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Development of Entrepreneurship-Integrated PjBL-STEAM Mathematics Teaching Materials to Enhance Vocational High School Students' Mathematical Critical Thinking

Dian Pramodyowati[1], In In Supianti[2*], Rani Siti Fitriani[3], Mardiah Hafizah Muhammad Hafizi[4]
[1*,2,3] Universitas Pasundan, Bandung, Indonesia
[4]Universiti Teknologi MARA (UiTM), Malaysia
**Corresponding author*
Email: dianpramodyowati83@gmail.com[1], supianti@unpas.ac.id[2*] , mardiah@uitm.edu.my[4]

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ABSTRACT
Vocational high school students' limited mathematical critical-thinking skills and the lack of contextual teaching materials that integrate mathematics, STEAM, and entrepreneurship remain important challenges in vocational mathematics education. This study aimed to develop entrepreneurship-integrated Project-Based Learning (PjBL)–STEAM mathematics teaching materials and examine their validity, practicality, and effectiveness in improving students' mathematical critical thinking. The study employed a Research and Development approach using the ADDIE model, consisting of analysis, design, development, implementation, and evaluation. The developed materials focused on Systems of Linear Equations in Two Variables and were delivered through a Google Sites-based digital platform. The participants were 24 tenth-grade students at a vocational high school in Majalengka Regency, West Java, Indonesia. Data were collected using expert-validation sheets, a student-response questionnaire, a mathematical critical-thinking test, interview protocols, and classroom observations. Quantitative data were analysed using descriptive statistics and normalised gain, while qualitative data were analysed descriptively to support interpretation of the quantitative results. The findings showed that the teaching materials obtained mean validation scores of 4.52 from mathematics education experts and 4.78 from the instructional media expert, indicating a high level of validity. Students' responses reached 77%, demonstrating strong practicality. The normalised gain score was 0.83, which was classified as high and indicated substantial improvement in students' mathematical critical thinking. The materials enabled students to analyse authentic entrepreneurship problems, formulate mathematical models, evaluate alternative strategies, and make evidence-based decisions. These findings demonstrate that entrepreneurship-integrated PjBL–STEAM materials provide a valid, practical, and effective instructional alternative for vocational mathematics education.

ABSTRAK
Rendahnya kemampuan berpikir kritis matematis siswa SMK dan terbatasnya ketersediaan bahan ajar matematika berbasis proyek yang mengintegrasikan pendekatan STEAM dengan konteks kewirausahaan menjadi tantangan utama dalam pendidikan matematika. Penelitian ini bertujuan mengembangkan bahan ajar

matematika berbasis Project-Based Learning (PjBL)–STEAM yang terintegrasi dengan kewirausahaan untuk meningkatkan kemampuan berpikir kritis matematis siswa. Penelitian ini menggunakan pendekatan Research and Development (R&D) dengan model ADDIE yang terdiri atas lima tahap, yaitu analysis, design, development, implementation, dan evaluation. Subjek penelitian terdiri atas 24 siswa kelas X SMK di Kabupaten Majalengka, Jawa Barat, Indonesia. Data dikumpulkan menggunakan lembar validasi ahli, tes kemampuan berpikir kritis matematis, pedoman wawancara, dan angket respons siswa. Kualitas bahan ajar dinilai berdasarkan validitas, kepraktisan, dan efektivitasnya. Hasil penelitian menunjukkan bahwa bahan ajar yang dikembangkan valid dan praktis, keduanya dalam kategori kuat, serta efektif meningkatkan kemampuan berpikir kritis matematis dengan peningkatan dalam kategori tinggi. Temuan ini memperkaya pengembangan bahan ajar matematika berbasis STEAM melalui integrasi proyek berorientasi kewirausahaan dan menyediakan alternatif pembelajaran untuk mengembangkan kemampuan berpikir kritis matematis siswa SMK.

INTRODUCTION

Mathematics education plays a crucial role in fostering students' higher-order thinking skills (HOTS). These skills encompass reasoning, analysis, evaluation, reflection, metacognition, and creativity, enabling students to solve problems logically and critically (Miterianifa et al., 2021). One core component of HOTS is mathematical critical thinking, defined as the ability to identify problems, analyse information, evaluate alternative solutions, and make decisions based on logical reasoning. In vocational education, these competencies are essential because they are closely related to graduates' readiness to meet workplace demands and adapt to the rapidly evolving industrial sector (Aryasandy et al., 2025).

Nevertheless, previous studies have consistently reported that vocational high school students' mathematical critical thinking remains relatively low (Aini, 2022; Azizah & Fadlikah, 2023; Hardianti et al., 2022; Irhamna et al., 2020; Purnamawati et al., 2022; Supianti et al., 2025), whereas Putriani and Aini (2022) found that it had reached only a moderate level. These findings indicate that mathematics instruction has not adequately facilitated the development of higher-order thinking skills. Classroom instruction remains dominated by teacher-centred explanations of concepts, which encourage students to memorise procedures rather than construct knowledge through inquiry, exploration, and authentic problem-solving (Kirana & Partasiwi, 2023). Consequently, students have limited opportunities to analyse information, connect mathematical concepts with real-world situations, and make logical decisions.

A growing body of research has examined STEM- and STEAM-based learning as a means of promoting higher-order thinking skills. Priatna et al. (2022) reported that Project-Based Learning (PjBL)–STEM was more effective than conventional instruction in improving students' mathematical problem-solving skills. Arin et al. (2025) found that STEAM-based learning enhanced students' learning motivation, classroom engagement, and conceptual understanding through contextual activities. Likewise, Sari and Sopiany (2023) demonstrated that PjBL–STEM improved students' mathematical visualisation skills, while Pebrianti et al. (2026) showed that authentic contexts in mathematics instruction enhanced

students' critical-thinking and mathematical problem-solving skills. These findings suggest that integrating project-based learning, STEM/STEAM approaches, and authentic contexts has considerable potential to promote students' higher-order thinking skills.

Despite these promising findings, previous studies have primarily focused on implementing instructional models or using specific contextual approaches rather than developing mathematics teaching materials that explicitly integrate STEAM with entrepreneurship projects, which are particularly relevant to vocational education. Moreover, most studies have emphasised improvements in mathematical problem-solving, learning motivation, or mathematical visualisation, whereas teaching materials specifically designed to foster vocational high school students' mathematical critical thinking remain limited. In vocational education, mathematics learning should explicitly connect mathematical concepts with workplace practices through contextual, productive, and authentic learning experiences.

To address this gap, the present study developed STEAM-based mathematics teaching materials integrated with entrepreneurship projects using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation). The materials were designed to engage students in project planning, investigation, exploration, implementation, presentation, reflection, and evaluation within entrepreneurship contexts relevant to vocational competencies. Through these experiences, students were expected to participate actively, collaborate effectively, and construct mathematical understanding in meaningful contexts. Unlike previous studies that mainly examined the implementation of STEM/STEAM instructional models, this study developed digital mathematics teaching materials that systematically integrated STEAM and entrepreneurship projects through the ADDIE model. Accordingly, the study aimed to produce valid, practical, and effective mathematics teaching materials and to examine students' mathematical critical thinking after learning with the developed materials.

METHOD

This study employed a Research and Development (R&D) approach using the ADDIE model, which comprises the Analysis, Design, Development, Implementation, and Evaluation phases, as illustrated in Figure 1. The study population comprised tenth-grade students at a public vocational high school in Majalengka, Indonesia, and the sample consisted of 26 students. The research instruments included interview protocols, a mathematical critical thinking test, validation sheets completed by subject-matter and media experts, and a student response questionnaire.

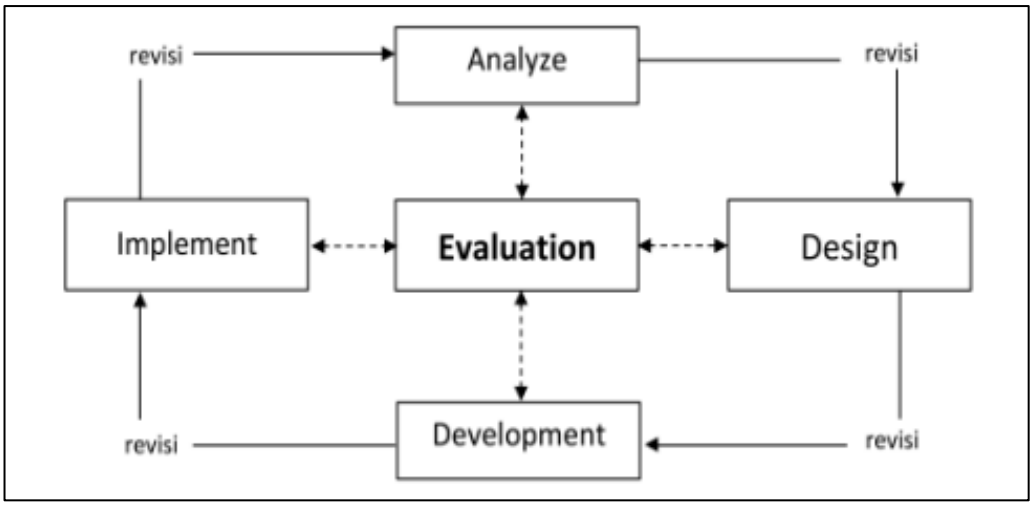

Figure 1. The ADDIE Development Model (Yaniawati et al., 2019)

The research procedure followed the phases of the ADDIE model, as described below. The analysis phase focused on identifying instructional needs and challenges in vocational high school mathematics education, particularly those related to students' mathematical critical thinking. At this stage, a literature review was conducted, followed by questionnaires and interviews with teachers and students to identify gaps between the expected learning outcomes and existing instructional practices.

During the design phase, the structure and specifications of the STEAM-based mathematics teaching materials integrated with entrepreneurship projects were developed to support students' mathematical critical thinking. Supporting research instruments were also designed, including interview protocols, a student response questionnaire, expert validation sheets for content and media experts, and a mathematical critical thinking test.

The development phase involved producing mathematics teaching materials that integrated Science, Technology, Engineering, Arts, and Mathematics (STEAM) with entrepreneurship projects. The initial prototype was then pilot-tested with 18 students at a public vocational high school in Majalengka. During this phase, the teaching materials and research instruments were validated by mathematics education experts and instructional media experts.

During the implementation phase, the developed teaching materials were used by 24 tenth-grade vocational high school students over six instructional meetings. Pretest and posttest data were collected to examine students' mathematical critical thinking. Interviews and classroom documentation were also used to complement the quantitative findings and provide a deeper understanding of students' mathematical critical thinking throughout the learning process.

The evaluation phase aimed to determine the quality and effectiveness of the developed teaching materials in enhancing students' mathematical critical thinking. Quantitative data were analysed using the normalised gain (N-gain) proposed by Hake (1999), calculated using the following formula:

$$N - gain = \frac{(Posttest\ score - Pretest\ score)}{(Maximum\ ideal\ score - Pretest\ score)}$$

The N-gain values were interpreted using the following criteria: high ($g > 0.70$), moderate ($0.30 < g \leq 0.70$), and low ($g \leq 0.30$). Data were collected using validation sheets

completed by three mathematics education experts and two instructional media experts, a student response questionnaire comprising 30 statements, a mathematical critical thinking test comprising 12 essay questions, interview protocols, and classroom observation sheets. The validation sheets were used to determine the validity of the teaching materials, the student response questionnaire was used to evaluate their practicality, and the mathematical critical thinking test was used to assess their effectiveness in improving students' mathematical critical thinking. The interview and observation data provided supporting qualitative evidence for interpreting the quantitative findings.

The quantitative data were analysed using descriptive statistical techniques. Expert validation and student response questionnaire data were analysed using mean scores to determine the validity and practicality of the teaching materials. Effectiveness was evaluated using the normalised gain (N-gain) based on students' pretest and posttest scores. Qualitative data obtained from interviews and classroom observations were analysed descriptively to support the interpretation of the findings.

Finally, a reflective evaluation was conducted based on feedback from teachers and students during implementation. The results were used to refine the teaching materials, prepare the final research report, and formulate practical recommendations for implementing STEAM-based mathematics teaching materials integrated with entrepreneurship projects to promote adaptive, innovative, and meaningful mathematics learning and foster students' mathematical critical thinking.

RESULTS AND DISCUSSION

This study developed mathematics teaching materials based on Project-Based Learning (PjBL) that integrated the STEAM approach and entrepreneurship projects for the topic of Systems of Linear Equations in Two Variables (SLETV) for vocational high school students. The development process followed the analysis, design, development, implementation, and evaluation phases of the ADDIE model.

The final product was a set of digital mathematics teaching materials hosted on Google Sites. The materials included instructional content, project activities, student worksheets, instructional videos, practice exercises, assessments, and evaluation tasks designed to accommodate the characteristics of vocational mathematics education (Figure 3).

During the analysis phase, curriculum requirements, students' learning needs and characteristics, and the mathematics teaching materials currently used in schools were analysed to identify instructional needs and establish a basis for developing the proposed materials.

Table 1. Findings from the Students' Needs Analysis Questionnaire in Mathematics Learning

Aspect	Key Findings	Instructional Implications
Difficulties in Learning Mathematics	Students experienced difficulties in understanding abstract mathematical concepts, particularly Systems of Linear Equations in Two Variables (SLETV), and had difficulty relating mathematical concepts to real-world problems.	Contextual teaching materials that connect mathematical concepts with authentic real-world problems through STEAM-based projects are needed to enhance students' conceptual understanding.

Aspect	Key Findings	Instructional Implications
	Classroom instruction was predominantly teacher-centered.	
Mathematical Critical Thinking Skills	Students demonstrated low levels of mathematical critical thinking, particularly in analyzing problems, evaluating solution strategies, and drawing logical conclusions.	A STEAM-based Project-Based Learning (PjBL) approach should incorporate activities that foster analysis, reasoning, decision-making, and open-ended problem solving through authentic projects.
Students' Perceptions of STEAM	Most students were not yet familiar with the STEAM approach as an integrated learning framework. However, they expressed strong interest when learning involved practical activities, visualization, and project work.	Mathematics instruction should explicitly integrate STEAM to help students recognize interdisciplinary connections and increase their learning motivation.
Technological Readiness	Students generally had adequate access to and basic skills in using digital technologies, including smartphones, Google Forms, Microsoft Excel, and simple graphic design applications.	Digital technologies can be utilized as learning media and project-support tools, making mathematics learning more interactive and relevant to the demands of 21st-century education.
Students' Perceptions of Entrepreneurship	Students showed interest in entrepreneurship-related activities but were not accustomed to connecting entrepreneurial concepts with mathematics learning.	Integrating entrepreneurship projects into mathematics learning can enhance the relevance of mathematical concepts, foster entrepreneurial mindsets, and develop contextual problem-solving skills.
Students' Expectations for Mathematics Learning	Students expected mathematics learning to be more engaging, practical, less monotonous, and directly connected to everyday life and future careers.	Developing entrepreneurship-integrated PjBL–STEAM teaching materials provides a promising solution to address students' needs and expectations for

Aspect	Key Findings	Instructional Implications
		meaningful mathematics learning.

As shown in Table 1, the preliminary needs analysis revealed that instruction on Systems of Linear Equations in Two Variables (SLETV) remained dominated by symbolic presentations of mathematical concepts, making it difficult for students to relate these concepts to real-life situations. Consequently, students' reasoning skills in identifying problems, selecting appropriate solution strategies, and constructing logical arguments and conclusions had not developed optimally. Furthermore, the existing teaching materials did not integrate STEAM with entrepreneurship contexts, limiting their potential to promote students' mathematical critical thinking effectively.

The design phase resulted in a prototype of mathematics teaching materials that integrated Project-Based Learning (PjBL) with STEAM through contextual entrepreneurship projects. The overall design of the materials is presented in Figure 2.

During the development phase, the initial prototype was transformed into Project-Based Learning (PjBL)-based mathematics teaching materials that integrated STEAM with entrepreneurship contexts. The materials were developed as a digital platform hosted on Google Sites, enabling students to access learning resources flexibly through computers and mobile devices. The primary objective was to provide interactive and contextual digital mathematics teaching materials that enhanced students' mathematical critical thinking through project-based learning activities.

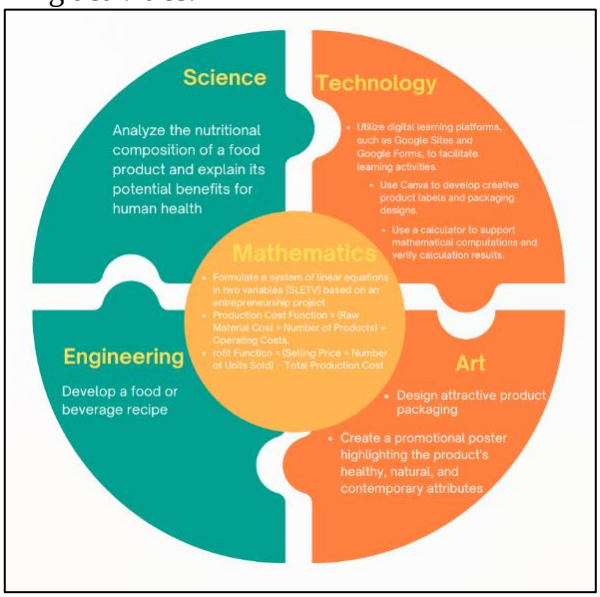

Figure 2. Specification of the STEAM-Based Mathematics Teaching Materials Integrated with Entrepreneurship Projects

Figure 2 illustrates the specifications of the developed teaching materials, which systematically connect the learning objectives, SLETV content, PjBL stages, STEAM components, entrepreneurship activities, and indicators of mathematical critical thinking. Each project begins with an authentic entrepreneurship problem that requires students to identify relevant information, formulate a mathematical model, select and evaluate possible solution strategies, and draw logical conclusions. The STEAM components are incorporated

through the analysis of product-related problems, the use of digital technology, the design of products or business plans, the development of visually appealing presentations, and the application of mathematical concepts. This integrated structure was designed to ensure that project activities were not merely supplementary tasks but functioned as the primary learning context through which students constructed mathematical understanding and developed critical-thinking skills.

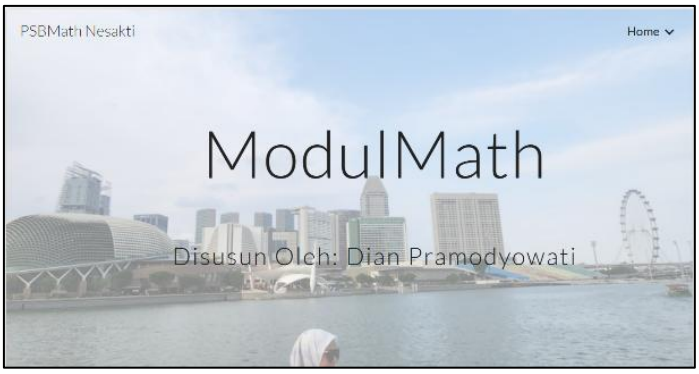

Figure 3. Homepage of the Entrepreneurship-Integrated PjBL–STEAM Mathematics Teaching Materials Developed Using Google Sites

Figure 3 presents the homepage of the Google Sites-based mathematics teaching materials, which served as the main entry point for students. The homepage functioned as a central navigation interface, providing access to course information, learning materials, STEAM-based project activities, and other instructional components. The interface was designed with a simple, well-organised layout to facilitate navigation and improve access to all learning features.

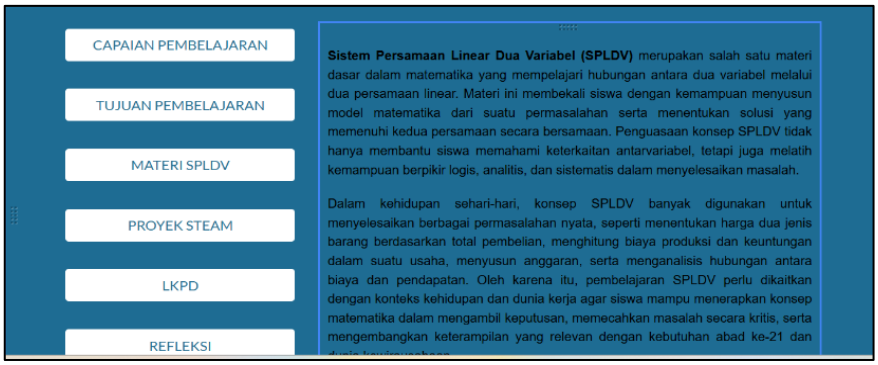

Figure 4. Structure of the Mathematics Teaching Materials Menu

Figure 4 illustrates the menu structure of the developed mathematics teaching materials, which comprised learning outcomes, learning objectives, instructional content on Systems of Linear Equations in Two Variables (SLETV), STEAM-based project activities, student worksheets, assessment, and learning reflection. The menu was systematically organised according to the Project-Based Learning (PjBL) syntax, guiding students through a structured learning process from conceptual understanding to project completion.

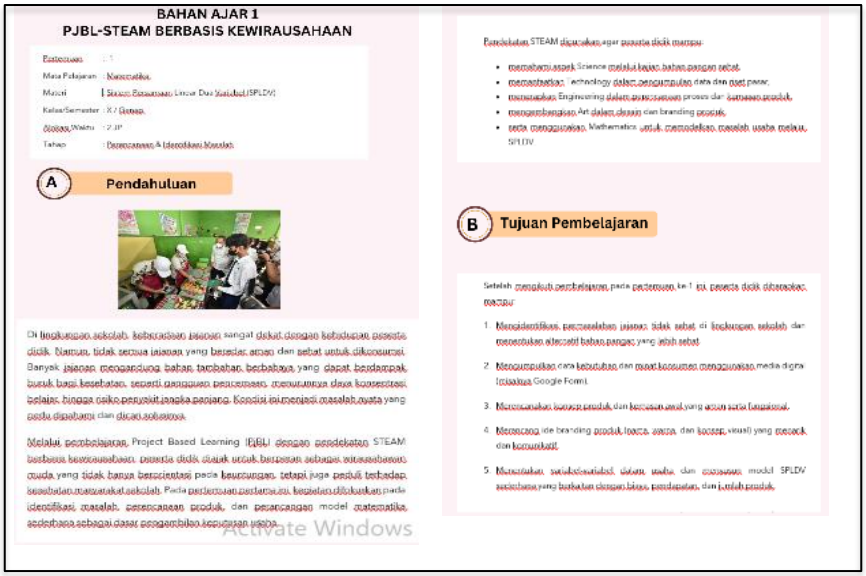

Figure 5. Content Structure, Learning Flow, Visual Design, and Navigation of the Mathematics Teaching Materials

Figure 5 presents the instructional content on Systems of Linear Equations in Two Variables (SLETV), which connected mathematical concepts with authentic contextual problems. The materials were supported by illustrations, worked examples, practice exercises, and guiding questions designed to encourage students to analyse problems critically. Rather than emphasising procedural knowledge alone, the content promoted conceptual understanding by engaging students in exploring multiple solution strategies.

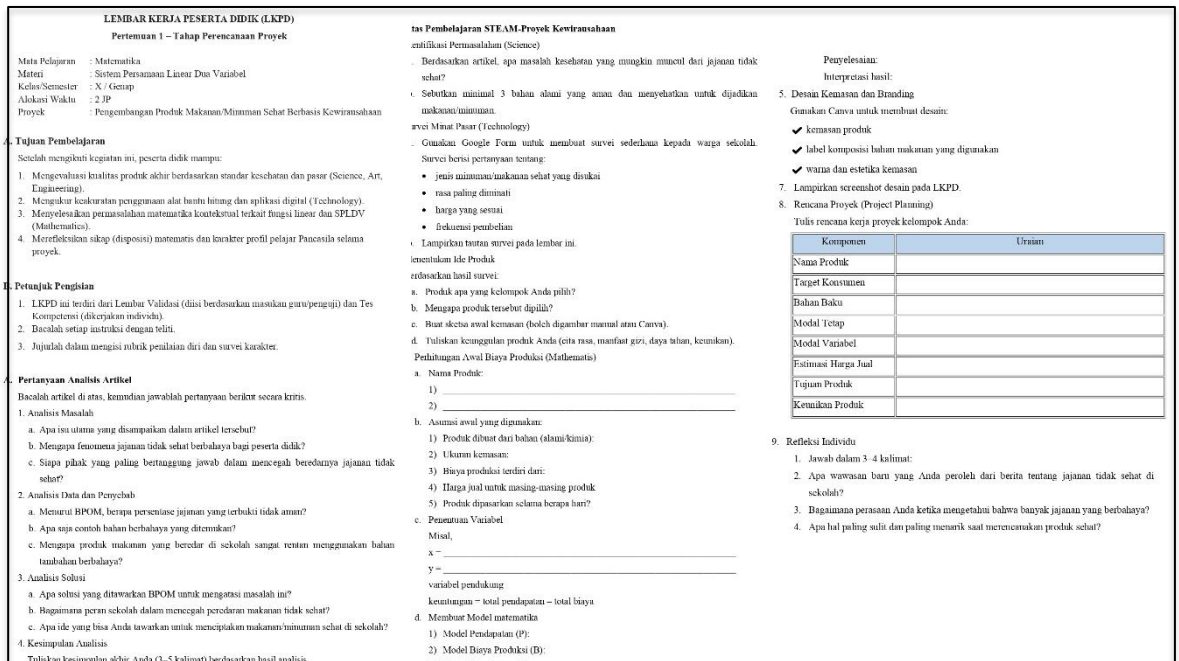

Figure 6. STEAM-Based Entrepreneurship Project

Figure 6 presents the STEAM-based entrepreneurship project, which formed the core component of the developed mathematics teaching materials. Students were assigned a project in which they designed and analysed a simple product by applying Systems of Linear Equations in Two Variables (SLETV) to support decision-making. The project integrated the five STEAM disciplines: Science through problem analysis, Technology through the use of Google Sites and digital applications, Engineering through product design and development, Arts through product and packaging design, and Mathematics through mathematical modelling and problem-solving using SLETV. Integrating entrepreneurship into the project provided meaningful learning experiences by engaging students in authentic situations that closely reflected workplace practices.

The validity of the developed mathematics teaching materials was evaluated through expert validation involving two mathematics education experts and one instructional media expert. The materials obtained a mean score of 4.52 from the mathematics education experts and 4.78 from the instructional media expert. These results indicated that the materials were highly valid and suitable for classroom implementation after the validators' suggested revisions had been incorporated.

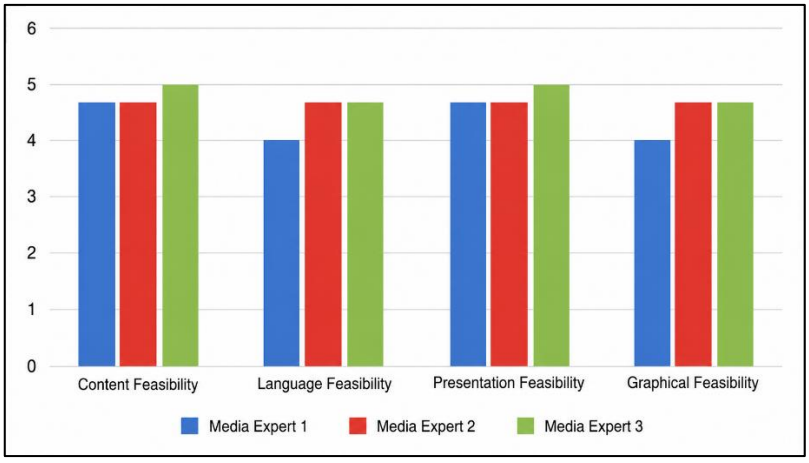

Figure 7. Results of the Teaching Materials Validation

The overall expert validation results are presented in Figure 7. More specifically, the instructional media expert's evaluation of visual design and interactivity indicated that the entrepreneurship-integrated PjBL–STEAM mathematics teaching materials had an attractive, readable, and interactive interface that effectively supported the learning process. The consistency of the visual design, its alignment with pedagogical principles, and its

suitability for vocational high school students were identified as the principal strengths of the materials.

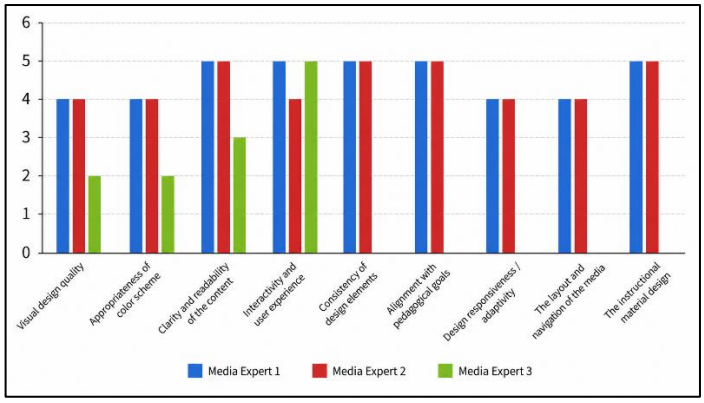

Figure 8. Results of the Instructional Media Expert Validation on Visual Design and Interactivity

As shown in Figure 8, the teaching materials received positive evaluations for interactivity, navigation, and responsiveness. These features helped students follow each stage of the project more easily. Overall, the validation results indicated that the visual design and interactivity met the established quality criteria and were suitable for classroom implementation. The materials were therefore expected to provide an engaging, user-friendly, and effective learning environment.

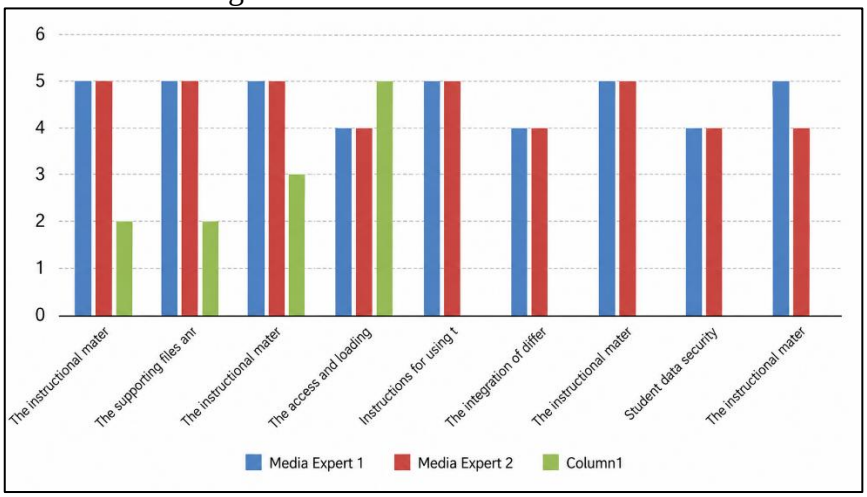

Figure 9. Results of the Instructional Media Expert Validation on the Technical Aspects

As illustrated in Figure 9, the instructional media expert rated the technical aspects of the entrepreneurship-integrated PjBL–STEAM mathematics teaching materials highly and considered them suitable for classroom implementation. The materials were easy to operate using various supp orting applications, compatible with digital devices commonly used in vocational high schools, and accompanied by clear, systematic guidelines for technology use. The supporting media also functioned reliably and flexibly in face-to-face and online learning environments, while allowing teachers to adapt the materials to classroom needs. Overall, the technical features supported an efficient, practical, and accessible learning process for teachers and students.

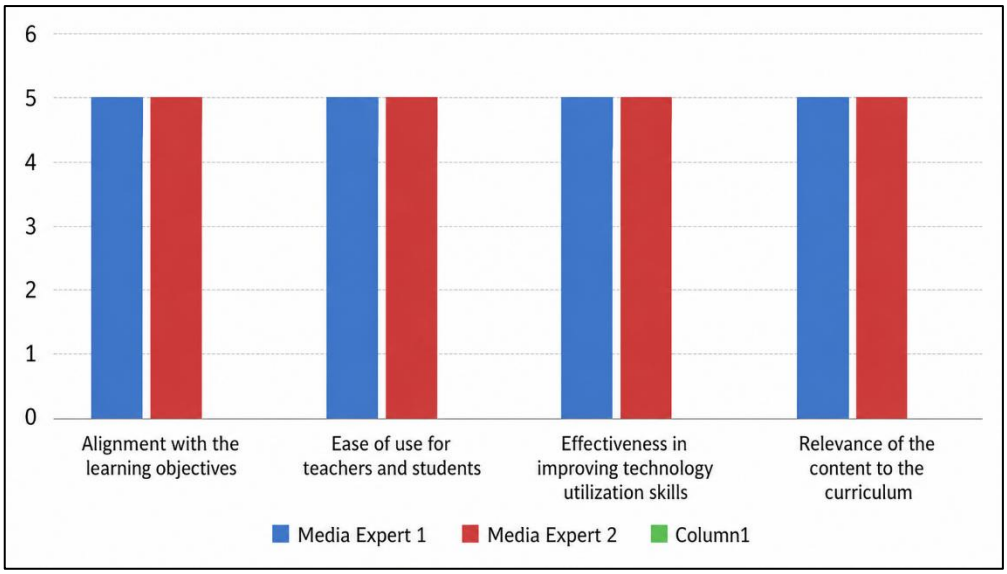

Figure 10. Results of the Instructional Media Expert Validation on the Pedagogical and User Aspects

As shown in Figure 10, the instructional media expert's validation indicated that the developed mathematics teaching materials met the required quality standards and were suitable for classroom implementation. The organisation of the instructional content, the integration of PjBL–STEAM with entrepreneurship, and the design of the Google Sites-based e-learning platform were well aligned with the instructional needs of vocational high school mathematics. The materials were therefore expected to promote students' active engagement throughout the learning process.

Table 2. Product Revisions and Follow-up Actions Based on Feedback from Mathematics Education Experts and the Instructional Media Expert

Material Expert Feedback	Product Revisions	Follow-up Actions
Each lesson should include an introductory section.	An introductory section was added to each lesson, consisting of an overview of the topic and a description of the project activities to be carried out during the learning process.	Ensure that the introduction clearly explains the relationship between the mathematical concepts and the project activities.
The main learning content should include specific learning objectives for each lesson.	The opening section was revised to include the background and rationale for implementing entrepreneurship-based PjBL–STEAM, as well as the learning outcomes and lesson objectives for Systems of Linear Equations in Two Variables (SLETV).	Formulate measurable learning objectives that are aligned with the intended learning outcomes, assessment, and project activities.

Material Expert Feedback	Product Revisions	Follow-up Actions
Authentic contextual problems should be supported by reliable and official sources.	The contextual problems were supplemented with screenshots of authentic news articles from official sources, and the references were included in the student worksheets.	Ensure that contextual problems are based on credible sources and that complete references are provided.
The teaching materials lacked contextual illustrations, and the use of foreign terms was inconsistent with academic writing conventions.	Relevant contextual illustrations were added to support students' conceptual understanding. In addition, foreign terms were revised by applying italic formatting and standard academic writing conventions.	Review the teaching materials to ensure consistency in terminology, language use, and contextual illustrations appropriate for vocational high school students.
The teaching materials should include learning videos.	Learning video links were added to the project planning section to support students' understanding of the project activities.	Select instructional videos that are aligned with the learning objectives and project activities.
The landing page should contain more engaging content and provide easier navigation.	The homepage was redesigned by adding descriptions of the learning outcomes and objectives, along with a navigation menu that provides direct access to each section of the teaching materials.	Conduct navigation testing to ensure that all menus and hyperlinks function properly and improve user accessibility.
The image quality and overall layout should be improved to enhance visual appeal.	Images were updated to better reflect the learning content, and the page layout was reorganized to improve readability and visual consistency.	Refine the visual design by emphasizing simplicity, consistency, readability, and user-friendly presentation.

Based on Table 2 feedback from the mathematics education experts, the developed teaching materials were well aligned with the instructional objectives of the entrepreneurship-integrated PjBL–STEAM approach. The revisions focused primarily on enhancing conceptual illustrations, incorporating instructional videos, improving consistency in language and formatting, and optimising the landing page and image quality. These refinements improved the overall quality of the materials and indicated that the final product was suitable for supporting effective mathematics instruction.

The practicality of the developed mathematics teaching materials was evaluated based on students' responses after they participated in learning activities using the

product. The student response questionnaire yielded an overall score of 77%, which was classified in the strong category (Table 3). These findings indicated that the materials were practical and well received by students.

Table 3. Results of the Student Response Questionnaire

Aspect	Item Numbers	Total Score	Mean	Percentage (%)	Category	Remarks
Content	1-3	209	3.9	78	Strong	No Revision Required
Language	4-6	202	3.7	74	Strong	No Revision Required
Presentation	7-9	206	3.8	76	Strong	No Revision Required
Graphics	10-12	200	3.7	74	Strong	No Revision Required
Integration with Mathematical Critical Thinking	13-15	221	4.1	82	Strong	No Revision Required
Total		1038	19.2	384	Strong	
Average		207.6	3,8	3.8		

The average response score for the entrepreneurship-integrated PjBL–STEAM teaching materials on Systems of Linear Equations in Two Variables (SLETV) was 77%, which fell within the strong category. This result indicated that the developed materials received positive responses from students and were sufficiently engaging and practical for mathematics instruction. The positive responses were also reflected in the learning process, as demonstrated by students' performance in completing the SLETV project tasks. Their work was subsequently analysed to determine the extent to which the indicators of mathematical critical thinking had been achieved. These findings suggested that the developed teaching materials were easy to use and engaging, supported students' understanding of the learning content, and promoted their active participation throughout the learning process.

The effectiveness of the developed teaching materials was evaluated using the normalised gain (N-gain) based on students' pretest and posttest scores on the mathematical critical thinking test. The analysis yielded an N-gain score of 0.83, which was classified as high. This result in Table 4 indicated that the entrepreneurship-integrated PjBL–STEAM mathematics teaching materials were effective in improving vocational high school students' mathematical critical thinking.

Table 4. Students' Mathematical Critical Thinking Scores

Mathematical Critical Thinking	
PjBL–STEAM	Conventional
82.56	54.33

The observed improvement in students' mathematical critical thinking indicated that the project-based activities provided opportunities to identify problems, analyse information, evaluate alternative solution strategies, and communicate project outcomes collaboratively. These learning experiences were consistent with the essential characteristics of mathematical

critical thinking, which emphasise analysis, evaluation, and evidence-based decision-making.

The findings showed that the entrepreneurship-integrated PjBL–STEAM mathematics teaching materials met the criteria for validity, practicality, and effectiveness as an instructional product. The high level of validity indicated that the content, instructional design, media presentation, and integration of entrepreneurship projects were well aligned with the needs of mathematics learning in vocational high schools. Furthermore, students' positive responses indicated that the materials were practical and provided an engaging, interactive, and user-friendly learning experience. The high normalised gain (N-gain) score also suggested that integrating Project-Based Learning (PjBL), STEAM, and entrepreneurship projects contributed substantially to improving students' mathematical critical thinking.

These findings support the study by Priatna et al. (2022), which reported that PjBL–STEM was effective in improving students' mathematical problem-solving abilities. The present findings are also consistent with those of Arin et al. (2025), who found that STEAM-based learning enhanced students' motivation and conceptual understanding of mathematics, and Pebrianti et al. (2026), who demonstrated that authentic contexts effectively promoted students' mathematical critical thinking. While these previous studies primarily examined the implementation of instructional models, the present study extends the literature by developing digital mathematics teaching materials that systematically integrate PjBL, STEAM, and entrepreneurship projects within a unified learning environment. This integration makes the materials particularly relevant to the characteristics and instructional demands of vocational high school mathematics education.

The integration of entrepreneurship projects within the STEAM framework also provided students with authentic learning experiences by connecting mathematical concepts to workplace situations. Through project planning, mathematical modelling, product design, data analysis, and collaborative decision-making, students actively constructed mathematical knowledge while developing higher-order thinking skills. These findings suggest that entrepreneurship-oriented STEAM learning can serve as an effective pedagogical approach for promoting mathematical critical thinking in vocational education.

CONCLUSION

The improvement in students' mathematical critical thinking after learning with the entrepreneurship-integrated PjBL–STEAM mathematics teaching materials reached the high category. Based on expert validation, student responses, and learning outcomes, the developed materials met the established criteria for validity, practicality, and effectiveness and were considered suitable for mathematics instruction. The materials provide an alternative learning resource that systematically integrates mathematical concepts, STEAM, and entrepreneurship and is therefore well suited to the characteristics and instructional needs of vocational high school mathematics education.

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