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Development of a Techno-mathematical Literacy: Integrated SMARTECH and Its Impact on Junior High School Students' Cognitive Engagement

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Abstract: This study aims to develop a SMARTECH e-module integrated with Techno-mathematical Literacy (TmL) and to analyze its content validity, practicality, and the observed changes in students' cognitive engagement following the e-module's implementation. The study used a mixed-methods design with a Design-Based Research (DBR) approach. The subjects consisted of 120 junior high school students selected through purposive sampling from three schools in different areas in West Java. In the implementation stage, a one-group pretest-posttest design was used. Data were collected through expert assessment sheets, student and teacher practicality questionnaires, cognitive engagement questionnaires, observation sheets, and interviews. Data analysis was conducted using descriptive qualitative methods to identify the e-module design characteristics; Aiken's V to assess content validity based on expert judgment; descriptive analysis to assess practicality; and paired-samples t-test, Cohen's d, and N-gain to examine changes in students' cognitive engagement. The results of the study indicate that the developed e-module has the main characteristics of a systematic learning flow, an easy-to-use digital interface, activities that encourage active thinking, and support for independent learning. The results of expert validation indicate that the e-module has adequate content validity across mathematical content suitability, TmL integration, instructional design, and activity flow (0,80 each), as well as language and readability (0.79). The results of the practicality test showed an average score of 4.35 (87%), which is classified as very practical. The pretest-posttest results showed that the use of the SMARTECH e-module was associated with a significant increase in students' cognitive engagement, with $t(119) = 55.46$, $p < 0.001$, Cohen's $d = 0.97$, and N-gain = 0.44. Qualitative findings support these results, namely, students were more active in exploring various strategies, comparing representations, engaging in conceptual discussions, and being more persistent in solving non-routine problems. Thus, the SMARTECH e-module is declared valid, highly practical, and has the potential to increase students' cognitive involvement in mathematics learning in junior high school.

Keywords: e-module, SMARTECH, techno-mathematical literacy, cognitive engagement, design-based research

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INTRODUCTION

Digital transformation in mathematics education is increasingly recognized as a strategic necessity for preparing students to meet the literacy demands of the 21st century. However, the research results indicate that technology use in learning will not be optimal without an appropriate design aligned with student characteristics. In their meta-analysis, Hillmayr et al., (2020) found that the use of technology in mathematics and science learning in secondary schools had a positive impact on learning outcomes, with an average g of 0.65. The magnitude of this influence is strongly influenced by the implementation context (who uses it, organizational culture, infrastructure readiness, and the purpose of use), so the benefits of technology will vary depending on the setting and the problem. In contrast, Ran et al., (2021) found that the influence of technology on mathematics performance tended to be small (Hedges' g = 0.23), and its effectiveness depended heavily on the specific function and suitability of the technology for the stated instructional objectives, not simply on its presence. These findings suggest that technology will be more meaningful when positioned as part of the pedagogical design, rather than simply as an additional learning medium (Hillmayr et al., 2020; Ran et al., 2021).

Other meta-analyses indicate that the influence of technology is largely determined by the type of technology, the mathematics content, and the characteristics of the learners. The use of mobile learning showed a moderate positive effect on mathematics achievement, with a g = 0.476. However, this effect was moderated by content area, not by educational level or intervention implementer. This means that mobile learning is not equally effective for all mathematics topics. Meanwhile, regarding the use of artificial intelligence, a recent meta-analysis reported a positive effect of 0,343 on K–12 mathematics learning, with stronger results when AI was used as intelligent or adaptive learning systems. These findings confirm that technology is more effective when designed to provide adaptation, personalization, and cognitive support tailored to students' learning needs (Güler et al., 2022; Yi et al., 2025).

The use of technology is not just a medium for providing interactive content. However, it must be an integral part of pedagogical interventions that influence students' thinking processes and their understanding of mathematics. Digital teaching materials like this are one of the uses of technology in mathematics learning that have great potential to meet students' needs for more contextual, activity-based, and problem-solving-oriented mathematics learning (Bray & Tangney, 2017).

Based on this description, the research results consistently support the view that the use of technology in mathematics education is condition-dependent. While technology has the potential to improve learning outcomes, its effectiveness is not automatic. Stronger impacts tend to emerge when technology is integrated through designs that align with learning objectives, adapt to student characteristics, align with mathematical content, and are complemented by adequate feedback and scaffolding. Therefore, in mathematics education research, the focus of analysis should not stop at the question of whether technology is used, but rather how technology is designed, positioned, and operated to meaningfully support student learning.

One of the competencies relevant to technology-assisted mathematics learning is techno-mathematical literacy (TmL). TmL is the ability to use technology to solve mathematical problems by representing mathematical data, interpreting quantitative information from given data, and communicating the given information in written form (Sylviana Zanthy et al., 2023; van der Wal et al., 2023). A study in ZDM – Mathematics Education shows that TmL is very important in STEM practice and can facilitate technology-based learning strategies, making technology not just an option but a means of meaningful learning (van der Wal et al., 2019). Therefore, integrating TmL into mathematics e-modules has the potential to develop students' mathematical literacy skills and support the digital ecosystem in learning.

The effectiveness of digital learning depends not only on the quality of the material presented, but also on student engagement, especially cognitive engagement. Cognitive engagement is students' involvement in the learning process, including their use of learning strategies, their efforts to complete tasks, perseverance, and self-regulation when facing assigned tasks. Sinatra et al., (2015) emphasize that the definition and measurement of engagement must be clearly explained for research results to be valid and reliable. Self-regulation in cognitive engagement is an important mechanism in explaining how and why students can learn effectively (S. Li & Lajoie, 2022). Joshi et al., (2022) in their research showed that student engagement, including cognitive engagement, is a crucial factor in determining the quality of mathematics learning in a virtual environment.

Based on these conditions, this study aims to develop SMARTECH (an e-module integrated with TmL) to test its impact on the cognitive engagement of junior high school students. Conceptually, this e-module, SMARTECH, which integrates TmL, is viewed as an intervention that presents various technology-based tasks (e.g., representation exploration, data interpretation, modeling, and justification). The tasks included in the e-module are expected to enhance students' cognitive engagement through deeper learning strategies, higher mental effort, and perseverance in problem-solving. From this perspective, cognitive engagement is expected to emerge through deeper learning strategies, greater mental effort, and sustained persistence in problem-solving. In contrast, self-regulated learning (SRL) provides a process framework for understanding how students plan, integrate, and reflect on their learning during the intervention. Thus, the quantitative findings in this study are intended to demonstrate changes in students' cognitive engagement after the implementation of the SMARTECH e-module. In contrast, the qualitative findings are used to support and explain these changes by revealing how students understand the technology output, choose solution strategies, re-examine their reasoning, persist when faced with difficulties, and reflect on their learning experiences. By integrating quantitative and qualitative findings, this study provides a more comprehensive understanding of how the SMARTECH e-module, when integrated with TmL, supports changes in students' cognitive engagement in mathematics learning. The relationship between TmL and cognitive engagement aligns with the view that TmL is a meaningful learning technology, while cognitive engagement, including self-regulation, is a process framework that explains students' strategic involvement, monitoring, and reflection during learning (van der Wal et al., 2019).

The novelty of this research lies in positioning the SMARTECH e-Module not as a standard digital mathematics e-module, but as an intervention that explicitly makes TmL a core competency in junior high school mathematics learning. This distinction is important because the initial study by van der Wal et al. (2017) focused on introducing TmL for aspiring engineers and its development in the context of higher engineering education, rather than on it as a high school module integrated into the junior high mathematics curriculum. Their study also emphasized the compression, teaching strategies, and development of TmL measurement instruments for first-year students. In contrast, this research translates the TmL framework into e-module architecture tasks that require junior high school students to explore representations, interpret data, model, and justify technological outputs. Thus, technology in SMARTECH functions not only as a medium for presenting material or a procedural tool, but as an object of mathematical meaning deliberately designed to build junior high school students' reasoning. This position also distinguishes this study from other studies on digital mathematics learning environments that highlight design characteristics for discovery learning from students' perspectives, without positioning TmL as the main competency goal in module design (van der Wal et al., 2017).

Furthermore, this study treats cognitive engagement as the primary outcome to be measured directly, rather than simply learning achievement, orientation, or general perceptions of technology. This distinction is relevant because meta-analyses of technology in mathematics education have shown that prior studies have largely focused on achievement and orientation. In contrast, this study specifically examines how TmL-based interventions encourage deeper learning strategies, mental effort, monitoring, and student reflection. Its methodological novelty lies in the use of Design-Based Research (DBR) to produce two contributions simultaneously: learning products that can be used in real-world contexts and evidence-based design principles derived through the design, implementation, evaluation, and redesign cycle (Reeves & Reeves, 2023). Thus, this study's contribution extends beyond the development of digital teaching materials to the expansion of the technology-based mathematics learning design framework in junior high schools.

In the context of mathematics learning, the use of technology is often limited to accessing materials and practicing. At the same time, activities involving data interpretation, modeling, and mathematical argumentation have not become consistent learning practices. Furthermore, students' cognitive engagement tends to wane when they encounter non-routine problems or tasks that require strategy and reflection. This situation indicates the need for learning interventions that not only use technology as a medium of interaction but also guide students in using it to build mathematical reasoning. Therefore, the development of e-modules that are structured, contextual, and oriented towards the meaningful use of technology is relevant.

Based on the background outlined above, this study focuses on the following research questions:

1. What are the design characteristics of the SMARTECH e-module integrated with Techno-mathematical Literacy (TmL) developed for mathematics learning at the junior high school level?
2. To what extent does the developed SMARTECH e-module demonstrate appropriate content and design, based on expert assessments, and practicality for use in mathematics learning at the junior high school level?
3. What is the effect of the SMARTECH e-module integrated with TmL on junior high school students' cognitive engagement in mathematics learning, and how do the qualitative findings explain the quantitative results?

METHOD

Participants

The primary subjects of this study were 120 junior high school students in West Java from three schools in three different regions. This study did not involve a control class, as the focus of the research was to develop, test, and reflect on the use of the techno-mathematical literacy–integrated SMARTECH e-module in the context of real-world mathematics learning. The sample was selected using a purposive sampling technique. This technique was chosen because the sample must meet the following criteria:

1. Students are at the junior high school level, the target users of the e-module;
2. Students have or are currently studying the Pythagorean Theorem;
3. Schools have the necessary digital facilities to support the use of the e-module, such as learning devices and internet access;
4. Mathematics teachers are willing to assist with the implementation of the e-module; and
5. Students are able to participate in all research activities, including completing the instruments before and after using the e-module.

In addition to students, this study also involved 3 expert validators to assess the quality of the e-modules and research instruments, as well as mathematics teachers as implementation partners to provide input regarding the practicality of using e-modules in learning.

Research Design and Procedures

This research used a Design-Based Research (DBR) from Amiel & Reeves (Buhl et al., 2022), adapted for the context of mathematics learning in Indonesia, supported by mixed methods. This design was chosen because the research aims not only to produce an integrated SMARTECH e-module on techno-mathematical literacy, but also to test the product's quality and analyze changes in students' cognitive engagement. The research procedure was carried out in accordance with the following SMARTECH e-module development flowchart.

Stage 1: Problem Analysis and Exploration

In the initial stage, the researcher conducted an in-depth literature review on techno-mathematical literacy based on the framework of van der Wal et al., (2017), mapping teacher and student needs, analyzing the technological context and school infrastructure, and exploring teacher technological readiness and competency. The results of this stage were used to develop an initial conceptual framework for e-module development. This stage aimed to ensure that the developed product was truly relevant to the needs of mathematics learning in junior high schools.

Stage 2: Solution Design and Development

Based on the initial conceptual framework, the researcher designed the e-module structure, compiled learning materials, learning activities, supporting features, and research instruments. This stage resulted in an initial prototype of the SMARTECH e-module. The prototype was then validated by experts to assess the suitability of the content, design, language, and integration of techno-mathematical literacy. The validation results were used as the basis for revisions before the product was piloted.

Stage 3: Implementation and Iterative Evaluation

The revised prototype was implemented in the experimental group through a limited number of trials and field testing. At this stage, data were collected through questionnaires, observations, and interviews. To measure changes in students' cognitive engagement, a pretest was administered before the e-module was used and a posttest after its implementation. The implementation results were analyzed to assess the e-module's effectiveness, student responses, and areas for improvement. In the implementation phase, the observed changes in cognitive engagement following the SMARTECH e-module were evaluated using a one-group pretest-posttest design. In this design, students in the experimental group were given a baseline measurement before using the e-module and a final measurement after implementation. The quantitative data were then supplemented with qualitative data to provide a more comprehensive explanation of the quantitative results.

Stage 4: Reflection and Improvement of Design Principles

Data from the implementation stage were reflected upon to identify product weaknesses, barriers to use, and design elements that needed improvement. Based on the reflection results, the researchers revised the e-module and its design principles. This stage continued iteratively until the product met the established criteria.

Final Stage: Synthesis and Dissemination

After the entire cycle was completed, the researchers analyzed and reflected on the results of all stages to formulate generalizable design principles. If the evaluation results indicated that the product met the established criteria, the final

SMARTECH e-module was produced and then prepared for dissemination.

The implementation of Design-Based Research (DBR) in this study was adapted for the context of mathematics learning in Indonesia (Reeves & Reeves, 2023). This design was chosen because of its pragmatic, theory-based, interventionist, collaborative, and adaptive characteristics. These five characteristics are appropriate for developing and testing the SMARTECH e-Module as a mathematics learning solution that integrates techno-mathematical literacy, namely the ability to use digital technology for exploration, representation, and solving complex mathematical problems.

Instruments

To answer the research questions, a variety of validated data collection instruments were used, including: (1) Expert validation sheets, which consisted of four aspects: (a) Suitability of mathematical content, to assess the material's suitability to learning outcomes, conceptual accuracy, depth of discussion, mathematical representation, and the quality of examples and exercises. (b) TML Integration, to assess the extent to which the e-module integrates technology to support concept exploration, interpretation of digital output, modeling, reasoning, and mathematical justification within a technological-mathematical literacy framework. (c) Instructional Design & Activity Flow, to assess the clarity of objectives, systematic activities, scaffolding, readability of instructions, appropriateness of the learning flow to student characteristics, and support for cognitive engagement. (d) Language and Readability, to assess the e-module's linguistic feasibility, including sentence clarity, appropriateness of language to the developmental level of junior high school students, text readability, consistency of terminology, and clarity of instructions to support independent use of the module.

The instrument consisted of 30 statements with a 5-point Likert scale. The following is an example of the instrument on the validation sheet:

Table 1. Examples of instruments on the validation sheet

Dimensions	Statement
Suitability of Mathematical Content	The material presented aligns with the learning outcomes of junior high school mathematics.
	The mathematical concepts in the e-module are presented accurately.
Tml Integration	The e-module utilizes technology to support student learning.
	The integration of technology in the e-module aligns with the mathematics learning objectives.
Instructional Design & Activity Flow	The learning objectives in the e-module are clearly formulated.
	The integration of technology in the e-module aligns with the mathematics learning objectives.
Language And Readability	The language used is appropriate for the developmental level of junior high school students.
	The sentences in the e-module are clearly structured and easy to understand.

In this study, expert judgments were analyzed using Aiken's V to assess the content validity of the developed e-module. These results were used to demonstrate the appropriateness of the module's content and design based on expert judgment and its feasibility for implementation, not to establish the product's overall construct validity.

Practicality Questionnaire

This questionnaire was administered to students and teachers after implementation to assess the e-module's ease of use, clarity of instructions, attractiveness of the display, usefulness of the content, and its applicability to mathematics learning. This instrument covers four aspects: ease of use, clarity of instructions, encouragement of student engagement, and support for independent learning. These four aspects represent the e-module's ease of use, clarity of instructions and presentation of material, the e-module's ability to encourage student engagement, and its support for independent learning. The instrument consists of 32 statements with a 5-point Likert scale, including 16 positive and 16 negative statements. This questionnaire was used to obtain user perceptions of the practicality of the SMARTECH e-module in junior high school mathematics learning, and the results were analyzed descriptively. The following is an example of an instrument based on the practicality aspect:

Table 2. Examples of practical instruments

Aspects	Statements	
	Teacher	**Student**
Ease of Use	The features in the SMARTECH e-module make it easier for teachers to deliver the Pythagorean Theorem.	I found the SMARTECH e-module easy to use when learning the Pythagorean Theorem.
Instruction Clarity	The instructions in the SMARTECH e-module were unclear, potentially leading to learning errors.	I found the instructions in the SMARTECH e-module difficult to understand.
Encouraging Student Engagement	The SMARTECH e-module supports a more interactive learning environment.	e-module makes learning mathematics more engaging.
Supporting Independent Learning	The SMARTECH e-module forces students to remain highly dependent on teacher explanations.	When using the SMARTECH e-module, I often need help from the teacher or a friend.

Student Cognitive Engagement Test Instrument

The test instrument used to measure students' cognitive engagement before and after using the SMARTECH e-module consisted of a pretest and posttest. The questions in the SMARTECH e-module were developed according to techno-mathematical literacy indicators, namely: (a) technology-assisted mathematical exploration through exploring changes in the sides of a right triangle using a digital geometry application; (b) use and interpretation of digital representations through interpreting digital plans to determine diagonals using the

Pythagorean Theorem; (c) technology-based mathematical communication/argumentation through constructing mathematical arguments based on calculation results displayed by digital tools; and (d) complex problem solving through solving contextual problems. Test scores were calculated based on the number of correct answers obtained by students for essay-based questions. These scores were then used as primary data in the inferential analysis to test the effect of using the SMARTECH e-module on student learning outcomes. The following is an example of a question presented in the SMARTECH e-module:

Figure 1. Assignment display in e-module

Some examples of skills students develop in the SMARTECH e-Module: (a) Students can describe a written proof of the Pythagorean theorem using their own language and correct mathematical notation through interactive exploration activities. (b) Students can determine the distance between two points in Cartesian coordinates through simulations within the e-Module, providing a fun learning experience and increasing student engagement. (c) Students can solve contextual problems related to the Pythagorean theorem using the adaptive practice feature and construct mathematical arguments through virtual group discussions, honing their visual and numerical understanding of the concept. The entire learning process consists of 8 sessions, including pre-tests, material descriptions, practice questions, evaluations, and post-tests, delivered via the SMARTECH e-Module.

Cognitive Engagement Questionnaire

Students' cognitive engagement was measured using a questionnaire structured around four aspects: focus while studying, effort and persistence, thinking patterns during learning, and self-management skills. The instrument consisted of 24 statements arranged on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Each aspect consisted of six items: three positive statements and three negative statements. This questionnaire was used to determine the extent to which students were cognitively engaged while using the SMARTECH e-Module on the Pythagorean Theorem. The following is an example of the instrument:

Observation and Interview Sheets

Interview and observation data were analyzed thematically to explain the quantitative results. Thematic analysis was conducted through

Table 3. Example of the cognitive engagement questionnaire

Aspects	Statements
Focused Attention	When studying with the SMARTECH e-Module, I pay close attention to the material.
Effort And Persistence	I give up quickly if I don't find the answer right away.
Strategy Use/Deep Processing	I connect images, examples, and explanations to understand the material.
Self-Regulation In Learning	After studying, I double-check to see if I understand.

the following stages: familiarization with the data, coding, grouping codes into themes, reviewing themes, and defining the final themes. The emerging themes were then linked to patterns of change in students' cognitive engagement scores, for example, by examining similarities among students whose scores increased or decreased. Meanwhile, the observation strategy was implemented systematically, using observation guidelines based on cognitive engagement indicators, detailed field notes, and multiple observations at different times. The integration of quantitative and qualitative data was carried out at the final interpretation stage, so that changes in students' cognitive engagement were explained not only numerically but also from students' learning experiences while using the SMARTECH e-module, including students' emotional aspects, technical difficulties when using the SMARTECH e-module, and the learning strategies they used.

Data Analysis

Data analysis was conducted based on the focus of each problem formulation and the characteristics of the data obtained. This study included two main types of data: Likert-based questionnaire data and test results, which were analyzed using different approaches.

For the first research question, namely the characteristics of the e-module design, data were analyzed descriptively qualitatively based on the results of the needs analysis, development documents, reflection notes, observation results, and input from the validator. This analysis aimed to describe the design characteristics of the SMARTECH e-module being developed.

For the second research question, namely the validity and practicality of the e-module, data from the expert validation sheet and the practicality questionnaire were analyzed descriptively quantitatively. Each item used a 5-point Likert scale with a score range of 1–5. For positive statements, scores were assigned directly (1 = strongly disagree to 5 = strongly agree), while for negative statements, reverse scoring was performed (1 becomes 5, 2 becomes 4, 3 remains the same, 4 becomes 2, and 5 becomes 1). The final score for each respondent was calculated as the average across all items, yielding a single composite score per individual. Next, the score was converted into a percentage or interpretative categories, such as very valid, valid, practical, or feasible to use. This analysis did not involve inferential testing because it aimed to describe general response trends.

For the third research question, concerning the influence of the SMARTECH e-module on students' cognitive engagement, this study used test and non-test instruments. The test instrument, a pretest and posttest consisting of eight descriptive questions, was used to obtain quantitative data. In contrast, the non-test instrument, a student cognitive engagement questionnaire, was used as supporting data.

Quantitative data were analyzed using inferential statistics based on pretest and posttest scores calculated using an assessment rubric. Prior to hypothesis testing, a normality test was conducted. If the data were normally distributed, a paired-samples t-test was used; if not, a Wilcoxon signed-rank test was used. In addition, effect size calculations were performed to determine the magnitude of the influence of SMARTECH e-module use on student learning outcomes.

Non-test data were obtained through a student cognitive engagement questionnaire constructed using a 5-point Likert scale covering four aspects: focused attention, effort and persistence, strategy use (deep processing), and self-regulation. During data processing, negative statements were reverse-scored to ensure consistent interpretation, with higher scores indicating greater cognitive engagement. The total score was obtained by summing all statement items, and the results were analyzed descriptively using the average value and percentage for each aspect.

The results of the questionnaire analysis were used to support and strengthen the interpretation of the quantitative analysis results. Thus, changes in pretest and posttest scores were analyzed statistically and interpreted in relation to students' levels of cognitive engagement during the learning process. The integration of these two types of data provides a more comprehensive picture of the impact of the SMARTECH e-module on mathematics learning at the junior high school level.

■ RESULT AND DISCUSSION

Stage 1: Problem Analysis and Exploration

The initial stage of this research provided a conceptual foundation for developing the SMARTECH e-module grounded in techno-mathematical literacy. Based on a literature review informed by van der Wal et al.'s framework, effective mathematics learning emphasizes not only conceptual mastery but also the integration of mathematical modeling skills, digital technology, and data interpretation to solve contextual problems. Therefore, techno-mathematical literacy can be understood as the ability to connect mathematical concepts with the application of technology in everyday life.

These findings are reinforced by the results of a needs analysis, which showed that most teachers still experience limitations in integrating technology into mathematics learning. Teachers tend to use technology only as a presentation tool, not as a means of conceptual exploration or problem-solving. This situation indicates a gap between the demands of 21st-century learning and learning practices in the field. These findings align with research showing that technology integration in mathematics education still faces obstacles in pedagogical competence and digital learning design (Amaludin et al., 2025; Purohit et al., 2022; Viberg et al., 2023).

Conversely, student analysis indicates a high level of interest and readiness for using technology in learning. Students tend to be more interested in interactive and digital-based learning media than conventional methods. These findings indicate significant potential for developing digital teaching materials to increase student engagement and mathematical literacy. This is supported by research showing that technology integration, including artificial intelligence, can significantly improve problem-solving skills and mathematical literacy (Y. D. Li & Wu, 2025; Yavuz et al., 2025).

Furthermore, analysis of the school's technological context and infrastructure indicates that technological facilities are relatively available, but their utilization in mathematics learning is not optimal. This confirms that the primary problem lies not in the availability of technology, but in how it is integrated into meaningful learning designs. Based on these overall findings, the analysis results were then operationalized into the SMARTECH e-module design, which integrates techno-mathematical literacy principles into various learning components. These design characteristics include learning structure, material presentation, learning activities, interactivity, technological context, and support for student cognitive engagement. The detailed design characteristics of the SMARTECH e-module are presented in Table 4.

Table 4. Design characteristics of the SMARTECH e-module

Design Components	Key Characteristics	TML Integration
Learning Structure	Structured in a sequence of orientation, concept exploration, structured exercises, reflection, and evaluation.	Encourages students to understand concepts through the stages of systematic thinking.
Material Presentation	Material is presented in concise text, visual illustrations, and contextual examples.	Connects mathematical concepts to the use of technology in everyday life.
Learning Activities	Includes problem-solving tasks, digital media-assisted exploration, and interactive quizzes.	Develops the ability to analyze mathematical problems in a technological context.
Interactivity	Self-navigation, immediate feedback, and adaptive exercises.	Helps students reflect on their thinking processes and problem-solving strategies.
Technological Context	Problems are linked to the use of applications, digital data, measurements, or technological representations.	Fosters connections between mathematics, technology, and decision-making.
Cognitive Engagement Support	Includes prompting questions, reflective tasks, and tiered challenges.	Encourages students' attention, mental effort, learning strategies, and persistence.

Based on Table 4, each component of the SMARTECH e-module design is systematically designed to integrate mathematics and technology into learning. This design emphasizes not only the delivery of material but also the guidance of students' thinking processes through structured, meaningful learning stages. Furthermore, the analysis shows that junior high school students need digital learning materials that are easily accessible, visually appealing, and able to connect mathematical concepts to the technological context of everyday life. Teachers also emphasize the importance of learning materials that can support independent learning, provide step-by-step exercises, and encourage active student engagement.

This direction of the SMARTECH e-module development aligns with previous research findings, which confirm that the effectiveness of technology in mathematics learning is highly dependent on the instructional design used. Research findings indicate that the use of digital technology will be more meaningful when explicitly integrated into learning activities, not simply as a tool for presenting material (Cirneanu & Moldoveanu, 2024; Rohmatulloh et al., 2022). Furthermore, recent studies have confirmed that a problem-based approach and real-world contexts in e-modules can enhance student engagement and conceptual understanding.

Thus, the systematic, interactive, and contextual design characteristics of the SMARTECH e-module demonstrate its suitability with the direction of digital teaching materials development in international literature. This e-module not only functions as a medium for delivering material, but also as a means to facilitate the development of students' mathematical literacy through technology integration. Overall, this problem analysis and exploration stage resulted in an initial conceptual framework for developing a techno-mathematical literacy-based e-module that integrates mathematical concepts, digital technology, and real-life contexts. This framework is designed to bridge the gap between students' high readiness for technology and teachers' limitations in implementing it in learning. Therefore, the SMARTECH e-module is expected to be a relevant, adaptive, and effective innovation in teaching materials for improving students' mathematical literacy.

Stage 2: Solution Design and Development

The design and development stage of this research resulted in an initial prototype of the SMARTECH e-module, systematically constructed based on a Techno-mathematical Literacy (TmL) framework and student cognitive engagement. At this stage, each component of the e-module, from material development and activity design to technology integration, was consciously designed to represent the relationship between mathematical concepts and the use of technology as a means of thinking.

Specifically, the e-module design emphasized three main principles: (1) conceptual fit, through the development of materials and tasks aligned with the structure of mathematical knowledge; (2) TmL integration, through technology-based exploration and interpretation activities; and (3) a progressive instructional flow, through stages of exploration, elaboration, and reflection. Furthermore, the language aspects were designed to be communicative to suit the cognitive characteristics of junior high school students. Thus, the development stage not only produced a product but also built a strong theoretical and pedagogical foundation.

The quality of the design process was then tested through expert validation as part of the Design-Based Research (DBR) framework, which emphasizes the importance of alignment between design and theory before implementation (Mckenney & Reeves, 2018; Tinoca et a., 2022). The expert validation results for the SMARTECH e-module are presented in Table 5.

Table 5. Summary of expert validation results

Aspects	Total Score	Mean	Aiken's V	Categories
Mathematics Content Suitability	126	4.20	0.80	valid
TML Integration	126	4.20	0.80	valid
Instructional Design and Activity Flow	126	4.20	0.80	valid
Language and Readability	125	4.17	0.79	valid

As shown in Table 5, the assessment results of the three expert validators indicate that the module has adequate evidence of content validity. The average Aiken's V score for the mathematical content suitability aspect falls within the valid category. This indicates that the material, examples, and assignments presented in the SMARTECH e-Module align with the objectives of junior high school mathematics learning and do not deviate from the expected conceptual structure and procedures. Research findings by (Bray & Tangney, 2017; Ran et al., 2021) revealed that in technology-assisted learning, content inaccuracies can lead to cognitive overload and misunderstandings, thus hindering student cognitive engagement. Therefore, the relatively high content validity of the SMARTECH e-Module serves as an important foundation for developing TmL activities and higher-order thinking processes.

Regarding the suitability of the mathematical content, the high validity value indicates that success at this stage is evident in the preparation of materials and assignments aligned with the Pythagorean Theorem. This means that applying the principle of conceptual suitability during the design stage directly impacts the quality of the e-module content. This finding is important because errors in the content design stage can increase students' thinking load and lead to misunderstandings in technology-based learning (Cirneanu & Moldoveanu, 2024; S. Li & Lajoie, 2022; Malik, 2023; Vieriu & Petrea, 2025).

Furthermore, high validity in the TmL integration aspect indicates that the developed activities successfully implemented TmL in the learning process. This means that, from the design stage, the use of technology through exploratory activities was appropriate and proved feasible, according to expert assessments. This finding confirms that the successful use of technology in learning depends not only on the technology itself, but more on how the technology is designed to support students' mathematical thinking processes (Drijvers & Sinclair, 2024).

In terms of instructional design and activity flow, high validation results indicate that the progressively designed learning structure through stages of exploration, elaboration, and reflection aligns with the principles of effective pedagogy. Thus, validity in this aspect can be seen as evidence that the instructional design planned during the development stage was successfully translated into a logical and easy-to-follow product for students. This aligns with research emphasizing that instructional design quality is a key factor in enhancing cognitive engagement in digital learning (S. Li & Lajoie, 2022).

Meanwhile, regarding language and readability, the validation results remained in the valid category, indicating that considering communicative language use during the design stage contributed to the clarity of the material's delivery. Although the score was slightly lower than other aspects, this indicates that the language aspect still has room for improvement, without compromising the overall feasibility of the product. From a learning theory perspective, readability is a crucial factor because overly complex language can divert students' cognitive resources from processing mathematical concepts to understanding the text, thereby reducing their cognitive engagement (S. Li & Lajoie, 2022; Sinatra et al., 2015). Therefore, the strong language validity of the SMARTECH e-Module is expected to support the creation of a learning environment conducive to mathematical exploration, reflection, and justification.

Overall, the relationship between the design stage and validity results in this study indicates that design quality directly determines the quality of the resulting product. This finding reinforces the DBR principle that validity is not merely a final evaluation result but a reflection of the accuracy of the design process.

Overall, Table 5 shows that the SMARTECH e-Module demonstrates strong, comprehensive validity across all aspects. This indicates that the product consistently represents the theoretical foundations used, namely Techno-mathematical Literacy (TmL) and cognitive engagement, and is ready further implementation with minor revisions. Within the DBR framework, this high level of validity strengthens the SMARTECH e-module's position as a digitally valid teaching resource, grounded in sound pedagogy, that supports technology-based mathematics learning junior high school students.

Furthermore, the novelty of this research lies in its explicit linking of the TmL-based design to empirical evidence of its validity, thereby demonstrating that techno-mathematical literacy can be implemented operationally as a structured e-module. This provides a theoretical contribution by clarifying how the TmL concept can be translated into a valid learning design, while also providing practical implications for the development of digital teaching materials in mathematics education. However, these results are still limited to the expert validation stage. Therefore, further research is needed to assess the extent to which these validated design qualities affect students' TmL abilities and cognitive engagement in real-world learning contexts.

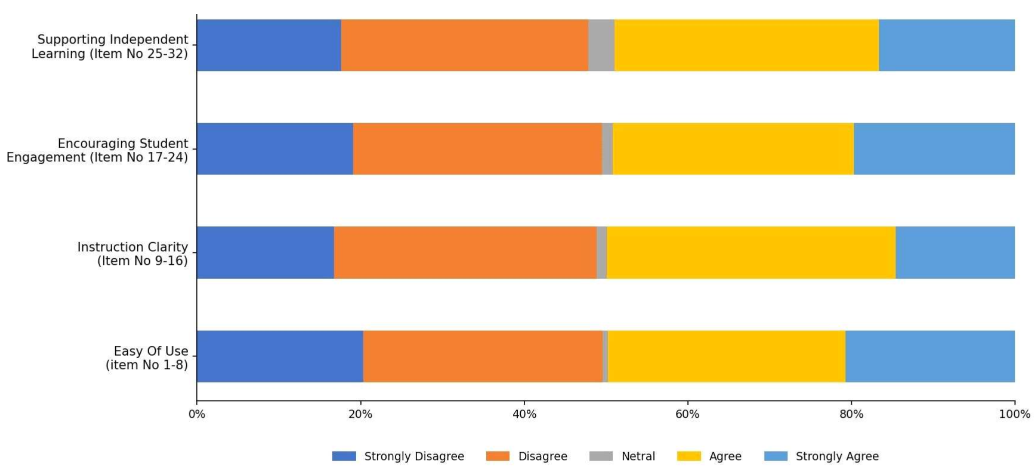
Stage 3: Iterative Implementation and Evaluation

The iterative implementation and evaluation stages of this study focused not only on measuring learning outcomes but also on gaining a deeper understanding of students' learning experiences while using the SMARTECH e-module. Therefore, qualitative analysis was essential to uncover how the SMARTECH e-module was used in real-world contexts and how students responded to its use. Qualitative data were obtained through student questionnaires, observations of learning activities, and interviews.

Within the design-based research (DBR) framework, practicality is a crucial element that bridges the gap between design quality and the feasibility of implementing an intervention in the classroom. Therefore, interventions need to be tested so that product development is based on empirical evidence from field use (McKenney & Reeves, 2018; Reeves & Reeves, 2023). From an implementation perspective, high practicality results can strengthen the SMARTECH e-module's conceptual plausibility and its realistic use in the classroom. These findings align with research by Rahmatullah et al. (2020), which demonstrated that mathematics e-modules can support student learning. Similarly, several other studies emphasize that meaningful and engaging digital learning materials, clear design, and user evaluation are crucial for improving the quality of mathematics learning (Hidayat et al., 2022; Hillmayr et al., 2020; Rohmatulloh et al., 2022). In other words, the findings in this study reinforce that the SMARTECH e-modules are not only visually appealing and engaging but also implementable by students and

teachers.

To illustrate the practicality of the SMARTECH e-modules, student responses are presented in the following figure.



	Easy Of Use (item No 1-8)	Instruction Clarity (Item No 9-16)	Encouraging Student Engagement (Item No 17-24)	Supporting Independent Learning (Item No 25-32)
Strongly Disagree	20.31	16.77	19.06	17.60
Disagree	29.27	32.08	30.42	30.21
Netral	0.63	1.25	1.35	3.23
Agree	29.06	35.31	29.48	32.29
Strongly Agree	20.73	14.58	19.69	16.67

Figure 2. Student response results based on practicality aspects

The practicality test results, as shown in Figure 2, present the distribution of student responses to the learning media across four aspects: ease of use, instructional clarity, encouragement of student engagement, and support for independent learning. It is important to note that the agree and strongly agree responses are derived from students' responses to positive statements, the disagree and strongly disagree responses are derived from students' responses to negative statements, and the neutral response is a combination of both. Furthermore, the mean score was calculated after reverse scoring, so that all scores were in the same direction (higher scores indicate more positive perceptions). Overall, the mean scores for all four aspects ranged from 4,29 to 4.41, indicating that the learning media was in the good category.

However, the percentage distribution for each aspect showed a relatively balanced pattern between responses to positive and negative statements. For the ease-of-use indicator, for example, 49.58% responded to negative statements compared to 49.79% to positive statements, with a mean of 4.41. This pattern indicates that ease of use is not yet fully perceived equally by all students. When linked to cognitive engagement, ease of use is a crucial prerequisite for students to allocate their cognitive resources to understanding the material rather than figuring out how to use the media. Therefore, for some students who still experience technical difficulties, cognitive engagement can be hampered because cognitive load is divided between the technical aspects and the learning content. This finding aligns with research showing that less intuitive technology design can reduce students' cognitive focus on learning (Getenet et al., 2024).

A similar trend was observed in instructional clarity, where 48.85% of responses to negative statements and 49.89% to positive statements resulted in a mean of 4.32. Interpretatively, this indicates that instruction clarity is not yet optimal for all students. In the context of cognitive engagement, instruction clarity is a crucial factor in technology-based mathematics learning, as unclear instructions can lead to student confusion and hinder the achievement of learning objectives. Therefore, the variation in responses in this aspect suggests that some students may not have achieved optimal levels of cognitive engagement due to differences in understanding the instructions contained in the SMARTECH e-module. This finding aligns with research showing that the effectiveness of technology in learning is highly dependent on its pedagogical function in guiding student learning activities (Molina et al., 2022).

Furthermore, regarding student engagement, the distribution of responses showed 49.48% negative and 49.17% positive statements, with the highest mean of 4.38. This indicates that the SMARTECH e-module can increase students' interest in learning mathematics, foster motivation to learn, and encourage greater activity during the learning process. These findings indicate that the e-module serves not only as a medium for delivering material but also as a means to increase student engagement (Balalle, 2024).

The questionnaire results were supported by observational findings, which showed that students were more active in learning, such as asking questions, discussing, and attempting to solve problems independently. These activities reflect higher cognitive engagement, characterized by analytical and reflective thinking processes during learning.

Furthermore, interview results indicated that students felt the e-module helped them understand concepts more systematically and engagingly. Students stated that the varied solution steps and exercises helped them not only memorize but also understand the concepts being learned. This demonstrates that the SMARTECH e-module can create a meaningful learning experience.

Meanwhile, regarding the aspect of supporting independent learning, the distribution of responses showed 47,81% for negative statements and 48,96% for positive statements, with a mean of 4,29, the lowest score. This indicates that support for independent learning is not optimal for all students. From a cognitive engagement perspective, independent learning is closely related to self-regulated learning, namely students' ability to plan, monitor, and evaluate their learning process. The variation in responses in this aspect indicates that not all students can optimize the media's role in supporting this process. Recent research has shown that cognitive engagement is strongly influenced by self-regulation skills and the support of an adaptive learning system (Mohammadi Zenouzagh et al., 2025).

Overall, these qualitative results demonstrate that the SMARTECH e-module is highly practical and capable of supporting student engagement in learning. These findings align with research showing that digital teaching materials designed in an engaging, clear, and user-friendly manner can improve the quality of mathematics learning (Harisman et al., 2025; Hillmayr et al., 2020; Rahmatullah et al., 2020). Therefore, based on the qualitative analysis, the SMARTECH e-module is not only feasible in design but also implementable in a real-world learning context.

Theoretically, this reinforces the view that student engagement in digital learning is a complex phenomenon shaped by the interplay among technology, pedagogy, and individual characteristics. In practice, these findings suggest that the development of learning media should prioritize more adaptive, inclusive, and user-centered designs, thereby narrowing the learning experience gap and improving overall learning effectiveness.

These findings reinforce the idea that the success of a learning innovation is determined not only by content validity but also by practicality and user experience during learning. However, to strengthen these qualitative findings, this study also conducted a quantitative analysis of students' cognitive engagement test results. In this study, cognitive engagement was not measured separately from the mathematics learning context but was operationalized through a cognitive engagement test instrument developed from techno-mathematical literacy (TmL) indicators. Thus, the pretest, posttest, N-Gain scores, hypothesis tests, and effect sizes in Table 6 represent students' achievements on the techno-mathematical literacy-based cognitive engagement test instrument.

Table 6. Recapitulation of student cognitive engagement test results developed from TmL

Analytical Aspect	Indicators	Value
Descriptive Statistics	N	120
	Mean Pretest	6.04
	SD Pretest	1.20
	Mean Postest	7.21
	SD Posttest	1.22
N-Gain	Mean N-Gain	0.44
Hypothesis testing	t test	55.46
	Df	119
	Sig (p-value)	0.00
Effect Size	Cohen's D	0.97

Based on Table 6, the average student score increased from 6.04 in the pretest to 7.21 in the posttest. This increase indicates higher cognitive engagement scores among students after using the SMARTECH e-module. In the context of this study, cognitive engagement refers to students' ability to understand, process, connect, and apply mathematical concepts through techno-mathematical literacy-based activities. Therefore, this increase in scores not only indicates improved test results but also reflects increased student cognitive engagement in technology-based mathematics learning.

The average N-Gain value of 0.44 indicates that the increase in score is in the moderate category. Furthermore, the t-test results showed a significant difference between the pretest and posttest scores ($p < 0.05$). This indicates that the increase in scores after using the SMARTECH e-module was not coincidental but related to the learning treatment provided. Furthermore, Cohen's d effect size of 0.97 falls in the large category, indicating that the use of the SMARTECH e-module has a strong influence on increasing students' cognitive engagement. This finding aligns with John Hattie's (Yan, 2023) view that an effect size above 0.8 reflects a high learning impact. Thus, the results of this study indicate that the use of e-modules is an effective approach in improving students' mathematics learning outcomes.

Thus, it should be emphasized that Table 6 does not measure general learning outcomes, but rather measures the results of a student cognitive engagement test, the instrument of which was developed from techno-mathematical literacy indicators. The term "learning outcomes" in this discussion is used narrowly to refer to students' scores on the instrument. Therefore, these quantitative findings indicate that the SMARTECH e-module is effective in increasing student cognitive engagement.

This improvement is inseparable from the SMARTECH e-module's characteristics, which are designed to facilitate independent, flexible, and interactive learning. The systematic presentation of material, the use of visual representations, structured exercises, and the provision of feedback encourage students to be more active in processing information. This finding aligns with research by Fredricks et al., (2019), which states that cognitive engagement is a crucial factor in improving learning outcomes.

Cognitive engagement is not just an activity but a reflection of it, such as elaborating concepts, monitoring understanding, using problem-solving strategies, and revising understanding when facing difficulties. Therefore, interventions that require elaboration, monitoring, and revision of strategies are more likely to increase student cognitive engagement (Sinatra et al., 2015). Interactive digital learning environments can encourage higher-order thinking in students (Bian & Zaid, 2025; Luo et al., 2025; Rakhmetov et al., 2025).

In the context of mathematics learning, particularly with the Pythagorean theorem, cognitive engagement is crucial because students are not only required to memorize formulas but also to understand relationships among concepts, interpret visual representations, and apply them in problem-solving. Therefore, the increase in pretest-to-posttest scores indicates that the use of the SMARTECH e-module can support students' thinking processes more actively and deeply. The results of this study align with other findings showing that the use of digital media in geometry learning can improve students' conceptual understanding and spatial abilities (Adams et al., 2023; Fitriyani & Kusumah, 2023; Jablonski & Ludwig, 2023; Lowrie et al., 2017; Scippo et al., 2025). Furthermore, Pratama & Darojat (2025) also reported that visualization-based e-modules significantly increased student engagement and learning outcomes. Thus, SMARTECH e-modules serve not only as a medium for conveying information but also as a means to develop students' conceptual understanding more deeply.

However, this study used a one-group pretest–posttest experimental design without a control group. These limitations warrant consideration because they allow uncontrolled external variables, such as prior learning experiences, student motivation, or other environmental factors, to influence the results. Therefore, interpretation of the research results requires caution. Nevertheless, the strength of this study's findings is supported by consistency across indicators, including increases in average grades, a relatively high N-Gain value, and a large effect size. Furthermore, these results are consistent with previous research demonstrating the effectiveness of e-modules in improving learning outcomes, despite using similar designs (Bond et al., 2021; Sofiah et al., 2025).

Furthermore, compared with previous research, this study's results demonstrate consistent effectiveness of e-modules for mathematics learning. However, several other studies have shown that the effectiveness of digital-based learning can vary depending on the instructional design, student characteristics, and the quality of interaction in the learning process. Therefore, the success of the SMARTECH e-module in this study may also be influenced by the module's interactive design and its ability to optimally encourage student cognitive engagement.

Overall, the results of this study indicate that SMARTECH e-module-based learning has significant potential to improve student learning outcomes and cognitive engagement. Despite limitations in the research design, the findings still provide significant theoretical and practical contributions and can serve as a basis for developing future research and learning practices.

Improved learning outcomes are also evident in the scatterplot visualization between pretest and posttest scores. Figure 3 shows that the data points form a positive linear trend with an upward trendline. This indicates that the higher the pretest score, the higher the posttest score achieved by students. The distribution of points, which generally follows the trendline, indicates that learning outcomes improved fairly consistently for most students. This relationship pattern can be seen in Figure 3.

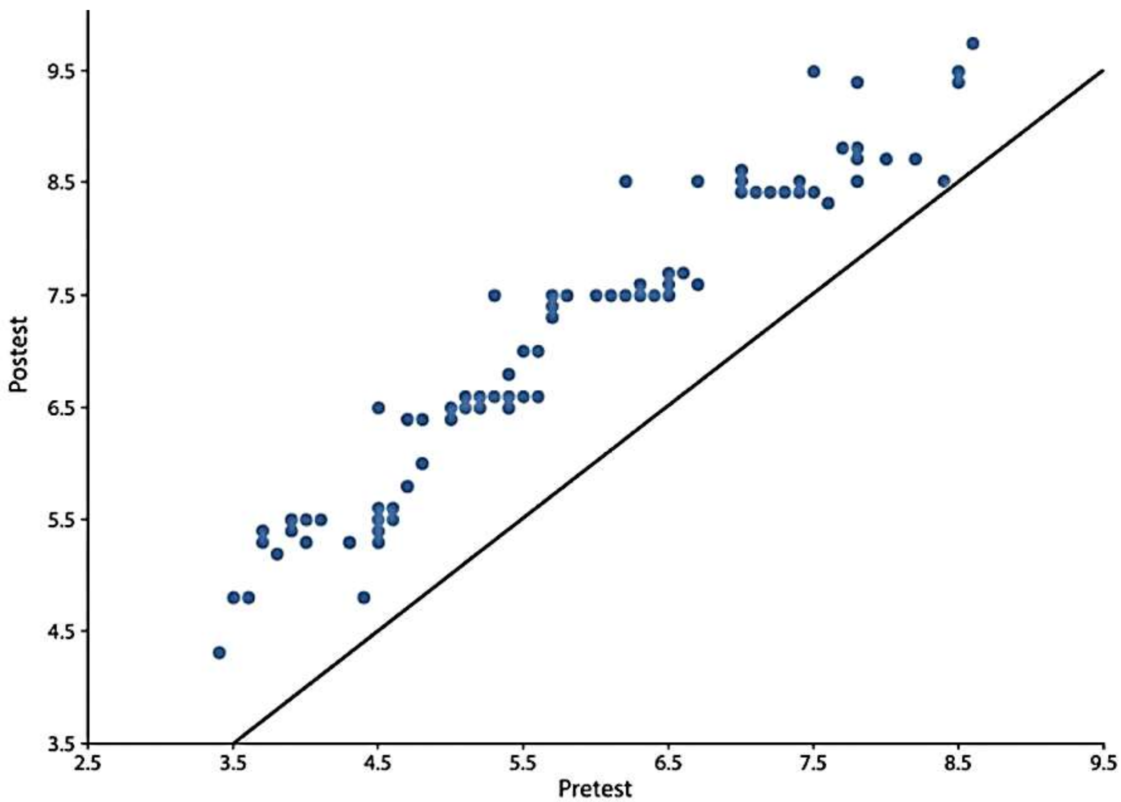


Figure 3. The relationship between pretest and posttest scores of students' cognitive engagement

Based on Figure 3, a positive linear relationship pattern is seen between pretest and posttest scores. The distribution of data that follows a trend line indicates that learning outcomes improved consistently among most students after using the SMARTECH e-module. This indicates that the intervention had a relatively even impact on increasing students' cognitive engagement. To provide a more detailed picture of the treatment's impact on each indicator of cognitive engagement, the results of the improvement are presented not only in tabular form but also as a bar chart (Figure 4). This visualization aims to clarify the comparison of the average pretest and posttest scores and the N-gain value for each measured indicator.

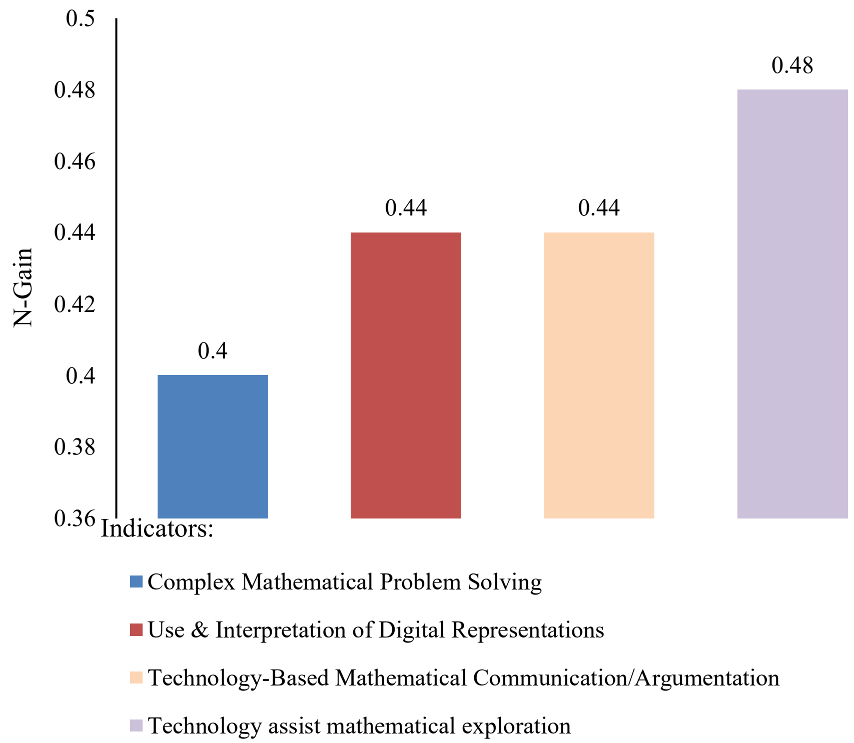


Figure 4. N-gain value based on indicators

Figure 4 shows that all TmL indicators experienced moderate improvement, with varying N-gain values for each indicator. The Technology-Assisted Mathematical Exploration indicator achieved the highest score of 0.48, followed by Use & Interpretation of Digital Representations and Technology-Based Mathematical Communication/Argumentation, each with 0.44, and Complex Mathematical Problem Solving, with the lowest score of 0.40. Overall, this pattern indicates that the SMARTECH e-module positively impacts students' cognitive engagement, but its effectiveness varies by the type of skill being developed.

The largest increase in the technology-assisted mathematical exploration indicator suggests that students are beginning to use technology as a tool for active exploration of concepts, rather than simply following procedures. This indicates a shift from mechanical use of technology to more conceptual and investigative use. These findings align with research showing that digital technology can encourage exploration- and inquiry-based learning, thereby enhancing conceptual understanding and student engagement in the mathematics learning process (Bian & Zaid, 2025; Cheng et al., 2023; Ran et al., 2021). Furthermore, the use of interactive media has also been shown to facilitate deeper visualization and manipulation of concepts.

In the technology-based mathematical representation and communication indicators, relatively balanced improvements indicate that students are becoming more skilled at reading, interpreting, and explaining information presented in digital formats such as graphs, tables, and models. This indicates that integrating multiple representations in e-modules significantly contributes to students' conceptual understanding and mathematical communication skills. These findings are supported by research suggesting that digital technology plays a crucial role in helping students understand abstract concepts through visual representations and strengthening mathematical argumentation skills through interpretive activities (Luo et al., 2025; Molina et al., 2022).

Meanwhile, the complex problem-solving indicator showed the smallest improvement among the indicators. However, this improvement remained in the moderate category, indicating that the e-module continues to contribute to the development of this skill. Theoretically, this result is understandable because complex problem-solving is a high-level skill that requires integrating multiple concepts and strategies and engaging in in-depth reflection. Recent research indicates that developing this skill requires a longer period of time and a more intensive and sustained learning design (Bian & Zaid, 2025; Rakhmetov et al., 2025).

Within the TmL framework, these four indicators are highly important and interrelated. Interpretively, this pattern suggests that the SMARTECH e-Module can encourage a shift in students' abilities from low-function use of technology in learning to using technology as a tool for mathematical exploration, interpretation, and communication. This aligns with the view that TmL is a form of "functional mathematical knowledge" mediated by tools and rooted in the context of use, thus requiring activities that explicitly demand an understanding of technological outputs (van der Wal et al., 2017). Furthermore, these findings are consistent with the argument that the effects of technology in mathematics learning depend on the technology's "function" and "role." When technology is used to enhance representation, visualization, and conceptual exploration (rather than simply practice), its impact on learning tends to be more significant. Research in the K-12 context suggests that variations in technology's effects are influenced by how the technology is used and the learning objectives it achieves (Ran et al., 2021).

Overall, the pattern of improvement in Figure 4 indicates that learning technology tends to have a stronger initial impact on exploration and representation than on higher-order strategic skills. This indicates that the use of the SMARTECH e-module has successfully guided students toward more active, exploratory, and conceptually-based learning. Thus, these results reinforce the view that the effectiveness of technology in mathematics learning depends heavily on how it is used to support students' cognitive activities, rather than simply as a means of conveying information (Ran et al., 2021).

To strengthen the interpretation of the quantitative results, the analysis was supplemented with qualitative data obtained from a student cognitive engagement questionnaire. The descriptive analysis showed that students' cognitive engagement was high, particularly in terms of focused attention (mean = 4.32) and strategy use (deep processing) (mean = 4.23). Students tended to pay close attention during learning and were able to connect various representations, such as images, examples, and explanations, to understand concepts. Furthermore, self-regulation (mean = 4.04) also showed positive results, as evidenced by students' habitual re-checking of their understanding after learning. However, regarding effort and persistence (mean = 3.83), some students still tended to give up easily when faced with difficulties.

Theoretically, these findings can be explained by the concept of cognitive engagement, which emphasizes students' active role in the deep processing of information. High levels of focused attention and strategy use indicate that students are not only superficially engaged but also engage in more complex processing. This aligns with the view that high cognitive engagement contributes to improved learning quality, as students actively construct conceptual understanding. Thus, the improvement in students' test results can be understood as a consequence of increased cognitive engagement during learning.

From a Techno-mathematical Literacy (TmL) perspective, the SMARTECH e-module serves as a medium that not only delivers material but also facilitates active student engagement. The integration of interactive features, structured presentation of materials, and visual representations in the e-module enables more meaningful interactions between students and the learning materials. This supports students' focus, the use of deeper learning strategies, and the development of self-regulation skills. In other words, the technology in the e-module serves not only as a medium for conveying information but also as a means of facilitating students' cognitive processes.

However, findings on the effort and persistence aspects indicate that not all dimensions of engagement are developing optimally. This indicates that internal student factors, such as motivation and resilience in the face of difficulties, remain challenges in e-module-based learning. Therefore, design enhancements are needed, for example, through adaptive feedback, scaffolding, or features that encourage students to persist in completing tasks.

Overall, the integration of quantitative and qualitative results indicates that the SMARTECH e-module not only affects students' test performance but also improves the quality of the learning process through greater cognitive engagement. Thus, these findings provide empirical support for the effectiveness of e-module design integrated with the TmL approach in increasing students' cognitive engagement, ultimately impacting learning outcomes.

Stage 4: Reflection and Improvement of Design Principles

The reflection at this stage integrated quantitative and qualitative findings to identify strengths, weaknesses, and areas for improvement in the design of the SMARTECH e-module. Quantitatively, the increase in students' cognitive engagement following implementation of the e-module indicated that the designed intervention had a positive impact. However, the meaning of these results becomes clearer when analyzed alongside qualitative findings describing actual changes in students' learning behavior.

The reflection results revealed several key patterns of change in student learning behavior, as follows.

Students More Often Try Multiple Strategies Before Asking Questions

When working on problem-solving exercises, several students were seen revisiting the example sections of the e-module, trying at least two different solutions from their notebooks and other sources, and then discussing their results with their group mates before raising their hands to ask the teacher. When experiencing difficulties, students did not immediately ask the teacher for the answer. Instead, they first tried the problem more than once using various methods, reviewed the steps they had taken, and then discussed the results with their group mates. These findings support the quantitative results, which showed an increase in students' use of learning strategies and mental effort in solving math problems, as well as a significant increase in cognitive engagement. This behavior is important because cognitive engagement is characterized not only by attention but also by students' willingness to actively process problems before seeking help. Thus, the SMARTECH e-module helps encourage deeper cognitive engagement. These findings indicate that the scaffolding design in the e-module has been effective. This is in line with research showing that technology-based learning can improve students' self-regulated learning and cognitive engagement (Helme & Clarke, 2001; Lo & Hew, 2020; Shao et al., 2025).

Students Compare Various Representations to Understand Concepts

The second finding indicates that students are beginning to use multiple forms of representation to understand and draw conclusions from the material. In some activities, students not only focus on the final answer but also compare information presented in tabular form. This is an important indicator of deeper cognitive processing. This finding aligns with a study by Hidayat et al.(2022) which suggests that meaningfully designed e-modules can support students' mathematical reasoning. Furthermore, Kumalasari et al. (2025) suggest that interactive e-modules have the potential to support mathematical problem-solving because the presentation of material is more responsive to students' learning needs. Thus, the use of various representations in SMARTECH is likely one mechanism explaining the increase in students' cognitive engagement.

In the conclusion-drawing activity, before presenting their conclusions to the class, students observed triangles on the SMARTECH e-module screen. They matched them to the values from their group's calculations. These findings suggest that increased cognitive engagement manifests not only in closer attention but also in students' ability to actively process and connect various mathematical representations.

Group Discussions Focus More on the "Process" than the "End Result."

There has been a change in the quality of group discussions, from simply seeking answers to discussing the solution process. Students have begun to actively argue, justify, and evaluate the steps to solving problems.

The third finding indicates a significant change in the quality of student group discussions, namely a shift from an orientation toward a final answer to a focus on the reasoning process. During use of the SMARTECH e-module, discussions were no longer dominated by attempts to obtain numerical results alone. However, they began to focus on the rationale behind each step in the solution. Students actively discussed why a formula was used, how the solution steps were carried out, and the relationship between the Pythagorean Theorem and the problems presented in the SMARTECH e-module. One student stated: "Now we don't just look for the answer, but also want to understand the reasoning behind using that formula. If we don't understand, we usually ask our friends again." This shift demonstrates the growing cognitive engagement of students, which recent research has shown to strongly correlate with the quality of mathematics understanding and learning outcomes (Papageorgiou et al., 2025).

This change was also reflected in the dynamics of interactions during group discussions. Based on observations, student conversations were more characterized by reflective questions that emphasized the thinking process. The following is an excerpt from a student conversation in one group:

Student A: "Why do you use this side?"

Student B: "Because this is the hypotenuse, the longest one."
Student A: "Oh, the hypotenuse is the one opposite the right angle, right?"
Student B: "Yes, that's why it becomes c in the formula."

This dialogue shows that students actively construct understanding through social interaction. This finding aligns with current trends in mathematics education research that emphasize the importance of discussion, argumentation, and reasoning in learning (Cevikbas et al., 2024).

Furthermore, students also demonstrated the ability to evaluate and validate the solution steps. Here are excerpts from other student conversations.

Student C: "Why do we have to square it first?"
Student D: "Because the formula says a squared plus b squared,"
Student C: "So why do we have to square it later?"
Student D: "So we can get back to the original side length."

In fact, some students in other groups verified the equation before using the formula.

Student E: "Can we use Pythagoras directly?"
Student F: "Don't do it straight away; first check whether this is a right triangle or not."

This pattern indicates the development of higher-order thinking skills, particularly analysis and evaluation, which are essential components of mathematical reasoning. This is supported by research by Shao et al. (2025), which states that the use of interactive digital media, such as e-modules, can improve students' metacognitive abilities and understanding of mathematical concepts.

Furthermore, interview results indicate an increase in students' metacognitive awareness. The following is an excerpt from another student's interview response when asked how they solved problems in the SMARTECH e-module.

Student G: "I used just to use the formula, but now I think first about whether this is a right triangle."
Student H: "If the answer is different, we discuss the method again. Sometimes the mistake is in the steps, not the calculations."

This is reinforced by observations when students check each other's work, as in the following conversation:

Student I: "Why are our results different?"
Student J: "Check the steps again, maybe I made a mistake in the calculations."

These findings indicate that students are beginning to monitor and evaluate their own thinking processes. Recent research also shows that interactively designed e-modules can improve students' metacognition and critical thinking skills (Sofiah et al., 2025).

Although several previous studies have demonstrated that e-modules can improve learning outcomes and problem-solving skills, other research reveals that most of these studies still focus on quantitative aspects (Firmansyah et al., 2025; Putra et al., 2025). These studies tend not to fully explore how e-modules directly affect the quality of discussion interactions and students' reasoning processes. Thus, there is a research gap in understanding how digital learning media contributes to transforming students' academic interaction patterns, particularly in mathematics learning. In this context, this study offers a novel contribution by demonstrating that the use of SMARTECH e-modules not only improves learning outcomes but also transforms the quality of student discussions, making them more problem-oriented. Specifically, this study reveals that students not only exchange answers but also engage in collaborative argumentation, justification, and concept verification. Findings: This strengthens and expands the results of previous research by providing empirical evidence based on qualitative data in the form of authentic student dialogue that reflects the process of knowledge construction.

These findings align with Helme and Clarke's framework, which states that cognitive engagement is related to the quality of students' interactions with mathematics tasks. They also align with Lo and Hew's findings that more active and interactive learning activities can enhance cognitive engagement. In this study, the discussion's focus on "process" indicates that the e-module successfully encouraged students to engage in more reflective and conceptual thinking (Helme & Clarke, 2001; Lo & Hew, 2020).

Overall, these findings confirm that the SMARTECH e-module serves not only as a medium for delivering material but also as an effective means of encouraging meaningful interactions and developing students' mathematical reasoning. Therefore, the integration of e-modules into mathematics learning needs to be strategically designed to facilitate discussion, reflection, and in-depth exploration of concepts.

Increased Persistence When Working on Non-Routine Questions

The fourth finding indicates that students became more persistent when faced with non-routine problems and did not give up as quickly on more challenging tasks. This persistence is an important component of cognitive engagement because it indicates sustained mental effort on demanding tasks. At the beginning of the lesson, some students appeared hesitant when faced with problems that did not directly resemble the examples. However, during the implementation of the SMARTECH e-module, students tended to persist longer, solving problems, rereading the instructions, and reviewing relevant sections of the material before giving up.

When working on non-routine problems, students who initially appeared to stop writing returned to the e-module, read the previous example, and then continued their work. Some students were also seen erasing their answers and writing new strategies without immediately asking the teacher for answers. This finding suggests that increased cognitive engagement is also reflected in students' persistence and persistence when facing more challenging tasks.

These findings align with Hui and Mahmud's review, which showed that interactive activity-based mathematics learning designs can positively impact students' cognitive and affective domains. Rohmatulloh et al. suggested that e-modules combined with appropriate learning approaches tend to support students' mathematical abilities. In this study, increased persistence on non-routine problems provides a strong explanation for why the increase in cognitive engagement was not only statistically significant but also evident in students' behavior during learning (Hui & Mahmud, 2023; Rohmatulloh et al., 2022).

Overall, the qualitative findings indicate that students' cognitive engagement increased after using the SMARTECH e-module, as evidenced by higher post-test scores and tangible changes in their learning behavior. Students became more strategic before asking for help, more actively compared mathematical representations, more oriented toward reasoning rather than just the final result, and more persistent when dealing with non-routine problems. Thus, the qualitative results reinforce the quantitative findings and provide a pedagogical explanation for how the SMARTECH e-module supports students' cognitive engagement in mathematics learning.

The qualitative results in this study are not merely complementary but provide a mechanistic explanation for the quantitative results. The increase in cognitive engagement scores is related to how the e-module structured students' learning experiences: encouraging them to try strategies, compare representations, deepen conceptual discussions, and persist longer on non-routine tasks. Because the study used a one-group pretest-posttest design, the interpretation is that the increase in cognitive engagement occurred after the e-module was implemented. In the context of this study, this does not constitute an absolute causal claim for all learning contexts.

Final Stage: Synthesis and Dissemination

After completing the reflection and revision stages, a synthesis of all research findings was conducted to gain a comprehensive understanding of the SMARTECH e-module's effectiveness in increasing students' cognitive engagement. This synthesis integrated quantitative and qualitative findings provide a comprehensive picture of the impact of implementing the e-module on mathematics learning.

The synthesis results showed that increased student cognitive engagement was reflected not only in higher posttest scores but also in significant changes in learning behavior. These changes included students' tendency to explore problem-solving strategies more actively, use various representations to understand concepts, engage in reasoning-oriented discussions, and demonstrate greater persistence in solving non-routine problems. Thus, the qualitative findings in this study provide a mechanistic explanation for the quantitative results.

Furthermore, the results of this study confirm that the effectiveness of the SMARTECH e-module is determined not only by the content but also by how the learning experience is designed and organized. The SMARTECH e-module has been proven to create a learning environment that encourages active interaction, reflection, and deeper exploration of mathematical concepts. This aligns with recent research findings that suggest that interactive digital learning designs significantly contribute to increased cognitive engagement and the quality of mathematics learning (Firmansyah et al., 2025; Putra et al., 2025).

Within the Design-Based Research (DBR) framework, this synthesis process emphasizes the importance of an iterative cycle of design, implementation, and reflection in producing adaptive and contextual learning products. This approach allows researchers to continuously refine e-modules based on empirical data obtained in the field, ensuring that the resulting product is not only theoretically valid but also practically effective (Reeves & Reeves, 2023).

The dissemination phase then involves preparing the final product, the SMARTECH e-module, comprehensively revised based on the entire research cycle. This product is accompanied by research documentation explaining the development process, implementation, and empirical findings. Dissemination is then carried out through scientific publications, academic forums such as seminars and conferences, and by utilizing institutional repositories for broader distribution.

Thus, the synthesis and dissemination stages not only serve to conclude the research results, but also to ensure that the resulting products and findings can be accessed, utilized, and further developed by practitioners and other researchers in the context of technology-based mathematics learning.

CONCLUSION

This research resulted in the SMARTECH e-module, which integrates the principles of Techno-mathematical Literacy (TmL) for junior high school mathematics learning on the Pythagorean Theorem. Expert assessments indicated that the e-module had adequate evidence of content validity. In contrast, practicality tests indicated that the e-module was perceived as highly practical by students and teachers, particularly in ease of use, clarity of instructions, support for student engagement, and support for independent learning.

Pretest-posttest results indicated a significant increase in student cognitive engagement after implementing the e-module. Qualitative findings also indicated that students became more active in trying before asking, used various representations when drawing conclusions, engaged in more conceptual discussions, and worked more diligently to solve non-routine problems. However, because this study used a single-group design without a control group, these findings should be interpreted with caution. Therefore, the SMARTECH e-module is more appropriately viewed as a product that demonstrates potential and promising results in supporting students' cognitive engagement, rather than as one that has proven its effectiveness.

This research also produced several design principles, namely: (1) explicit and gradual learning flow, (2) use of technology as a learning mediator, (3) activities that encourage the use of strategies, comparison of representations, and conceptual reasoning, (4) clear instructions and navigation, (5) gradual support for independent learning, and (6) inclusion of non-routine problems to foster students' persistence and mental effort. These principles can serve as a reference for other researchers and developers when designing mathematics e-modules oriented towards students' cognitive engagement.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the author(s) employed ChatGPT to assist with language refinement. The author(s) 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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