

Developing a STEM-Based Mathematics E-Module for Vocational Schools to Promote SDG 4 and Twenty-First Century Skills

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Abstract: The limited use of contextual digital teaching materials has contributed to students' low understanding of mathematical concepts in vocational schools. This study aimed to develop a STEM-based mathematics e-module that is valid, practical, and effective for supporting mathematics learning in vocational education. The study employed a Research and Development (R&D) approach using the ADDIE model, consisting of the Analysis, Design, Development, Implementation, and Evaluation stages. The research involved Grade X students of SMKN 1 Koto Baru, a mathematics teacher, and expert validators in mathematics content, instructional media, and language. Data were collected through observations, interviews, questionnaires, achievement tests, and documentation. The developed e-module achieved an overall validity score of 89%, comprising 91% from material experts, 89% from media experts, and 87% from language experts, indicating that the product was highly valid. Practicality evaluation showed teacher and student response scores of 92% and 90%, respectively, both categorized as very practical. Furthermore, students' learning outcomes improved from a mean pretest score of 58.40 to a posttest score of 84.60, with an N-Gain of 0.63 (moderate category). These findings demonstrate that the STEM-based mathematics e-module is feasible and effective for improving mathematics learning in vocational schools while contributing to the implementation of quality education (SDG 4) through technology-enhanced and student-centered learning.

Keywords: ADDIE; Digital Learning; E-modules; Mathematics; SDGs ; STEM

Introduction

The rapid advancement of digital technology and the transition toward Industry 4.0 and Society 5.0 have transformed the demands placed on vocational education. Vocational High Schools (SMKs) are expected not only to equip students with occupational competencies but also to foster higher-order thinking skills, digital literacy, creativity, collaboration, and problem-solving abilities that are essential for the twenty-first-century workforce (Adha et al., 2023; Budiarto et al., 2024). In line with Sustainable Development Goal 4 (SDG 4), which emphasizes inclusive and quality education for all, mathematics learning in vocational education should provide

meaningful learning experiences that connect theoretical knowledge with authentic workplace contexts. Mathematics therefore serves not merely as a compulsory subject but as a fundamental discipline that supports analytical thinking and decision-making across diverse vocational fields (Sukendra et al., 2023).

Despite its strategic role, mathematics learning in many vocational schools continues to face significant challenges. Learning activities remain predominantly teacher-centered and rely heavily on printed teaching materials that emphasize procedural exercises rather than conceptual understanding (Hendri et al., 2021). Such instructional practices often fail to relate mathematical concepts to students' vocational competencies, making mathematics appear abstract and

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difficult to apply in real-life situations (Baidowi et al., 2023; Siregar et al., 2024). As a result, students frequently experience low motivation, limited engagement, and difficulties in understanding mathematical concepts, which ultimately affect their academic achievement and readiness for the workplace.

Recent developments in educational technology have created new opportunities to address these challenges through digital learning resources. Among various digital media, e-modules have gained considerable attention because they enable the integration of multimedia elements, including text, images, videos, animations, simulations, and interactive assessments within a single learning platform (Arifin et al., 2025). Unlike conventional printed modules, digital e-modules facilitate independent, flexible, and student-centered learning while providing immediate feedback and interactive learning experiences (Maghfiroh et al., 2024). Consequently, e-modules are considered an effective alternative for improving students' conceptual understanding and learning motivation, particularly in mathematics education.

The integration of the Science, Technology, Engineering, and Mathematics (STEM) approach further enhances the educational value of digital learning resources. STEM education encourages students to solve authentic problems by integrating scientific inquiry, technological applications, engineering design, and mathematical reasoning into a unified learning experience (Kelley & Knowles, 2016). Previous studies have consistently reported that STEM-based learning contributes positively to students' critical thinking, creativity, collaboration, and problem-solving skills while improving learning outcomes across various educational settings (Asrizal et al., 2024; Lafifa et al., 2023; Margot & Kettler, 2019). Therefore, integrating STEM principles into mathematics e-modules has considerable potential to create contextual learning experiences that are more relevant to vocational education.

Several previous studies have successfully developed STEM-based e-modules for mathematics and science learning and reported improvements in students' higher-order thinking skills and academic achievement (Adha et al., 2023; Masykur et al., 2024; Setiawati et al., 2024; Vebriani et al., 2024). Nevertheless, most existing studies were conducted in general secondary education or focused primarily on digitizing instructional materials without comprehensively integrating STEM principles into mathematics learning that reflects the characteristics and contextual needs of vocational schools. In addition, relatively few studies have simultaneously evaluated the validity, practicality, and effectiveness of STEM-based mathematics e-modules developed specifically for vocational students

using a systematic instructional design model. This indicates that empirical evidence regarding the development of contextual STEM-based mathematics e-modules for vocational education remains limited.

Based on these gaps, this study develops a STEM-based mathematics e-module for Grade X vocational school students using the ADDIE instructional design model. The novelty of this research lies in the integration of STEM principles into a contextual mathematics e-module specifically designed to support vocational learning through interactive digital features and authentic mathematical problem-solving activities. Furthermore, the developed product is systematically evaluated in terms of its validity, practicality, and effectiveness to ensure its feasibility for classroom implementation. Therefore, this study aims to develop and evaluate a STEM-based mathematics e-module that supports meaningful mathematics learning, strengthens twenty-first-century competencies, and contributes to the implementation of quality education in vocational schools in accordance with the objectives of SDG 4.

Method

This study employed a Research and Development (R&D) approach to develop a STEM-based mathematics e-module for vocational high school students. The objective of the study was to produce a learning product that meets the criteria of validity, practicality, and effectiveness for mathematics learning. The development process adopted the ADDIE instructional design model proposed by Branch (2009), which consists of five sequential stages: Analysis, Design, Development, Implementation, and Evaluation. The ADDIE model was selected because it provides a systematic, iterative, and flexible framework for developing technology-enhanced learning resources (Branch, 2009; Sugiyono, 2017).

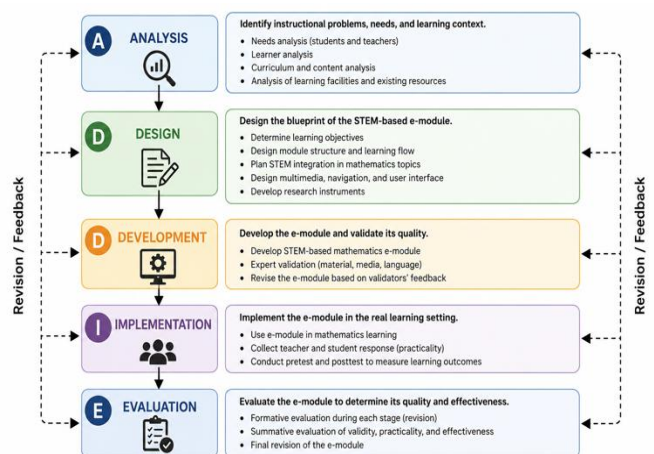


Figure 1. Research Producedure on the ADDIE Model

The research was conducted at SMKN 1 Koto Baru during the 2026/2027 academic year. The participants consisted of Grade X vocational students who participated in the product implementation stage, one mathematics teacher, and expert validators comprising material experts, media experts, and language experts. The developed e-module was evaluated through expert validation, practicality testing, and effectiveness testing.

Stages of Analysis

The analysis stage aimed to identify instructional needs and problems encountered in mathematics learning. This stage included needs analysis, learner analysis, curriculum analysis, content analysis, and analysis of available learning facilities. Data were collected through classroom observations, interviews with mathematics teachers, student questionnaires, and document analysis of students' learning outcomes (Arifin et al., 2025).

Design Stage

During the design stage, the initial prototype of the STEM-based mathematics e-module was prepared. Activities included designing the module structure, organizing learning materials, integrating STEM components into mathematics topics, preparing multimedia elements (images, videos, animations, and interactive exercises), designing user navigation, and developing research instruments, including validation sheets, practicality questionnaires, and learning achievement tests (Maharani et al., 2023).

Development Stage

The development stage focused on producing the e-module and validating its quality before classroom implementation. The e-module was developed using appropriate digital authoring software and subsequently evaluated by material experts, media experts, and language experts. Revisions were carried out based on validators' recommendations to improve content accuracy, instructional design, media quality, language clarity, and STEM integration (Spatioti et al., 2022; Wulandari et al., 2021).

Implementation Stage

The validated e-module was implemented in mathematics learning involving Grade X vocational students. During this stage, students learned using the developed e-module, while teachers facilitated the learning activities. Practicality data were collected using teacher and student response questionnaires, whereas effectiveness was measured through pretest and posttest scores to determine improvements in students' mathematical understanding (Kustandi & Daddy, 2020).

Evaluation Stage

The evaluation stage was conducted continuously throughout the development process using formative and summative evaluation. Formative evaluation was performed after each ADDIE phase to identify necessary revisions, while summative evaluation examined the overall quality of the developed product based on its validity, practicality, and effectiveness (Branch, 2009).

Research Instrument

The instruments employed in this study consisted of observation sheets, interview guidelines, needs analysis questionnaires, expert validation sheets, teacher and student practicality questionnaires, and mathematics achievement tests.

Data analysis techniques

Validity and practicality data were analyzed using the Likert scale to determine the feasibility level of the developed e-module. The validity formula used Formula 1.

$$V = \left(\frac{TSe}{TSh} \right) \times 100\% \quad (1)$$

The effectiveness of the e-module was analyzed using students' pretest and posttest scores through the calculation of N-Gain as represented by Formula 2.

$$N - Gain = \left(\frac{Score\ Posttest - Score\ Pretest}{Score\ Max - Score\ Pretest} \right) \quad (2)$$

Result and Discussion

Research Results

This research produced a product in the form of a STEM-based mathematics e-module for grade X vocational school students developed using the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model. The e-module product is designed to help students understand mathematical concepts contextually through the integration of science, technology, engineering, and mathematics in learning.

Stages of Analysis

The analysis stage was conducted to identify instructional problems, learner needs, curriculum requirements, and the availability of learning resources before developing the STEM-based mathematics e-module. Data were collected through classroom observations, interviews with mathematics teachers, student questionnaires, and document analysis. This stage served as the foundation for designing a learning product that aligns with the characteristics and learning needs of vocational high school students.

The classroom observations revealed that mathematics instruction at SMKN 1 Koto Baru was still predominantly teacher-centered and relied mainly on printed textbooks and conventional teaching materials. Although teachers occasionally used presentation slides, the instructional media lacked interactive features that could actively engage students during the learning process. Consequently, students tended to memorize mathematical procedures rather than develop conceptual understanding and problem-solving skills.

Interviews with mathematics teachers also indicated that no STEM-based digital teaching materials had been implemented to support contextual mathematics learning in vocational education.

To further identify students' learning needs, a questionnaire was administered to determine their perceptions of mathematics learning and their expectations regarding digital learning media. The results of the needs analysis are presented in Table 1.

Table 1. Student Needs Survey Results.

Statement	Percentage %
Students have difficulty understanding mathematical concepts	78.00
Mathematics is perceived as abstract and difficult to relate to vocational competencies	74.00
Students need interactive digital learning media	82.00
Students interested in using technology-based e-modules	80.00

The questionnaire results indicate that the majority of students experienced conceptual difficulties in mathematics learning. As many as 78.00% of students reported difficulty understanding mathematical concepts, while 74.00% perceived mathematics as an abstract subject with limited relevance to their vocational competencies. These findings suggest that existing instructional practices have not yet provided meaningful learning experiences that connect mathematical concepts with authentic vocational contexts.

Furthermore, 82.00% of students expressed the need for interactive digital learning media, and 80.00% indicated their interest in learning through technology-based e-modules. These findings demonstrate that students are receptive to digital learning innovations that provide more interactive, flexible, and engaging learning experiences. Such results also indicate that integrating multimedia features into mathematics instruction may enhance students' motivation and facilitate conceptual understanding.

The findings from teacher interviews support the questionnaire results. Teachers reported that the available teaching materials primarily consisted of printed textbooks and worksheets, which offered limited opportunities for students to explore mathematical concepts independently. In addition, existing instructional resources had not integrated Science, Technology, Engineering, and Mathematics (STEM) principles into mathematics learning. As a result, mathematics instruction remained procedural and less contextualized to vocational education.

Overall, the needs analysis confirms a substantial gap between current instructional practices and the characteristics of twenty-first-century vocational education. Therefore, developing a STEM-based mathematics e-module was considered an appropriate

solution to provide contextual, interactive, and technology-enhanced learning experiences that support conceptual understanding, problem-solving skills, and students' readiness for future workplace demands.

Design Stage

The design stage focused on transforming the findings of the needs analysis into a comprehensive blueprint for the STEM-based mathematics e-module. At this stage, the instructional structure, learning activities, multimedia components, navigation system, assessment instruments, and STEM integration were systematically designed to ensure that the developed product met the learning characteristics of vocational high school students.

The instructional design was developed based on the principles of student-centered learning and contextual learning. The learning objectives, learning outcomes, and assessment activities were aligned with the Independent Curriculum (Merdeka Curriculum) to ensure consistency between instructional content and curriculum requirements. Furthermore, each learning activity was designed to encourage students to actively construct mathematical knowledge through exploration, problem-solving, and reflection rather than relying solely on procedural exercises.

The structure of the e-module consisted of several main components, including the cover page, learning objectives, concept maps, learning materials, contextual examples, STEM-based learning activities, interactive exercises, formative assessments, summaries, and evaluation tests. Multimedia elements such as illustrations, videos, animations, hyperlinks, and interactive quizzes were incorporated to increase learner engagement and facilitate conceptual understanding. The interface was designed using a simple and

consistent navigation system to enable students to access learning materials independently and efficiently.

The integration of STEM principles became the primary consideration during the design process. The Science component was represented through contextual scientific phenomena related to mathematical concepts. The Technology component was implemented through the use of digital learning media and interactive multimedia features. The Engineering component encouraged students to analyze authentic vocational problems and design appropriate solution strategies. Meanwhile, the Mathematics component emphasized mathematical reasoning, representation, and problem-solving processes required to solve contextual problems. This integration was intended to help students recognize the relevance of mathematics in vocational education and future workplace applications.

Based on the completed instructional design, the initial prototype of the STEM-based mathematics e-module was produced. Figure 2 presents the cover design of the developed e-module, while Figure 3 illustrates the user interface and learning navigation designed to facilitate independent learning.



Figure 2. E-Module Cover

The cover was designed to reflect the characteristics of vocational education through modern visual elements, mathematical illustrations, and technology-oriented graphics. In addition to presenting the module title and institutional identity, the cover was intended to enhance students' initial interest and motivation before beginning the learning activities.

The user interface was designed with clear navigation menus, consistent layouts, readable typography, and interactive buttons to ensure ease of

use. Students could access learning objectives, instructional materials, videos, interactive exercises, and evaluation activities through a structured navigation system. This interface design supports self-directed learning by enabling students to learn independently according to their own pace and learning needs.

Overall, the design stage successfully produced a systematic instructional blueprint that integrates curriculum requirements, STEM principles, multimedia learning resources, and user-friendly interface design. This blueprint subsequently served as the foundation for developing and validating the STEM-based mathematics e-module in the next stage.



Figure 3. E-Module Usage Instructions

Development Stage

The development stage focused on producing the STEM-based mathematics e-module and evaluating its quality through expert validation before classroom implementation. At this stage, the initial prototype developed during the design phase was refined by integrating multimedia components, contextual mathematics materials, interactive learning activities, formative assessments, and STEM-based problem-solving tasks into a single digital learning resource. The completed prototype was subsequently evaluated by material experts, media experts, and language experts to determine its feasibility for implementation in vocational mathematics learning.

The expert validation process was conducted to ensure that the developed e-module fulfilled the requirements of content accuracy, instructional quality, media design, language clarity, and STEM integration.

Suggestions and recommendations provided by the validators were used as the basis for revising and improving the product prior to implementation.

Material Expert Validation Results

Material validation was conducted to evaluate the appropriateness of the instructional content, conceptual accuracy, curriculum alignment, and integration of STEM principles within the developed mathematics e-module. The validation results are presented in Table 2.

Table 2. Material Expert Validation Results

Assessment Aspects	Percentage %	Category
Material suitability	92.00	Very valid
Conceptual precision	90.00	Very valid
STEM Integration	89.00	Very valid
Curriculum alignment	93.00	Very valid
Average	91.00	Very valid

The results indicate that all assessed aspects achieved the Very Valid category, with an overall validation score of 91.00%. The highest score was obtained for curriculum alignment (93.00%), indicating that the learning objectives, instructional materials, and assessment activities were well aligned with the competencies specified in the Merdeka Curriculum. Material suitability also achieved a high score (92.00%), demonstrating that the mathematical content was systematically organized, scientifically accurate, and relevant to vocational learning contexts.

The STEM integration aspect received a score of 89.00%, which was slightly lower than the other aspects. According to the validators, although STEM principles had been successfully incorporated throughout the learning activities, additional authentic engineering-based examples could further strengthen the contextual relevance of the e-module. Consequently, several revisions were made by enriching vocational problem scenarios and improving the integration of engineering design activities within the learning tasks.

Media Expert Validation Results

Media validation aimed to evaluate the quality of the user interface, navigation system, visual communication, interactivity, and overall usability of the developed e-module. The validation results are presented in Table 3.

Table 3. Media Expert Validation Results

Assessment Aspects	Percentage %	Category
Visual display	90.00	Very valid
Interactivity	88.00	Very valid
Navigation	87.00	Very valid
Interface quality	91.00	Very valid
Average	89.00	Very valid

The developed e-module achieved an overall media validation score of 89.00%, indicating that the product possesses a highly feasible interface for classroom implementation. The interface quality obtained the highest score (91.00%) because the layout, typography, colour composition, and visual consistency were considered attractive and appropriate for vocational students. Meanwhile, navigation received the lowest score (87.00%), mainly due to suggestions from validators regarding the addition of shortcut buttons and clearer navigation instructions. These recommendations were incorporated into the revised version of the e-module before implementation.

Linguist Validation Results

Language validation was conducted to assess readability, language clarity, grammatical accuracy, and consistency in the use of mathematical terminology. The results are presented in Table 4.

Table 4. Language Expert Validation Results

Assessment	Percentage %	Category
Language clarity	88.00	Very valid
Readability	86.00	Very valid
Terminology accuracy	87.00	Very valid
Average	87.00	Very valid

The language validation produced an average score of 87.00%, indicating that the developed e-module uses clear, communicative, and understandable language appropriate for vocational high school students. Minor revisions were recommended to improve sentence effectiveness, terminology consistency, and grammatical accuracy, thereby enhancing the readability of the instructional materials.

Following the completion of all expert evaluations, the revised validation results were summarized to determine the overall feasibility of the developed product.

Table 5. Recapitulation of Material, Media, and Language Validation

Validator	Percentage %	Category
Material expert	91.00	Very valid
Media expert	89.00	Very valid
Language expert	87.00	Very valid
Average	89.00	Very valid

Overall, the developed STEM-based mathematics e-module achieved an average validation score of 89.00%, indicating that the product met the criteria of Very Valid and was therefore suitable for implementation in mathematics learning after minor revisions suggested by the expert validators.

Implementation Stage

The implementation stage was conducted after the STEM-based mathematics e-module had been declared valid through expert validation. This stage aimed to evaluate the practicality and effectiveness of the developed e-module when applied in real classroom learning. The implementation involved Grade X vocational students at SMKN 1 Koto Baru and a mathematics teacher who facilitated the learning process. During this stage, students used the e-module throughout mathematics learning activities, while observations, response questionnaires, and learning achievement tests were administered to evaluate the product's performance.

Practical Results

The practicality of the developed e-module was evaluated based on teacher and student responses after its implementation in mathematics learning. The practicality assessment focused on the ease of use, clarity of learning materials, interface design, navigation, and the overall usefulness of the e-module in supporting classroom instruction. The results of the practicality evaluation are presented in Table 6.

Table 6. Recapitulation of Teacher and Student Response Results to the E-Module.

Response	Percentage %	Category
Teacher	92.00	Very practical
Students	90.00	Very practical
Average	91.00	Very practical

The results indicate that the developed e-module achieved an overall practicality score of 91.00%, categorized as Very Practical. The mathematics teacher assigned a score of 92.00%, indicating that the e-module was easy to integrate into classroom instruction and effectively supported the delivery of mathematics content. According to the teacher, the structured learning sequence, interactive multimedia components, and contextual STEM activities contributed to a more engaging and efficient learning process.

Similarly, students provided a practicality score of 90.00%, demonstrating that the e-module was easy to use and supported independent learning. Students reported that the multimedia features, interactive exercises, videos, and contextual examples helped them understand mathematical concepts more effectively than conventional printed teaching materials. The user-friendly navigation system also enabled students to access learning resources independently without experiencing significant technical difficulties.

Overall, these findings indicate that the developed e-module possesses a high level of usability and practicality for mathematics learning in vocational

schools. The positive responses from both teachers and students suggest that the integration of interactive multimedia and STEM-based learning activities successfully created a more engaging, student-centered, and technology-supported learning environment

Effective Results

The effectiveness of the developed e-module was evaluated by comparing students' mathematics learning outcomes before and after the implementation through pretest and posttest assessments. The comparison of students' achievement scores is presented in Table 7.

Table 7. Comparison of Pretest and Posttest

Remarks	Average
Pretest	58.40
Posttest	84.06

The results demonstrate a substantial improvement in students' mathematics achievement following the implementation of the STEM-based e-module. The average score increased from 58.40 in the pretest to 84.60 in the posttest, representing an improvement of 26.20 points.

To determine the effectiveness of the developed product, the normalized gain (N-Gain) was calculated. The analysis produced an N-Gain value of 0.63, which falls within the moderate category. This finding indicates that the developed e-module was effective in improving students' conceptual understanding and mathematics learning outcomes.

The improvement in learning achievement can be attributed to several characteristics of the developed e-module. First, the integration of STEM principles enabled students to connect mathematical concepts with authentic vocational problems, thereby promoting meaningful learning experiences. Second, the inclusion of multimedia elements such as videos, animations, illustrations, and interactive quizzes enhanced students' engagement and conceptual understanding. Finally, the self-paced learning environment provided by the e-module encouraged students to review learning materials independently according to their individual learning needs.

Overall, the implementation results demonstrate that the developed STEM-based mathematics e-module is not only highly practical but also effective in improving students' mathematics learning outcomes. These findings confirm that the developed product is suitable for broader implementation in vocational mathematics learning.

Discussion

The findings of this study demonstrate that the developed STEM-based mathematics e-module fulfilled

the criteria of validity, practicality, and effectiveness for vocational mathematics learning. The overall expert validation score of 89.00% indicates that the instructional content, interface design, language quality, and STEM integration were considered highly appropriate for classroom implementation. The high validity score suggests that the developed product successfully combines curriculum requirements, mathematical concepts, interactive multimedia, and STEM learning principles into a coherent instructional resource. These findings are consistent with those reported by Setiawati et al. (2024) who concluded that STEM-based e-modules possess high instructional feasibility because they effectively integrate scientific knowledge, technology, and higher-order thinking skills into meaningful learning activities. Similarly (Vebriani et al., 2024) emphasized that contextual STEM integration improves the quality of digital learning resources designed for vocational education.

The practicality evaluation further indicates that the developed e-module is highly acceptable for both teachers and students. The teacher response score of 92.00% and the student response score of 90.00% demonstrate that the e-module was easy to use, visually attractive, and capable of supporting independent learning. These findings suggest that the integration of multimedia components, including interactive exercises, videos, animations, and contextual examples, successfully enhanced students' engagement throughout the learning process. The user-friendly navigation system also enabled learners to access instructional materials independently without requiring extensive teacher assistance. These results support the findings of Masykur et al. (2024). who reported that interactive STEM-based e-modules improve students' learning motivation and facilitate self-directed learning through multimedia-rich instructional environments. Likewise, Wulandari et al. (2021) concluded that interactive digital modules significantly increase students' learning interest because they provide greater flexibility and accessibility than conventional printed teaching materials.

The effectiveness analysis revealed a substantial improvement in students' mathematics achievement after using the developed e-module. The average score increased from 58.40 in the pretest to 84.60 in the posttest, producing an N-Gain value of 0.63, which falls within the moderate effectiveness category. This result indicates that the developed e-module successfully improved students' conceptual understanding of mathematics. The improvement can be explained by several instructional characteristics embedded within the product. First, mathematical concepts were presented through authentic vocational contexts, enabling students to recognize the relevance of

mathematics to their future professional fields. Second, STEM integration encouraged students to solve contextual problems using scientific reasoning, technological tools, engineering design processes, and mathematical analysis. Third, multimedia learning resources reduced cognitive barriers by presenting abstract mathematical concepts through visual and interactive representations. These findings are consistent with Kelley & Knowles (2016), who argued that integrated STEM learning connects theoretical concepts with authentic real-world applications, thereby promoting meaningful learning experiences. Similar findings were reported by Adha et al. (2023) and Suherman et al. (2025), who found that STEM-based learning significantly enhances students' critical thinking, problem-solving ability, and academic achievement.

The findings also demonstrate that integrating STEM principles into mathematics e-modules contributes to the development of twenty-first-century competencies. Throughout the implementation process, students were encouraged to investigate contextual problems, discuss alternative solutions, interpret quantitative information, and communicate mathematical reasoning collaboratively. These learning activities support the development of critical thinking, creativity, collaboration, communication, and digital literacy, which are widely recognized as essential competencies for vocational graduates in the digital era. According to Margot & Kettler (2019), successful STEM implementation requires learning environments that encourage interdisciplinary thinking and authentic problem-solving. Likewise, Lafifa et al. (2023) concluded that STEM integration positively influences students' twenty-first-century skills by promoting inquiry, collaboration, and innovation throughout the learning process.

Another important finding of this study is the contribution of interactive multimedia to students' learning motivation and engagement. The developed e-module integrates videos, illustrations, animations, hyperlinks, and interactive quizzes into a single digital learning environment, allowing students to learn independently according to their own pace. Such multimedia integration provides richer learning experiences than conventional printed teaching materials because students receive immediate feedback and multiple representations of mathematical concepts. These findings are consistent with the multimedia learning principles proposed by Smaldino et al. (2014), which emphasize that digital learning media improve learner attention, motivation, and conceptual understanding through the integration of visual, auditory, and interactive elements. Furthermore, Asrizal et al. (2024) reported that digital teaching materials

integrating STEM and emerging technologies significantly improve students' learning engagement and innovation skills.

From a broader educational perspective, this study contributes to the implementation of Sustainable Development Goal 4 (Quality Education) by providing an innovative digital learning resource that supports equitable access to high-quality mathematics instruction in vocational schools. The developed e-module encourages student-centered learning, strengthens digital literacy, promotes higher-order thinking skills, and facilitates contextual mathematics learning relevant to vocational education. Consequently, this study extends previous research by demonstrating that the integration of STEM principles within interactive mathematics e-modules not only improves students' academic achievement but also supports the development of competencies required for lifelong learning and future employment. Therefore, the developed e-module represents a practical instructional innovation for strengthening mathematics education in vocational schools while supporting ongoing educational digital transformation.

Conclusion

This study successfully developed a STEM-based mathematics e-module for vocational high school students using the ADDIE instructional design model. The evaluation results demonstrate that the developed e-module fulfilled the criteria of validity, practicality, and effectiveness, as evidenced by an overall expert validation score of 89.00%, teacher and student practicality scores of 92.00% and 90.00%, respectively, and an N-Gain value of 0.63, indicating a moderate improvement in students' mathematics learning outcomes. These findings confirm that integrating STEM principles with interactive digital learning resources provides meaningful and contextual mathematics learning experiences that enhance students' conceptual understanding, learning engagement, and twenty-first-century competencies. Despite these promising findings, this study has several limitations. The implementation was conducted in a single vocational school with a limited number of participants, which may restrict the generalizability of the findings to other educational contexts. In addition, the effectiveness evaluation focused primarily on students' cognitive learning outcomes and did not examine the long-term impact of the e-module on higher-order thinking skills, digital literacy, or learning retention. Furthermore, the successful implementation of the developed e-module depends on the availability of adequate digital devices and technological infrastructure within schools.

Future studies are recommended to evaluate the developed e-module in a broader range of vocational schools and across different vocational study programs to improve the generalizability of the findings. Further research may also integrate emerging technologies, such as artificial intelligence, adaptive learning systems, or learning analytics, to provide more personalized learning experiences and to investigate their impact on students' critical thinking, problem-solving abilities, and digital competencies. Such developments are expected to strengthen the contribution of digital mathematics learning toward achieving Sustainable Development Goal 4 (Quality Education) and supporting the ongoing digital transformation of vocational education.

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Author Contributions

"Conceptualization, D.A. and R.; methodology, D.A.; software, D.A.; validation, R., N.H. and S.A.; formal analysis, D.A.; investigation, D.A.; resources, D.A.; data curation, D.A.; writing—original draft preparation, D.A.; writing—review and editing, D.A.; visualization, D.A.; supervision, D.A.; All authors have read and agreed to the published version of the manuscript."

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Conflicts of Interest

The authors declare no conflict of interest.

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