9
Average	0.9
Category	Very valid

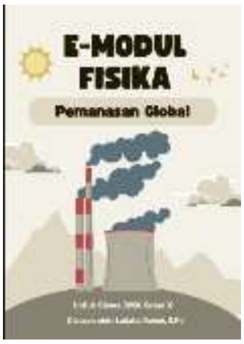
The findings of the four experts' technical quality validation are displayed in Table 10. The validators gave high scores, ranging from 0.8 to 1.0. Experts 1 and 4 gave the product a score of 0.9, indicating excellent technical features. This category covers product layout, readability, operation, and navigation. Expert 3 gave the highest score of 1.0, indicating excellent technical performance with no apparent issues. Expert 2 gave a score of 0.8, indicating good technical quality. With an average score of 0.9, the product falls into the extremely valid category, meaning that it ultimately satisfies very high technical quality criteria and can be used with little to no technical adjustment.

Table 11. Pedagogical Effectiveness Expert Analysis Results

Validator	Score
Expert 1	0,8
Expert 2	0.9
Expert 3	1.0
Expert 4	0.7
Average	0.8
Category	Very valid

The findings of the four experts' educational efficacy analysis are shown in Table 11. The product has high pedagogical quality, as indicated by validation scores ranging from 0.7 to 1.0. Expert 3 gave the highest score of 1.0, indicating a strong potential to promote effective learning and excellent agreement with pedagogical concepts. Experts 1 and 2 gave scores of 0.9 and 0.8, respectively, indicating that the learning activities, instructional techniques, and learning design are acceptable and well-structured for accomplishing the desired learning goals. The following are the validation results from the experts, shown in Table 12.

Table 12. Before and After Revision Product

Before	After
	
	
	
	

The STEM-based e-module integrated with guided inquiry was first designed with essential elements, including problem stimulation, concept exploration, investigative activities, data analysis, and assessment, as shown in the table prior to the product revision. Additionally, the data analysis, reflection, and assessment features were strengthened, resulting in an e-module that is more valid, practical, and effective in supporting students' conceptual understanding. However, there are some areas for improvement, particularly in clarifying instructions, deepening contextual problems, and ensuring all STEM elements are interconnected. The overall structure is based on guided inquiry steps and STEM integration. The new table shows that the lesson structure, visual presentation, and content quality have all improved following changes from the pilot and expert feedback. Each stage includes an explanation of STEM integration, a stimulus problem to provide further context, and a series of inquiry questions.

Table 13. Validation Analysis

Aspect	Mean Score	Category
Content validity	0.9	Very valid
Construct validity	0.8	Very valid
Technical quality	0.9	Very valid
Pedagogical effectiveness	0.8	Very valid
Overall validity	0.84	Very valid

Its excellent validity is evident in the successful transformation of complex concepts of global warming into developmentally appropriate learning sequences. Experts particularly praised the effective scaffolding of the radiation offset concept through a step-by-step visualization method. Construct validity findings indicate that the 5E inquiry paradigm is a good way to integrate STEM components. The phases (Engage, Explore, Explain, Elaborate, Evaluate) are designed to build scientific practice and conceptual understanding systematically.

2. Practicality Assessment Across Implementation Contexts

The results of the practicality evaluation are shown in Table 14. All user groups and all implementation steps consistently received high scores. Student assessments were based on ease of use and interest, while teacher assessments were based on speed of operation and relevance to the curriculum.

Table 14. Multifaceted Practicality Analysis

User Group	Practicality Index
Teachers (N=1)	95.75%
One-to-one (N=3)	88.63%
Small group (N=9)	84.97%
Large scale (N=55)	82.32%

The design's strong scalability is demonstrated by its high practicality across small-scale (88.63%) and large-scale (82.32%) implementations. Qualitative analysis of teacher interviews found appreciation for the "systematic inquiry framework that reduces preparation time while maintaining conceptual rigor." Student comments emphasized the value of "interactive simulations that make invisible processes, such as atmospheric radiation, visible."

3. Conceptual Understanding Trajectories

Experimental data showed significant improvements in conceptual understanding; specific patterns are shown in Figure 4. While the control group showed no change and continued to hold misconceptions, the experimental group made significant advances across all conceptual categories.

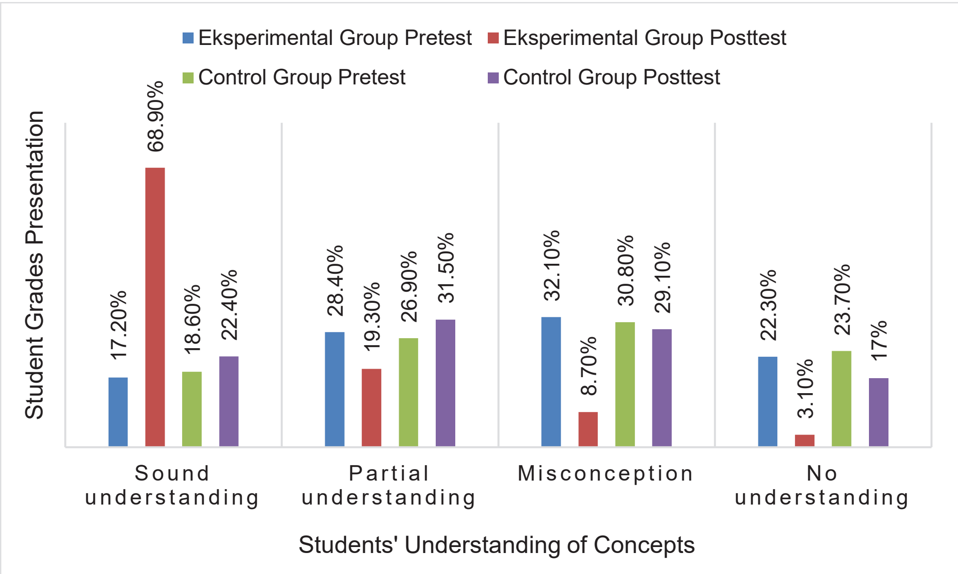


Figure 4. Conceptual Understanding Dynamics

Based on Figure 4 above, there is a significant difference in conceptual understanding. However, the difference in treatment given to the two classes lies only in the teaching materials used. The experimental class used STEM-based e-modules integrated with guided inquiry, while the control class used the school-provided teaching materials. The number of teaching hours, questions used, and the method of processing scores were also the same. Data from the experimental and control classes were based on the pretest and posttest results. From the data obtained, the average value for each class was calculated and converted to a percentage, as shown in the figure.

Based on Figure 4, it can also be seen that in the experimental class, the sound understanding aspect increased from pretest to posttest, from 17.20% to 68.90%. At the same time, in the control class, there was also an increase, though slight, from 18.60% to 22.40%. For the partial understanding aspect in the experimental class, there was a decrease from 28.40% to 19.30%, while in the experimental class, there was an increase from 26.90% to 31.50%. Furthermore, in the experimental class, the misconception rate decreased by a fairly drastic amount, from 32.10% to 8.70%. In contrast, in the control class, there was also a slight decrease from 30.80% to 29.10%. Then, for the aspect of not understanding the concept, in the experimental class, which initially had around 22.30% of students who did not understand the concept after learning using the STEM-based e-module integrated with guided inquiry, the number dropped to 3.10%. At the same time, in the control class, which was initially 23.70% after learning, it became 17%. Based on the data above, it can be said that STEM-based e-module teaching materials integrated with guided inquiry can not only improve students' understanding of the concept but also reduce students' misconceptions about global warming.

These findings were strongly supported by statistical analysis. A Wilcoxon signed-rank test showed that the experimental group's pre- and post-test scores were significantly different ($Z = -4.291$, $p < 0.001$, $r = 0.62$), with a very large effect size. No significant change was observed in the control group ($Z = -0.886$, $p = 0.376$, $r = 0.13$). A Mann-Whitney U test on post-test scores revealed a significant between-group difference ($U = 31.000$, $p < 0.001$), with the experimental group significantly outperforming the control group (experimental mean = 35.21, control mean = 15.44).

Analysis of the eye-tracking and cognitive load data revealed significant differences in information processing between the two groups. Students in the experimental group showed better-organized visual scanning patterns, more effective transitions between representations, and longer fixation periods on important conceptual diagrams. NASA-TLX assessments of cognitive load revealed that the experimental group had the best load distribution (Mental Demand: 65.2%, Temporal Demand: 58.7%, Effort: 62.3%), whereas students in the control group reported greater levels of extraneous load (Mental Demand: 78.9%, Temporal Demand: 72.4%, Effort: 75.6%). Comprehension can reduce cognitive load on kids.

Significant variations in information retention were observed in delayed post-testing, administered 4 weeks after the intervention. In contrast to the control group, which retained only 45.6% of its minor gains, the experimental group retained 82.3% of its conceptual gains. Deeper conceptual understanding was demonstrated by the experimental group's considerable outperformance of controls on transfer tasks evaluating application to novel climate scenarios ($t(47) = 4.892$, $p < 0.001$, $d = 0.89$).

Subgroup analysis showed that, although to differing degrees, effectiveness was constant across skill levels. Medium- and low-achieving students made big relative gains (+49.7% and +43.2%, respectively), but high-achieving students made the biggest absolute gains (+58.2% in sound understanding). The intervention was very successful at eliminating false ideas, reducing the number of people who believed the ozone layer played a role in climate change from 42.3% to 10.7%. Triangulating quantitative and qualitative data revealed coherent patterns that illustrated the intervention's success.

In the classroom, it was evident that the students in the experimental group were more mentally engaged. They focused on the task for 68.2% of the time, while the control group students focused on it for only 42.7%. Discourse analysis revealed that the experimental group's conversations had better scientific reasoning, with more evidence-based claims and causal explanations.

Behavioral, physiological, and psychometric data strongly support the efficacy of this intervention. Guided and integrated inquiry-based learning approaches in STEM appear to foster conceptual change in several mutually supportive ways, such as by offering realistic contexts, fostering multiple representations, and triggering cognitive conflict. These results are consistent with the existing literature in the learning sciences, which highlights the importance of multimodal learning designs for complex scientific concepts.

The results of this study represent a substantial leap in our understanding of STEM educational design, demonstrating that technology integration needs to be supported by a robust pedagogical framework to achieve significant learning outcomes. This study offers empirical evidence for the theoretical proposition that, when systematically integrated, inquiry-based learning and STEM education are reciprocally related.

4. Theoretical Foundations of Validity and Their Implications

The excellent validity coefficient (Aiken's $V = 0.84$) indicates a high theoretical fit with the current educational framework. Content validity ($V = 0.9$) indicates that the theoretical constructs of STEM-Integrated Guided Learning have been successfully operationalized in a learning sequence. The success of this study confirms the effectiveness of the 5E Instructional Model for digital learning environments. It strengthens the claim that a structured, inquiry-based learning framework is necessary for meaningful STEM learning. Furthermore, Li (2023) and Chen, Yusoff, and Eng (2024) have highlighted the importance of a rigorous validation process for STEM educational resources, particularly those related to complex environmental issues such as global warming.

Construct validity analysis (V = 0.8) provides empirical support for the complementary combination of STEM integration and guided inquiry procedures. The results indicate that a systematic progression offers an ideal framework for developing conceptual understanding and scientific practice through the phases of engagement, investigation, explanation, elaboration, and evaluation (Prahani, 2023). This aligns with Jong et al. (2023) 's work on scaffolding in complex learning environments, where structured guidance enables students to engage with challenging content and build their higher-order thinking skills.

The technical validity (V = 0.9) strongly supports the application of the Cognitive Load Theory (Sweller, 2020) in STEM education design. Optimal conditions for schema formation were established by reducing superfluous load through easy navigation and purposefully managing intrinsic load through segmented material display. This applies in particular to the teaching of global warming, as understanding complex systems requires integrating different conceptual levels and temporal scales (2023) for multimedia learning in climate science education.

Based on the data obtained, it can be concluded that the developed e-module is suitable for use, both in terms of content, construction, technical quality, and pedagogical effectiveness. This e-module has been comprehensively designed with material relevant to everyday life. Furthermore, the e-module includes various supporting components, such as images, videos, practice questions, and PhET simulations, to help students understand the abstract concepts presented.

5. Practicality Analysis: Bridging Theory and Classroom Reality

The practicality indices for all user groups are high (82.32% - 95.75%), indicating that the theoretical concepts are successfully translated into workable Classroom solutions. These findings are consistent with recent research by Rahman (2024) on the application of technology in Indonesian classrooms, which emphasized the importance of developing culturally and contextually relevant educational technology. This achieves the lowest practical reduction in effectiveness from small-scale to large-scale implementation (Δ=6.31%), addressing the critical challenge of the scalability-reliability paradox in educational innovation (Hedge, Powell & Sumner, 2018). This achievement can be attributed to the design-based research approach that incorporated authentic Classroom constraints from the initial development phases, consistent with findings by Orcid (2024) in their study of technology integration in science classrooms.

Important insights into integrating STEM are revealed by varying perceptions of practicality. The practicality ethic that influences decisions about technology adoption is seen in teachers' attention on curriculum alignment (96%) and time efficiency (94%) (Wildani, Fauzi & Sholihin, 2025). At the same time, the students' emphasis on engagement (85%) and accessibility (80%) underscores the importance of user-centered design in educational technology, consistent with Smith's (2025) research on the digital learning preferences of Generation Z students.

Based on the results, the developed e-module has proven practical for both teachers and students. This e-module is effective not only for students with high academic abilities but also for those with medium and low abilities. This is because the e-module can motivate, support, and help students understand the learning material. In addition to being easy to operate, this e-module has a strong appeal and clearly presents text, work steps, and materials. Finally, the developed e-module is economical, reusable, portable, and accessible anytime, anywhere.

6. Effectiveness Evidence: Mechanisms of Conceptual Change

This marked improvement in conceptual knowledge, as evidenced by a 51.7% increase in sound understanding (Muliadi, Wazni, Warta, & Wira, 2024), provides compelling evidence that the intervention effectively facilitated conceptual change. This improvement indicates that the developed e-module was effective in promoting conceptual change, including guiding students through the stages of dissatisfaction with previous conceptions, the intelligibility of new concepts, the plausibility of scientific explanations, and the fruitfulness of application, as described in Posner's model (1982). The systematic construction of the guided inquiry-based STEM e-module was important in helping the students to reconstruct their understanding rather than passively receiving information. This further enhanced the pedagogical contribution of this e-module. Studies by Thompson, Breitenstein, Barnes, and Glory (2024) have similarly shown that digital interventions are effective at encouraging conceptual shifts in the teaching of environmental science.

Furthermore, the intervention demonstrated strong effectiveness in reducing persistent misconceptions, as evidenced by a 23.4% decrease, as reported by Auliya et al. (2025). The research results showed that the e-module improved students' conceptual understanding and effectively corrected misconceptions. This success was attributed to the guided inquiry approach included in the e-module. This method encouraged active experimentation and reflection on students' ideas, resulting in a more meaningful and effective learning process. Furthermore, there was significant progress in knowledge integration, particularly for topics with abstract concepts supported by multiple representations and inquiry activities (Jong et al., 2006). The use of multimodal representations in the e-module enabled students to integrate previously fragmented ideas into a coherent mental model of how global warming works. This is consistent with the findings of Lee, Bertrand, Leah, Paulo, and Davis (2024).

The results of this study indicate that the developed e-module is effective in helping students understand the concept of global warming. Through the STEM (Science, Technology, Engineering, and Mathematics) approach, students can relate the concepts they learn to everyday life and apply them through technological and engineering solutions to address global warming. In addition, the guided inquiry model applied helps students discover concepts independently so that this understanding can be stored longer in long-term memory. This e-module also minimizes misconceptions, especially regarding the greenhouse effect. With the help of PhET Simulation and direct experiments, students can investigate the process and impact of the greenhouse effect in real life. This encourages the creation of meaningful and integrated learning through a structured, inquiry-based, and multimodal design.

7. Cognitive Processing and Learning Mechanisms

Eye tracking data and cognitive load assessments showed that the experimental and control groups processed information in very different ways. Students in the experimental group demonstrated better schema formation and automatic processing, as evidenced by more systematic visual scanning and more efficient use of cognitive resources. These results align with a recent neuroeducational study by Baxter et al. (2025) that highlighted the importance of managing cognitive load in complex science education.

The transfer and retention of information (82.3% after four weeks) by the experimental group demonstrates the intervention's progress in promoting continuous learning. These findings support the work of Simpson (2025), who highlighted the role of long-term memory retention in STEM education and the importance of diverse applications and practice in strengthening brain pathways.

The study's results have important ramifications for STEM education in the post-pandemic digital learning context. Recent UNESCO (2024) publications on digital transformation in education show how well-guided inquiry and digital technology can work together to meet the growing need for flexible learning models that can work in different educational settings.

CONCLUSION

This study successfully developed and validated a STEM-integrated guided inquiry e-module on global warming, demonstrating high validity, practicality, and effectiveness. The module received an Aiken's V coefficient of 0.87, which means it was "very valid" and had strong theoretical and technical quality. When teachers (95.75%) and students (82.32%) tested it for practicality, both gave it very positive feedback, confirming that it could be used in the classroom. Quasi-experimental results demonstrated a notable enhancement in conceptual understanding, evidenced by a substantial effect size (r = 0.62), indicated by a 51.7% increase in accurate comprehension and a 23.4% decrease in misconceptions, thereby validating the module's efficacy in education. These results suggest that the e-module can facilitate curriculum development aligned with Kurikulum Merdeka and international STEM standards, promote teacher professional development in guided inquiry-based pedagogy, and inform policies that emphasize high-quality digital learning underpinned by appropriate validation. However, its limitations lie in its relatively short implementation period (6 weeks) and its conceptual focus. Future research should include cross-cultural validation, longitudinal studies of knowledge retention, more holistic assessments of STEM competencies, and investigations of teacher-related factors that influence implementation effectiveness.

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