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Development of AI-Assisted Adaptive Teaching Materials to Improve Mathematical Communication in Vocational High School Students

Abstrak

Rendahnya kemampuan komunikasi matematis siswa SMK dan praktik pembelajaran yang berpusat pada guru menunjukkan adanya kesenjangan dengan tuntutan Kurikulum Merdeka, yang menekankan pada penguatan komunikasi matematis. Penelitian ini bertujuan untuk mengembangkan dan mengevaluasi bahan ajar adaptif berbasis Kecerdasan Buatan (AI) pada materi Sistem Pertidaksamaan Linear Dua Variabel (SPtLDV) guna mendukung peningkatan komunikasi matematis siswa SMK. Metode penelitian yang digunakan adalah *Research and Development* (R&D) dengan model 4D yang mencakup tahapan *define* (pendefinisian), *design* (perancangan), *develop* (pengembangan), dan *disseminate* (penyebarluasan). Pada tahap pengembangan, bahan ajar divalidasi oleh tiga ahli materi dan tiga ahli media. Hasil validasi menunjukkan bahwa bahan ajar memiliki validitas konten dan media yang sangat tinggi dengan nilai I-CVI ≥ 0,80 dan S-CVI/Ave = 1,00. Selain itu, hasil respons dari 40 siswa menunjukkan tingkat kepraktisan yang sangat baik dengan skor rata-rata 3,60 (90%). Tahap penyebarluasan dilakukan melalui sosialisasi terbatas kepada guru matematika SMK. Berdasarkan hasil tersebut, dapat disimpulkan bahwa bahan ajar adaptif berbasis AI yang dikembangkan bersifat valid, praktis, serta berpotensi mendukung pembelajaran matematika yang lebih personal dan mendorong peningkatan kemampuan komunikasi matematis siswa SMK.

Kata kunci: Pembelajaran Adaptif; Kecerdasan Buatan; Komunikasi Matematis; Pengembangan Bahan Ajar; Siswa SMK.

Abstract

The low mathematical communication skills of vocational high school students and teacher-centered learning practices indicate a gap with the demands of the Independent Curriculum, which emphasizes strengthening mathematical communication. This study aims to develop and evaluate adaptive teaching materials assisted by Artificial Intelligence (AI) on the Two-Variable Linear Inequality System (SPtLDV) material to support the improvement of mathematical communication in vocational high school students. The research method used is Research and Development (R&D) with a 4D model that includes the define, design, develop, and disseminate stages. At the develop stage, the teaching materials were validated by three material experts and three media experts. The validation results showed that the teaching materials had very high content and media validity with an I-CVI value ≥ 0.80 and S-CVI/Ave = 1.00. In addition, the results of 40 student responses showed a very good level of practicality with an average score of 3.60 (90%). The dissemination stage was carried out through limited socialization to vocational high school mathematics teachers. Based on these results, it can be concluded that the AI-assisted adaptive teaching materials developed are valid, practical, and have the potential to support more personalized mathematics learning and encourage increased mathematical communication skills of vocational school students.

Keywords Adaptive Learning; Artificial Intelligence; Mathematical Communication; Teaching Material Development ; Vocational Students.

Abstrak

Handapna kamampuh komunikasi matematis siswa SMK sarta prakték pangajaran anu masih museur kana guru nuduhkeun ayana kasenjangan jeung tuntutan Kurikulum Merdeka, anu nekenkeun kana penguatan komunikasi matematis. Ieu panalungtikan miboga tujuan pikeun ngembangkeun jeung ngaévaluasi bahan ajar adaptif berbasis Kecerdasan Buatan (AI) dina

matéri Sistem Pertidaksamaan Linear Dua Variabel (SPtLDV) pikeun ngarojong kana ngaronjatna kamampuh komunikasi matematis siswa SMK. Métode panalungtikan anu digunakeun nyaéta *Research and Development* (R&D) kalayan modél 4D anu ngawengku tahap *define* (watesan), *design* (rarancang), *develop* (ngembangkeun), jeung *disseminate* (nyebarkeun). Dina tahap ngembangkeun, bahan ajar divalidasi ku tilu ahli matéri jeung tilu ahli média. Hasil validasi nuduhkeun yén bahan ajar miboga validitas kontén jeung média anu kacida luhurna, kalayan nilai I-CVI ≥ 0,80 jeung S-CVI/Ave = 1,00. Salian ti éta, hasil réspon ti 40 siswa nuduhkeun tingkat kapraktisan anu kacida hadéna, kalayan skor rata-rata 3,60 (90%). Tahap panyebaran dilaksanakeun ngaliwatan sosialisasi terbatas ka guru matematika SMK. Dumasar kana hasil panalungtikan, bisa dicindekkeun yén bahan ajar adaptif berbasis AI anu dimekarkeun miboga sipat valid, praktis, sarta boga poténsi pikeun ngarojong pangajaran matematika anu leuwih personal sarta ngadorong kana ngaronjatna kamampuh komunikasi matematis siswa SMK.
Kecap konci: Pangajaran Adaptif; Kecerdasan Buatan; Komunikasi Matematis; Ngembangkeun Bahan Ajar; Siswa SMK.

INTRODUCTION

The rapid development of Artificial Intelligence (AI) is now not only used in industry but has also begun to be applied in education. This technology has been widely utilized by teachers to support the teaching and learning process. In mathematics learning, AI can be utilized in the implementation of adaptive learning, an approach that adjusts the material, difficulty level, and learning pace according to the student's own abilities. According to Yi et al. (2024), AI-based adaptive learning has a consistent positive impact on K-12 students' math scores, with a small to medium effect size (around 0.34) compared to traditional methods. AI-based adaptive learning consistently provides significant improvements in math scores compared to traditional methods (Dabingaya, 2022; Yi et al., 2024; Lee et al., 2022). In learning that implements AI, both teachers and students show high interest in the implementation of this system because it can facilitate more efficient and interactive learning (Wahjusaputri et al., 2024).

According to Canonigo (2024), the implementation of AI in mathematics learning focuses heavily on improving cognitive outcomes, such as conceptual understanding, problem-solving skills, and mathematics achievement. This means that students' mathematical communication skills (e.g., explaining thought processes, discussing, or arguing mathematically) have not been a primary focus in the design and evaluation of AI implementations (Lee & Yeo, 2022). However, mathematical communication is a crucial skill in mathematics learning because it allows students to express their own thinking, enabling them not only to understand concepts but also to convey mathematical ideas and relate them to real-world situations.

Mathematical communication skills are an important competency for vocational high school students because they support their readiness to face the demands of the working world. This is in line with several research results stating that mathematical communication skills have a strategic role because they are directly related to students' readiness to face the challenges of the working world that require analytical, collaborative, and communicative thinking skills in solving real-world problems (Pugacheva et al., 2020; Kim, 2024; Rifai, 2025). Mailisman (2020) and Danny et al., (2024) stated that the mathematical communication skills of vocational high school students are still relatively low, especially in terms of written communication and non-routine problem solving. This is caused by students' lack of habituation in solving contextual problems and the use of learning methods that are still predominantly conventional. This condition indicates the need for learning innovations that not only focus on cognitive aspects but also are able to stimulate students' mathematical communication skills. One learning innovation that can support this is the development of AI-based adaptive teaching materials that enable enhanced learning experiences according to students' needs and abilities.

In Indonesia, research on the development of AI-assisted adaptive learning materials is still very limited and generally focuses on high school level or general online learning (Lee et al., 2022). Research conducted by Susanto et al., (2022) shows that students desire the use of AI that can visualize concepts and guide mathematical problem solving, but the application of AI-based adaptive learning materials is still very limited. A literature review conducted by Agustina et al., (2024) shows that the integration of adaptive technology in the Indonesian education system is only a general concept and has not yet touched on the development of concrete AI-based adaptive learning materials in mathematics. Adaptive AI in mathematics learning is still rarely implemented explicitly in available applications, despite its enormous potential for personalization, real-time feedback, and difficulty adjustment (Mustafa, 2024).

Furthermore, research rarely focuses on vocational schools and has not extensively examined the role of adaptive systems in developing students' argumentation, symbol interpretation, and problem-solving skills. A review by Fahrurozi et al. (2025) shows that the application of AI in mathematics learning in vocational schools is still exploratory and focuses on personalization, without assessing students' mathematical communication or reflection skills. Research attempting to implement adaptive AI at the vocational school level has begun to emerge, for example, by Purnomo et al. (2025) who tested an AI-based adaptive platform in the Computer Networks subject at SMK Negeri 2 Mataram. However, the focus of this research was not on mathematics learning, and it did not develop an adaptive system that could adjust the material or provide reflective feedback on students' mathematical thinking processes.

Meanwhile, a study by Relmasira et al. (2023) found that in Indonesian elementary schools, the emphasis is more on developing AI literacy and designing learning interventions, rather than on specific adaptive mathematics teaching materials. This situation indicates a gap in the development of teaching materials that not only adaptively adjust the material's difficulty level but also encourage students' mathematical communication and reflection. In other words, innovation is still needed in designing adaptive AI-based teaching materials that directly target improving vocational high school students' mathematical communication skills.

Based on this gap, this study attempts to fill the void by developing AI-assisted adaptive learning materials specifically designed for applied mathematics in vocational high schools. The novelty of this study lies in the combination of a rule-based adaptive feedback approach and simple learning analytics that allows for automatic content adjustment and feedback based on student responses. Furthermore, the development of the teaching materials focuses on improving mathematical communication, not just cognitive outcomes. Therefore, the purpose of this study is to develop and test the effectiveness of AI-based adaptive teaching materials in improving vocational high school students' mathematical communication skills. This study is expected to not only answer whether AI can improve student learning performance but also reveal how AI-based adaptive design and pedagogical strategies can foster mathematical representation, argumentation, and explanation skills in the context of 21st-century vocational learning..

METHOD

This study is a Research and Development (R&D) project utilizing the 4D model, aimed at producing AI-based adaptive open educational resources to enhance the mathematical communication skills of vocational high school (SMK) students. The 4D model—comprising the stages of Define, Design, Develop, and Disseminate—serves as a systematic framework widely used to design educational tools and learning experiences that meet student needs through in-depth analysis. This model supports a structured process beginning with needs and curriculum analysis (Define), followed by the planning and creation of learning materials (Design and Develop), and concluding with distribution or implementation (Disseminate) (Muqdamien et al., 2021; Indaryati et al., 2025); it also aligns with AI adaptive learning research approaches that emphasize personalization and structured instructional design (Yi et al., 2024; Lee & Yeo, 2022; Mustafa, 2024).

A complete explanation of each stage of the 4D model is as follows.

1. Define Stage

This stage aims to identify learning needs through questionnaire analysis, interviews, student characteristics, mathematical communication gaps, and curriculum analysis. The analysis results form the basis for developing the initial specifications for AI-based adaptive teaching materials.

2. Design Stage

This stage develops the content structure, learning flow, visual display, and navigation of the teaching materials. A rule-based adaptive feedback mechanism is used to support AI personalization. This stage also develops supporting instruments, expert validation sheets, and mathematical communication rubrics that reference and adapt several research findings (Sayed et al., 2022; Murtaza et al., 2022).

3. Develop Stage

This stage creates a prototype of the AI-based teaching materials according to the design, which is then validated by material and media experts. Revisions are made based on validator input to ensure the quality of the content, display, and interactivity until the product is deemed suitable for use.

4. Dissemination Stage

This stage includes finalizing the product, compiling documentation, and disseminating it to teachers and other relevant parties. In research that ends with expert validation, this stage is conducted without classroom trials, as the product's feasibility has already been assessed through expert validation.

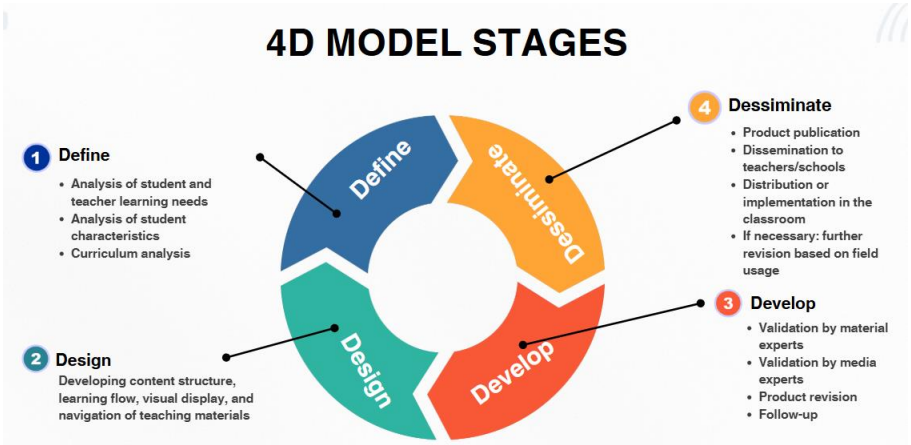

Figure 1: 4D Model Diagram

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Research Subject

The research subjects consisted of 40 students and one mathematics teacher involved in the needs analysis and expert validation stages. Research into the development of teaching materials generally involves validation by experts consisting of material experts and media/technology experts, such as AI, to assess the feasibility of content, presentation, and other technical aspects. Validation by three material experts and three media/AI experts is a common practice to ensure teaching materials meet quality and pedagogical standards before wider use (Nurbaiti et al., 2025; Febrian et al., 2023).

Data Collection Instruments And Techniques

Instruments used in teaching materials development research generally include needs analysis questionnaires to collect data from students and teachers, interview forms to deepen information on needs, validation sheets from material and media experts to assess the feasibility of the teaching materials, and documentation of the development process as evidence of activities. Data collection techniques used include questionnaires, expert validation, and documentation, which allow for a comprehensive assessment of the material, media, and user needs. Expert validation typically involves several experts, such as material, media, and language experts, who provide quantitative and qualitative assessments to ensure the teaching materials are valid and practical (Hikmawati et al., 2024; Egidia, 2025).

Data Analysis Techniques

Data analysis techniques in this study included quantitative and qualitative analysis according to the objectives of each development stage. Expert validation data for adaptive teaching materials were analyzed using the Content Validity Index, which includes calculating the Item-Content Validity Index Universal Agreement (I-CVI/UA) to assess full agreement between validators on each item, and the Scale-Content Validity Index Average (S-CVI/Ave) to obtain the overall average scale validity. Student and teacher needs analysis questionnaire data were analyzed using the formula P = (Score obtained)/(Maximum score) × 100% to determine trends in user needs and characteristics. To analyze the effectiveness of AI-assisted adaptive teaching materials on improving students' mathematical communication skills, inferential statistical tests were used, beginning with assumption tests in the form of normality and homogeneity tests. Once the assumptions were met, pretest and posttest data were analyzed using paired t-tests to identify significant differences before and after using the teaching materials. Gain scores were calculated to assess the extent of improvement in students'

mathematical communication skills. The overall analysis results were used to assess the feasibility, necessity, and effectiveness of the developed product. Student responses were analyzed based on the average score on a Likert scale of 1–4 and categorized according to interpretation criteria referenced by Sugiyono (2019) and Riduwan (2015).

Table 1. Categories of Student Response Results to AI-Assisted Adaptive Learning Materials

Average Score	Percentage	Category	Indicator
3,26 – 4,00	81% – 100%	Excellent	The teaching materials are very easy to use, interesting, and really support students' mathematical learning and communication.
2,51 – 3,25	61% – 80%	Good	The teaching materials are easy to use and support learning with some aspects that can still be improved.
1,76 – 2,50	41% – 60%	Satisfactory	The teaching materials are quite helpful for learning, but still require a lot of improvement.
1,00 – 1,75	0% – 40%)	Unsatisfactory	Teaching materials are less helpful for learning and need comprehensive improvement.

RESULTS AND DISCUSSION

Define Stage

As the initial step in the define stage, researchers conducted a needs analysis of students and teachers in mathematics learning and a curriculum analysis. The student needs analysis was obtained from a questionnaire completed by 33 students at a vocational high school. The instrument consisted of 28 Likert-scale statements and several open-ended questions related to difficulties in learning mathematics, learning experiences, student needs, and expectations regarding teaching materials. The teacher needs analysis was obtained from a questionnaire completed by three mathematics teachers at the vocational high school. The instrument consisted of 28 Likert-scale statements and several open-ended questions related to learning conditions, student needs, and expectations regarding teaching materials. The following are findings from each aspect of the student and teacher needs questionnaire.

Table 2. Findings of the Student Needs Questionnaire in Mathematics Learning

Aspects	Main findings	Learning implications
Difficulties in learning mathematics	Most students have difficulty understanding teacher explanations and writing down solution steps; learning is perceived as too fast and unclear.	Coherent explanations using simple language, a flexible pace, and sufficient examples and repetition are needed.
Mathematical communication skills	The majority of students struggle to communicate mathematical steps and reasoning; however, students perceive methods that facilitate	Learning needs to foster mathematical communication through step explanations, the

Aspects	Main findings	Learning implications
	explanation and theuse of diagrams as enhancing understanding.	use of visual representations, and language scaffolding.
Adaptive learning experiences	Most students are unfamiliar with adaptive learning, but they show a strong interest in graded questions and automated feedback.	Developing adaptive learning materials is a priority to meet diverse learning needs.
Technological Readiness	The majority of students own and are accustomed to using digital devices, although they still face challenges with internet stability and mastery of new applications.	Learning media must be data-efficient, easy to use, and remain functional even on limited connections.
Students' Perspectives on AI	Most students recognize the potential of AI in learning and show a high level of interest, although they still need an explanation of how it works and its benefits.	AI has the potential to be well-received if presented in a clear, structured, and easy-to-understand manner..
Open-ended questions (main content)	Students appreciate contextual and visual materials, access to videos/tutorials, and a safe classroom environment for asking questions and presenting.	Materials should include visualizations, instructional videos, and foster a supportive and reflective classroom climate.

Table 3. Findings of the Teacher Needs Questionnaire in Mathematics Learning

Aspect	Main findings	Learning implications
Mathematics learning conditions	Learning is still dominated by lectures and practice exercises, tending to be teacher-centered. Students struggle to grasp abstract concepts, particularly with word problems and math and reasoning skills.	Learning innovations are needed that are more student-centered and contextual, emphasizing problem modeling and conceptual understanding.
Mathematical communication skills	Students rarely express mathematical ideas and reasoning independently; some have communication potential but lack confidence.	Learning needs to provide regular space for explaining thinking processes with gradual scaffolding to increase student confidence.
Utilizing media and technology in learning	Teachers have used digital applications, but technical challenges and time constraints have prevented their optimal use.	Practical, easy-to-use media, supported by targeted technical training, are needed.
Understanding and Perspectives on AI	Teachers do not yet understand the application of AI in learning and have never used AI-based teaching materials, but they are open to its use.	AI has great potential, but socialization and practice-based training with concrete examples of AI use in the classroom are needed.
School facilities and readiness	School infrastructure is relatively adequate, and teachers are ready to collaborate, although they still need assistance in developing adaptive teaching materials.	The school supports innovation, allowing AI development and training programs to be designed collaboratively with teachers.
Open-ended questions (main content)	Teachers emphasize the need for teaching materials that support story modeling, reinforce basic arithmetic, visualize concepts, and provide flexible learning access..	Teaching materials need to integrate visualization, step-by-step exercises, and online and offline modes to adapt to student needs.

Design Stage

In the design stage, AI-assisted adaptive learning materials are designed, incorporating an integrated content structure, learning flow, visual displays, and navigation. The content structure is systematically structured, starting with learning objectives, concept maps, core material, contextual examples, student worksheets, adaptive discussions with AI, and practice questions (Sukacke et al., 2022; Azizah et al., 2021). The learning flow is designed in stages, from concept introduction, exploration, elaboration, reflection, and evaluation, supported by rule-based adaptive feedback. Visual displays are presented simply and communicatively through the use of graphs, tables, and a neat layout to facilitate conceptual understanding. Navigation of the learning materials is designed to be clear and user-friendly through meeting numbering, consistent headings, and user instructions, supporting independent and personalized learning (Aris, 2024; Robles et al., 2023).

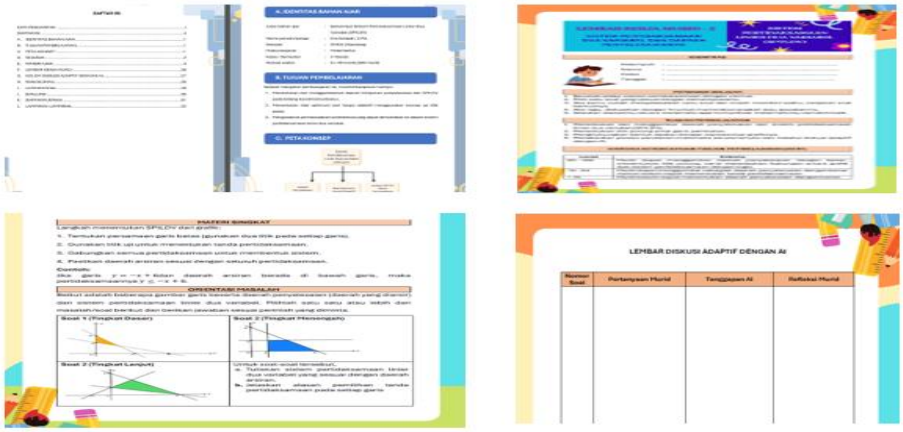

Figure 1. Content structure, learning flow, visual display and navigation of teaching materials

Develop Stage

The develop stage aims to produce AI-assisted adaptive teaching materials that are suitable for use through validation, revision, and practicality testing. At this stage, the designed teaching materials are developed into a complete product and tested for quality to ensure their validity, practicality, and suitability for supporting learning in the Two-Variable Linear Inequality System (SPtLDV) and students' mathematical communication. This stage involves validation testing by material experts and media experts. Content validity testing is conducted to ensure that each item in the teaching material instrument aligns with the indicators, learning objectives, and theoretical constructs being measured. Assessments are conducted by three experts using a four-category scale. An item is considered valid if it receives a score of 3 or more from all assessors. The following table shows the validation results from the material experts and media experts.

Table 4. Results of the Material Expert Validation Test Calculation

Domain	No. of Items	Mean Relevance	Mean Clarity	Mean Sufficiency	Items with I-CVI ≥ 0.80
Content and Discipline Accuracy	10	3.8	3.7	3.7	10/10
Pedagogical Components	9	3.8	3.6	3.7	9/9
Language	4	3.7	3.6	3.5	4/4
Design Appearance	4	3.6	3.5	3.4	4/4
Assessment	4	3.7	3.6	3.6	4/4
TOTAL	**29**	**3.79**	**3.62**	**3.69**	**29/29**

Table 5. Results of Media Expert Validation Test Calculations

Domain	No. of Items	Mean Relevance	Mean Clarity	Mean Sufficiency	Items with I-CVI ≥ 0.80
General Aspects	5	3,8	3,7	3,7	5/5
Media Aspects	13	3,7	3,6	3,6	13/13
Language Aspects	7	3,8	3,7	3,6	7/7
TOTAL	25	3,77	3,66	3,65	25/25

Tables 6 and 7 present the results of the product revisions and follow-up actions taken based on input from subject matter and media experts. The input provided served as an important basis for refining the product to align with learning objectives, student characteristics, and the principles of conceptual and visual clarity. Product revisions focused on improving question wording, strengthening mathematical reasoning, enhancing written communication exercises, and optimizing visual elements and AI usage guidelines. Follow-up actions were taken to ensure the revisions could be consistently and effectively implemented in the learning process.

Table 6. Product Revisions and Follow-Up Based on Input from Subject Matter Experts

Expert Input	Product Revisions	Follow-up
The editing of the questions is too complex	Simplifying the contextual language of the questions without reducing the depth of the concept.	The questions are revised with shorter and more contextual sentences.
Less emphasis on mathematical reasoning	Adding a “why” explanation to the step of determining the settlement area.	Added reflective questions to the student worksheet (LKM)
Lack of written communication practice	Adding open-ended questions that ask students to explain their answers	Mathematical communication rubric adapted

Table 7. Product Revisions and Follow-Up Based on Media Expert Input

Expert Input	Product Revisions	Follow-up
Lack of visual markers	Added icons for materials, examples, exercises, and discussion AI.	Icons are applied consistently throughout the learning materials
The graph is not clear	Enlarge the graph and adjust the clarity of the image (visual).	The visual of the settlement area is made clearer.
AI instructions are not yet explicit	Added a short guide to using AI discussions.	Instructions are placed at the beginning and discussion sheets

Table 8 presents student responses to the AI-assisted adaptive learning materials developed. Assessments were based on several aspects, including ease of use, clarity of material and examples, visual presentation and layout, AI-assisted adaptive feedback, and support for mathematical communication. The data in the table shows average scores, percentages, and assessment categories, reflecting students' level of acceptance and perception of the quality of the learning materials used in the learning process.

Table 8. Results of Student Responses to AI-Assisted Adaptive Learning Materials

Assessment Aspect	Number of Items	Average Score	Percentage (%)	Category
Ease of use of teaching materials	4	3,65	91,25	Excellent
Clarity of material and examples	4	3,58	89,50	Excellent
Visual presentation and layout	4	3,55	88,75	Excellent
AI-assisted adaptive feedback	4	3,60	90,00	Excellent
Support for mathematical communication	4	3,62	90,50	Excellent
Average	**20**	**3,60**	**90,00**	Excellent

Disseminate Stage

In the Disseminate stage, the AI-based adaptive SPtLDV teaching materials, which were declared feasible in the Develop stage, were disseminated on a limited basis to 10th-grade mathematics teachers at vocational high schools through outreach and mentoring activities. Dissemination included providing a brief user guide, explaining the adaptive features and AI-based feedback, and providing examples of the materials' application in SPtLDV learning. This stage aimed to introduce the product to potential users, obtain initial feedback on implementation, and encourage the use of the materials in learning practices. Dissemination activities were limited in accordance with the research objectives, and therefore, testing the learning effectiveness is recommended for further research

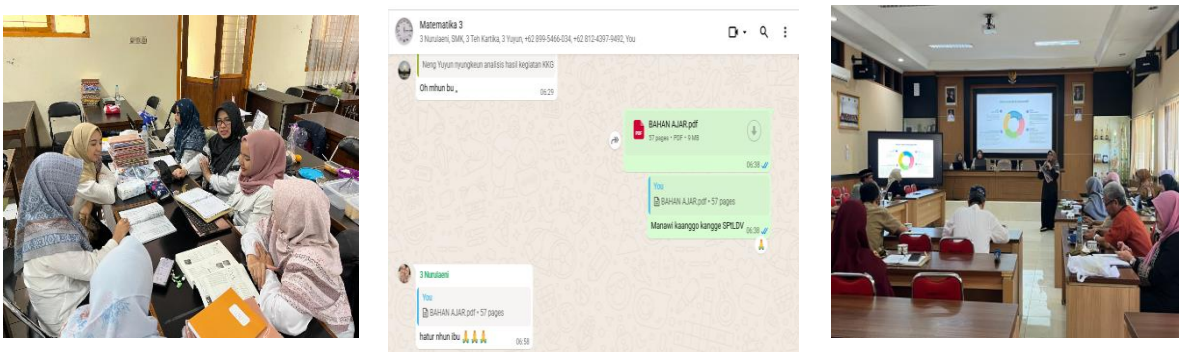

Figure 2. Dissemination process to the learning community

Based on the research results, several key findings were obtained, indicating that the majority of students (60-70%) experienced difficulty understanding teacher explanations and writing down mathematical solution steps coherently. This indicates that conventional teacher-centered learning approaches are not yet effective in building in-depth understanding and mathematical expression skills. These findings align with research by Mailisman (2020) and Danny et al. (2024) which stated that vocational high school students' mathematical communication skills, especially in written form and non-routine problem solving, are still low due to a lack of familiarity with contextual problems and the dominance of conventional methods.

On the other hand, student interest in adaptive learning (85-90%) and AI technology (around 70%) was very high. This indicates students' psychological readiness to embrace technology-based learning innovations. However, direct experience with AI remains limited, indicating the need for a gradual approach with clear explanations. This finding is consistent with research by Susanto et al. (2022), who reported that students desire AI that can visualize concepts and guide problem-solving, but its implementation is still rare.

The gap between the curriculum requirements (the Independent Curriculum), which emphasizes communication and differentiation, and the reality of classroom learning practices reinforces the urgency of developing adaptive AI-based teaching materials. As Mustafa (2024) noted, adaptive AI has significant potential for personalization, real-time feedback, and difficulty adjustment, which can bridge this gap.

On the other hand, based on the results of the teacher needs questionnaire analysis, teachers acknowledged that mathematics learning in vocational schools is still dominated by lectures and practice exercises (87.5%), which are teacher-centered and provide little opportunity for students to develop communication and independent reasoning skills. This situation is exacerbated by students' difficulties in understanding abstract concepts and solving word problems. This finding supports Lee & Yeo's (2022) statement that AI implementation has focused more on cognitive outcomes, while aspects of mathematical communication and reflection are often neglected. Teachers expressed a very high need for visual (100%), adaptive (87.5%), and AI-supported (87.5%) teaching materials. This reflects an

awareness of the importance of interactive and personalized media to accommodate the diversity of student abilities. However, teachers' limited understanding and experience in using AI poses a challenge to implementation. This finding aligns with the study by Agustina et al. (2024), which states that the integration of adaptive technology in Indonesia remains at the conceptual level and requires concrete support for educators.

In line with this, the analysis of Mathematics Learning Outcomes in Phase E of the Independent Curriculum shows that in mathematics learning, students are required to solve contextual problems and communicate the process and results mathematically. However, the teaching modules used in schools do not explicitly include learning strategies that encourage students to write down mathematical reasoning or reflect on the steps taken to solve the problems. This gap between curriculum demands and learning practices indicates the need for teaching materials that emphasize not only the final results but also students' mathematical thinking and communication processes.

Therefore, the development of AI-assisted adaptive teaching materials not only addresses pedagogical needs but also requires training and technical support for teachers, as Wahjusaputri et al. (2024) noted regarding the importance of developing learning models involving AI to improve the quality of learning in vocational schools (Ng et al., 2023; Zhang & Zhang, 2024; Jhuriani & Modiyani, 2025; Tütüniş, 2025).

Validation results from subject matter and media experts indicate that the AI-based adaptive learning materials meet very high content and media validity criteria (I-CVI $\geq$ 0.80; S-CVI/Ave = 1.00). All domains of content, pedagogy, language, display, and assessment accuracy were deemed relevant, clear, and sufficient. This indicates that the developed product meets the academic and technical quality standards required to support adaptive, communication-focused mathematics learning.

The high level of agreement among validators also reflects the consistency and maturity of the learning material design. A well-designed AI-based adaptive learning system can have a significant positive impact on learning outcomes, especially when developed through a rigorous validation process (Naseer & Khawaja, 2025; Yi et al., 2024; Wang et al., 2024; Sh & Supriyono, 2023; Moreira-Choez et al., 2025).

Revisions based on expert input, such as simplifying the language, emphasizing mathematical reasoning, and adding written communication exercises, have strengthened the research's focus on developing mathematical communication skills, rather than solely cognitive achievement. This approach supports Canonigo's (2024) findings that AI can be utilized to improve students' conceptual understanding and self-confidence if designed with metacognitive and communicative aspects in mind.

The revision process, based on input from material and media experts, has resulted in significant improvements to the teaching materials, particularly in terms of visual clarity, navigation consistency, and emphasis on mathematical thinking processes. The addition of visual icons, AI usage guides, and reflective questions to the Student Worksheets (LKM) is an effort to increase interactivity and student cognitive engagement.

The integration of adaptive discussion with innovative AI is a response to the findings of Fahrurozi et al. (2025) who stated that the application of AI in vocational schools is still exploratory and needs to be developed to be more reflective of students' thinking processes. By providing automated feedback and guiding questions, this teaching material not only adjusts the difficulty but also encourages students to articulate their reasoning, as emphasized in Rifai et al.'s (2025) study on an open-ended approach to improving mathematical communication.

The results of the student response questionnaire showed that the AI-assisted adaptive learning materials received an excellent rating, with an overall average score of 3.60, or 90%. High scores on ease of use, AI adaptive feedback, and support for mathematical communication indicate that the learning materials are easy to use, help students understand errors, and encourage students to communicate mathematical ideas more coherently. These findings indicate that the learning materials are not only theoretically valid but also practically valid and very well received by vocational high school students.

CONCLUSION

This research aims to develop adaptive teaching materials assisted by Artificial Intelligence (AI) to support the improvement of mathematical communication skills in vocational high school students. The results indicate a gap between the demands of the Independent Curriculum, which emphasizes differentiated learning and mathematical communication, and the conventional, teacher-centered mathematics learning practices in vocational high schools. This situation results in students' low ability to communicate mathematical ideas and thinking processes, despite high interest in technology and personalized learning.

Through the application of the 4D development model, this research successfully produced AI-assisted adaptive teaching materials of excellent quality. Validation results by material and media experts indicate that the teaching materials have a very high level of content and media validity, making them suitable for use in mathematics learning. The developed teaching materials not only function to adjust the difficulty level of the material but also systematically encourage mathematical communication through adaptive feedback, concept visualization, and reflective practice.

This research provides practical and conceptual contributions to the field of mathematics education and educational technology, particularly in the development of AI-based teaching materials at the vocational high school level, which has so far been limited. Pedagogically, the research findings emphasize that the use of AI in mathematics learning needs to be directed not only at content personalization but also at mathematical communication as part of 21st-century competencies in vocational settings. Therefore, the developed AI-assisted adaptive teaching materials have the potential for wider application, with recommendations for further research to test their effectiveness through classroom experimental designs.

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