



Developing STEAM-Based Digital Mathematics Teaching Materials to Enhance Creativity

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Abstract

This study was motivated by the low level of creativity among elementary school students in mathematics learning, which is still largely dominated by conventional methods and rote memorization. The aim of this study was to develop digital mathematics teaching materials based on the STEAM approach (Science, Technology, Engineering, Arts, and Mathematics) to enhance students' creativity. This study employed a Research and Development (R&D) design using the ADDIE model, which consists of Analysis, Design, Development, Implementation, and Evaluation. The analysis stage was conducted through classroom observations and interviews to identify learning needs. The developed product was validated by education experts, subject-matter experts, and STEAM experts, and was subsequently tested for practicality by teachers and students, as well as for effectiveness through the implementation of STEAM-based digital mathematics teaching materials at Lab School SD Unismuh Makassar. The results of the needs analysis indicated a demand for more interactive learning strategies and media that could help students understand concepts visually and contextually. The design of STEAM-based digital mathematics teaching materials in elementary schools is not only oriented toward academic outcomes, but also toward shaping students' character, creativity, and 21st-century skills. The evaluation results from the three validators (education expert, subject-matter expert, and STEAM expert) showed an average score of 3.28 or 85.56%, which falls into the very valid category. The practicality test involving teachers and students yielded an average score of 3.3 or 82.5%, which falls within the interval of $70\% \leq P < 85\%$ and is categorized as practical. This indicates that the teaching materials were considered easy to use, clear, and relevant to students' learning needs. The implementation results showed a significant improvement. The analysis demonstrated that STEAM-based digital mathematics teaching materials contributed to an increase in students' creativity. Descriptively, the mean creativity score increased from 2,799 (pretest) to 3,399 (posttest). This improvement was also supported by a class N-gain score of 0.500 (moderate category), indicating a meaningful improvement in learning from an educational perspective. Furthermore, the paired-sample difference test revealed a significant difference between the pretest and posttest results (Sig. 2-tailed = 0.002 < 0.05), confirming that the use of STEAM-based digital teaching materials had a significant effect on improving students' creativity.

Keywords: Teaching Materials; Digital Mathematics; STEAM; Creativity

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INTRODUCTION

21st-century learning demands an improvement in the quality of education that can accommodate critical, creative, collaborative, and problem-solving skills. Amidst rapid technological developments, the challenge for the world of education is how to integrate technology with innovative learning processes. Mathematics learning in elementary schools (SD) plays a crucial role in building the foundation of students' logical, critical, and creative thinking skills. The design and development of digitally oriented STEAM (Science,

Technology, Engineering, Arts, and Mathematics) resources for mathematics education is an important area to encourage creative learning, especially in the context of contemporary educational challenges and the ongoing digital transformation (Rilexen SP Mulder W et al., 2024; Martín-Cudero D et al., 2024; Rafiq-uz-Zaman M, 2025). This approach emphasizes interdisciplinary integration, innovation, and practical application, going beyond the limitations of traditional STEM education in fostering creativity (Bedewy et al, 2023; Rafiq-uz-Zaman M, 2025; Li, J., 2024). This approach aims to overcome the limitations of traditional STEM education by incorporating the arts, thereby enhancing creativity, critical thinking, and problem-solving skills, which are crucial for 21st-century competencies (Rafiq-uz-Zaman, M.,2025; Cheung, A.K.K.,2024; Samuel Iwanger Ruth et al., 2025). Digital mathematics resources, often referred to as Digital Learning Spaces (DLS) or Personal Teaching/Learning Environments (PTE/PLE), utilize technology to create dynamic and engaging learning contexts that foster a deeper understanding of complex mathematical concepts (Yuliardi, R et al, 2024; Cirneanu, A.-L et al, 2024).

STEAM education, by incorporating the Arts, aims to promote comprehensive problem-solving, divergent thinking, and adaptability along with analytical skills (Rafiq-uz-Zaman M, 2025). This is particularly relevant in mathematics, where the STEAM approach can enhance the understanding of mathematical concepts, critical thinking, creativity, and problem-solving skills, especially in primary education (Ibragimova, M., 2024; Sasmita et al, 2025). For example, a systematic review of mathematics education from the STEAM approach at the secondary and pre-university levels highlighted the urgent need for renewal of quality education through new methodologies that emphasize creation, collaboration, and learning by doing (Martín-Cudero D et al., 2024). The integration of positive emotions and flow experiences in STEAM education can further enhance student motivation, which is a key factor that often hinders its effectiveness (Tang, X., 2024).

The digitization of learning resources plays a crucial role in this transformation. Digital learning spaces (DLS), an advanced version of conventional Learning Management Systems (LMS), can be customized to create personalized teaching and learning environments that foster mathematical creativity (Yuliardi, R et al., 2024). Web-based science learning media with a STEAM approach, for example, have been shown to enhance students' creative thinking skills (Rilexen SP Mulder W et al., 2024). Digital tools in STEM education also have a positive impact on student creativity, as evidenced by a study focusing on prospective physics teachers in specialized fields (Skakov, M et al., 2025). The use of digital media, such as Canva for Education, integrated with a STEAM approach, can enhance students' creative mathematical thinking skills, even in elementary school settings (Heshinta, L et al., 2025).

Key principles in designing and developing digitally oriented STEAM mathematics resources for creative learning include: (1) Interdisciplinary Integration: STEAM curriculum design requires effective strategies to integrate science, technology, engineering, arts, and mathematics to provide richer and more hands-on learning experiences (Li, J., 2024). This can involve projects where students apply physics concepts to create sound effects for animated videos, thereby developing creativity through integrated STEAM education (Filipe, J et al., 2024); (2) Technology Integration: New technologies, such as virtual simulations, can significantly enhance student engagement in STEAM learning environments (citation:29). (Virtual reality (VR) technology, for example, can simulate real-world environments for teaching programming, offering an innovative learning method for STEAM education (Jin, Z et al., 2024). The use of digital fabrication tools can also introduce prospective teachers to the creation of mathematical aids, deepening their understanding of mathematical content and pedagogy (Stigberg, H et al, 2024); (3) Focus on Creativity and Innovation: STEAM education explicitly aims to foster creativity and innovation, which are essential 21st-century skills (Kangas, K et al., 2022; Rafiq-uz-Zaman M, 2025; Litvin, A et al., 2024). Project-based STEAM programs have been shown to be effective in developing creativity in elementary

school science education (Cheng, L., 2022); (4) Teacher Readiness and Pedagogical Design: The development and curation of technology-based learning resources by prospective teachers is crucial for differentiated learning in STEM education (Estaiteyeh, M et al., 2024). The competence of prospective teachers in developing mathematics-centered STEAM learning materials is also very important (Han, H et al., 2024). The design and implementation of effective digital learning resources are influenced by factors such as digital content design, teacher pedagogical roles, and student interactions with learning resources (Fiangga, S et al., 2021); and (5) Accessibility and Inclusivity: The STEAM + X framework expands the transdisciplinary nature of STEAM, encourages the integration of multiple disciplines with various cross-cultural iterations, and fosters inclusive practices (Bedewy, SE., 2023; Unterfrauner, E et al., 2024). However, challenges remain, especially in areas with inadequate technology access, so strategies are needed to empower educators to use accessible technology for STEAM implementation (Santos et al., 2025).

The development of digital learning resources for realistic mathematics education has proven beneficial for virtual learning, particularly in situations such as the COVID-19 pandemic (Fiangga, S et al., 2021). The design of these learning resources should consider how digital content, teachers' pedagogical roles, and student interactions influence learning effectiveness (Fiangga, S et al., 2021). Furthermore, the continued evolution of digital technologies requires adaptive strategies in educational innovation for STEAM education (Lavicza, Z et al., 2022). When considering the development of such resources, an ethical enactivist approach can be beneficial, leveraging new educational technology tools and immersive learning opportunities to design intelligent and dynamic learning systems that enhance self-esteem and global well-being (Aguayo, C et al., 2023). Reflections on the concept of STEAM education in art and design education in the context of digitalization emphasize the core value of interdisciplinary integration, particularly the importance of design thinking and creative solutions (Li, Z., 2024). The integration of data science and the Internet of Things (IoT) into STEAM education through new and emerging technologies further exemplifies this transdisciplinary approach (Liston, M et al., 2022).

Digital resources for mathematics teaching and learning have expanded significantly with the advent of the internet, resulting in a "resource" approach in mathematics education research (Tgalova, J., 2024). Formative models for assessing STEAM educational creations are also being developed to help parents and instructors evaluate STEAM products (Hsu, T.-C et al., 2022). The implementation of hybrid teaching modes in STEAM subjects, guided by models such as ADDIE (Analysis-Design-Development-Implementation-Evaluation), can effectively investigate the effectiveness of such approaches from an educational research perspective (Huang, X., 2024). Teacher perceptions of the STEAM approach are generally positive, with a significant majority agreeing that this approach transforms the classroom into a creative environment (Alkhatatneh, S., 2024). However, clearer guidelines and support are still needed to realize the full potential of STEAM in the curriculum (Alkhatatneh, S., 2024).

The goal is to move beyond traditional lecture-based models and embrace innovative approaches such as digital escape rooms, which offer immersive and engaging experiences that encourage critical thinking, problem-solving, and teamwork in STEM education (Sidekerskienė, T et al., 2023). This is crucial for developing AI literacy among elementary school students, especially in the era of generative AI, where constructivist, constructionist, and transformative learning theories can be applied through classroom interventions (Relmasira., 2023). Overall, the design and development of digitally oriented STEAM resources for mathematics education is a multifaceted effort that integrates pedagogical innovation, technological advancements, and a deep commitment to fostering creativity and critical thinking in learners at all levels of education (Tsakeni, M., 2024; Papadopoulou, E.A., 2024; Pazmiño Núñez et al., 2025).

A fundamental aspect in the development of such resources involves constructivist pedagogy, which emphasizes student agency, exploration, and problem-solving (3). This aligns with the idea that learning is an active process in which students construct knowledge and meaning from their experiences. Digital platforms facilitate this by offering interactive simulations, adaptive instruction, and content tailored to individual student needs (Samuel Iwanger Ruth et al., 2025; Cirneanu, A.-L et al, 2024). For example, web-based DLS can integrate customizable elements that enable the formation of diverse learning networks, going beyond conventional Learning Management Systems (LMS) (Yuliardi, R et al, 2024).

Computational thinking is another integral component, often integrated through programming languages such as Scratch or Python, dynamic geometry software such as GeoGebra, or data visualization tools to model mathematical concepts (Koyunkaya, M.Y. et al., 2024). This allows students to engage with mathematics not just as a set of rules, but as a tool for creating and understanding complex systems. Technologies such as augmented reality, computer-aided design (CAD) software, and 3D printing further enable the visualization and modeling of real-world mathematics in STEAM settings (Haas, B. et al., 2023). The integration of artificial intelligence (AI) into STEAM education also offers new opportunities for personalized and adaptive instruction, enhancing critical thinking, creativity, and problem-solving skills by tailoring content and facilitating interactive simulations (Samuel Iwanger Ruth et al., 2025; Cahyono, A.N. et al., 2025). For example, research has investigated the use of AI-based Motion Capture (MoCap) to create mathematical dances, promoting creativity among learners through the synergy of mathematics and technology (Cahyono, AN et al., 2025).

Artistic expression is utilized by combining visual design, music, animation, or storytelling to represent mathematical structures, such as symmetry or fractals (Cahyono, AN et al., 2025). These practices enable teachers to integrate cultural, architectural, and historical contexts into STEAM learning, thereby encouraging creative thinking and innovation (Rafiq-uz-Zaman, M., 2025). This ensures that digital resources can meet the needs of diverse learners, providing appropriate support for various knowledge bases (Chernikova, O et al., 2019). Furthermore, formative assessment is embedded within digital interactions, providing real-time feedback and utilizing learning analytics to inform both students and educators (Cirneanu, A.-L et al, 2024). Empirical evidence supports that such digital resources enhance conceptual understanding, motivation, and creative confidence (Kangas, K et al., 2022; London, E., 2022). Project-based STEAM programs have also demonstrated effectiveness in fostering creativity in primary school science education, with students actively engaged in creating objects perceiving higher value in their learning outcomes (London, E., 2022). This aligns with the “IKEA effect” in education, where students’ investment in creating an object leads to increased perceived value and desire for it (London, E., 2022).

Collaborative design processes involving mathematics teachers, computer scientists, and researchers are crucial for creating innovative digital resources, fostering social creativity within these communities of interest (El-Demerdash et al., 2025; Kynigos, C et al, 2020). This co-design approach ensures that resources are effective and contextually appropriate, by sharing decision-making power and engaging all stakeholders as active co-creators (Videla, R et al., 2025; El-Demerdash et al., 2025). Specific examples of STEAM-oriented digital mathematics resources include platforms designed to enhance mathematical creativity (citation:4)(8), digital escape rooms that encourage critical thinking and problem-solving in STEM education (Sidekerskienė, T et al., 2023). These innovations provide immersive and engaging experiences that go beyond traditional lecture-based models (Sidekerskienė, T et al., 2023). The use of digital tools such as GeoGebra in mathematical modeling problems further illustrates how technology can support prospective mathematics teachers in designing and solving complex tasks collaboratively (Koyunkaya, MY et al., 2024).

Overall, the development of STEAM-based digital mathematics teaching materials represents a significant shift towards a more engaging, interdisciplinary, and creative learning environment. It leverages technological advances to cultivate essential skills for future generations, bridging the gap between theoretical knowledge and practical application while incorporating diverse forms of expression and problem-solving strategies (Cheung, ACK., 2024; Martín-Cudero et al, 2024; Pazmiño Núñez et al., 2025)

METHOD

This research is a research and development (R&D) design that uses the ADDIE development model, by Robert Maribe Branch (2009). The research was carried out in 5 stages, namely the Analysis, Design, Development, Implementation and Evaluation stages. The Analysis stage, at this stage, needs analysis and Front-end were carried out. At the Needs Analysis stage, material analysis, curriculum analysis, technology analysis, and media analysis were carried out. The Design stage, at this stage, plans were made for the development of STEAM-based spatial e-modules to increase student creativity. The Development stage, at this stage, revised STEAM-based digital mathematics teaching materials were developed based on expert input (Valid). The Implementation stage, at this stage, after the STEAM-based digital mathematics teaching material plan was deemed suitable for use, it was then tested on teachers and students, the implementation in the form of: a). Simulation, b). Limited Trial, on several students and the results will be evaluated as a basis for further revisions (Practical). Evaluation stage (Evaluation), at this stage research was conducted on STEAM-based digital mathematics teaching materials that had been tested previously, and applied to students (Effective). The subjects of this research were 15 fifth-grade students of Unismuh Elementary School, Makassar, South Sulawesi Province. Sampling was carried out using saturated sampling techniques.

The instrument used in this study is a validation questionnaire instrument conducted by material experts and media experts to assess the feasibility of the developed STEAM-based digital mathematics teaching materials, as well as teacher and student response questionnaires to determine the practicality of STEAM-based digital mathematics teaching materials after use. Then the test was given twice, namely before the learning process using STEAM-based digital mathematics teaching materials in the form of pre-test questions and after the learning process using STEAM-based digital mathematics teaching materials in the form of post-test questions. Data analysis techniques used for product validation are quantitative and qualitative data analysis. The validity of STEAM-based digital mathematics teaching materials to increase student creativity is obtained through the results of validation by material experts and experts, the practicality of STEAM-based digital mathematics teaching materials is obtained from teacher and student response questionnaires and to measure effectiveness using descriptive statistical analysis for validity and practicality as well as parametric analysis (paired sample t-test) to measure the increase in student creativity using STEAM-based digital mathematics teaching materials. Then, an N-gain test was conducted to determine the effectiveness of the STEAM-based digital mathematics teaching materials to increase the creativity of the students that had been developed.

Validity Test of Digital Mathematics Teaching Materials

Validity testing was carried out by comparing the average validity scores of education experts, material experts and STEAM experts using a Likert scale consisting of 4 assessment scales as shows in Table 1.

Table 1. Validity Criteria

Score	Category
3.26–4.00	Very Valid
2.51–3.25	Valid

Score	Category
1.76–2.50	Less Valid
1.00–1.75	Invalid

Digital mathematics teaching materials on spatial geometry with a STEAM approach to improve students' creativity are said to be valid from material and media experts if the average validity value is in the valid category obtained at least valid.

Practicality Test of Digital Mathematics Teaching Materials

The developed learning media is deemed practical if the results of the teacher and student questionnaire responses show a positive assessment. This assessment is obtained through data analysis of the questionnaire responses completed by the teachers and students. A learning medium is considered practical if the percentage of teacher and student questionnaire responses reaches at least 70%. This analysis is conducted using the following formula, where P = Percentage of Answers; ΣNR = Total response value for each aspect; NR Max = Total value of all questionnaire responses for each aspect.

$$P = \frac{\Sigma NR}{NR \text{ Max}} \times 100\%$$

The percentages obtained are then interpreted with reference to the following criteria.

Table 2. Percentage Criteria for Answers

Evaluation	Category
$85\% \leq P$	Very Practical
$70\% \leq P < 85\%$	Practical
$50\% \leq P < 70\%$	Less practical
$P < 50\%$	Impractical

Digital mathematics teaching materials on spatial geometry with a STEAM approach to improve students' creativity are said to be practical based on teacher and student response questionnaires with an average score in the practical category obtained at least practical.

Testing the Effectiveness of Digital Mathematics Teaching Materials

The effectiveness of STEAM-based digital mathematics teaching materials on spatial shapes to improve students' creativity can be seen from the achievement of the minimum completion criteria (KKM), namely 75. The creative thinking test questions consist of 5 questions (see Appendix 1), creative thinking indicators (in Table 3).

Table 3. Assessment Indicators

Indicator	4 (Very Good)	3 (Good)	2 (Enough)	1 (Need Guidance)
Fluency	Generates many relevant ideas/answers (≥ 4 correct alternatives/methods/examples).	Generate several relevant ideas (3 correct alternatives/ways/examples).	Generates a few relevant ideas (2 correct alternatives/ways/examples).	Only 1 idea or mostly irrelevant/incorrect.
Flexibility	Using a variety of strategies/representations and being able to switch approaches (e.g. formulas + nets + reasoning/diagrams).	Using 2 different strategies/representations (e.g. formula and net).	Dominant 1 strategy; other strategies are less precise/less complete or very similar variations.	Just 1 approach without any variations.

Indicator	4 (Very Good)	3 (Good)	2 (Enough)	1 (Need Guidance)
Originality	There are unique/unusual ideas but they are still correct and relevant (e.g. net designs/story problems/rare size combinations).	There is a slight element of novelty; at least 1 idea is slightly different from the general answer.	Answers tend to be general/standard; novelty is limited.	Copycat/minimal, or "unique" but irrelevant/incorrect.

Then, the measurement of the pre-test and post-test results given before and after the learning process using STEAM-based digital mathematics teaching materials to improve student creativity was analyzed through several stages. First, the measurement of the pre-test and post-test results given before and after the learning process was carried out. The difference between these two scores indicates an increase in students' creativity abilities. To measure the extent of this increase, the normalized gain formula (N-gain) is used as follows, where S_{pre} = Average pre-test score; S_{post} = Average post-test score; S_{max} = Maximum score.

$$N - gain = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}}$$

The N-gain values obtained are classified into three effectiveness categories as presented in Table 4 (Hake, 1999).

Table 4. Interpretation of Gain Value

Evaluation	Category
$g > 0.7$	Tall
$0.3 > (N - gain) \geq 0.7$	Currently
$(N - gain) < 0.3$	Low

Furthermore, increased effectiveness is also measured by the percentage increase in overall student learning outcomes. This percentage is calculated based on the difference between the average pre-test and post-test scores, which is then converted into a percentage increase. This percentage is interpreted based on the following criteria:

Table 5. Criteria for Determining Student Creativity

Percentage (%)	Category
0.0 – 1.0	Lack of creativity
1.1 – 2.0	Quite Creative
2.1 – 3.0	Creative
3.1 – 4.00	Very Creative

RESULTS AND DISCUSSION

The result of this research and development is a STEAM-based digital mathematics teaching material. This research was conducted on fifth-grade students at Unismuh Makassar Elementary School, referring to the ADDIE development model, namely:

Analysis Stage

The initial step in developing digital mathematics teaching materials was to conduct a field study to determine what was needed. In the process, interviews were conducted to determine important things such as classroom learning conditions, the material being studied, the initial conditions of students, and their needs in learning. Analysis showed that the facilities at the school were adequate to support teaching and learning activities with the presence of smart TVs that could be utilized in the learning process in the classroom. The material on spatial figures developed was part of the lessons in grade V. The spatial figures consist of

cubes, cuboids, pyramids, and prisms. Student analysis showed that students had difficulty in understanding mathematical concepts, one of the causes being the lack of strategies and interesting learning media that were able to present them visually, and students' concentration while learning tended to be easily divided or disturbed.

Interviews revealed that students' creativity in solving math problems is still relatively low. This is due to an in-depth understanding of concepts, which leads students to simply follow the steps and examples provided by the teacher. This situation indicates a need for more interactive learning strategies and media that can help students understand concepts visually and contextually. This is expected to encourage active student involvement and improve creativity and understanding in solving math problems, particularly in the field of geometric shapes.

Design Stage

In the design phase, researchers began designing and compiling digital mathematics teaching materials for spatial geometry (cubes, cuboids, pyramids, and prisms) according to student needs with a STEAM-based structure. This design includes a systematic presentation of concepts, integrating mathematical concepts into real-world situations close to students' experiences. The principle of contextual learning is key, where each mathematical topic is harmoniously linked to Science, Technology, Engineering, and Art. For example, the concept of measuring length can be linked to a project to create a simple bridge model, so that students not only understand numbers and formulas but also see how these concepts are applied to solve real-world problems. The design of teaching materials must take into account the characteristics of elementary school students' cognitive development. The material is presented gradually from simple to complex, with easy-to-understand language and engaging visual illustrations. The use of interactive media such as animations, simple simulations, short videos, and educational games will help visualize abstract mathematical concepts more concretely. The digital interface must be child-friendly, containing clear navigation, intuitive icons, and instant feedback features that can motivate students to continue learning.

This digital teaching material accommodates project-based activities that encourage collaboration, creativity, and higher-order thinking skills. Simple projects like designing a school garden by calculating area and perimeter or creating a batik pattern with fold and rotational symmetry can be a means of applying mathematical concepts in a fun way. Assessment is conducted authentically, taking into account work processes, innovation skills, and teamwork. With this design, mathematics learning in elementary schools is not only oriented towards academic outcomes but also shapes students' character, creativity, and 21st-century skills.



Figure 2. STEAM-Based Digital Mathematics Teaching Materials

Development Stage

The validation process was conducted prior to student trials to identify and address issues related to content, presentation, and technical aspects, ensuring effective and reliable learning materials. The validation process was conducted by three validators: an education expert, a STEAM expert, and a mathematics subject matter expert.

Table 6. Education Expert Validation Test

No.	Aspect	Score	Percentage	Short note
1	Suitability with the characteristics of elementary school students	4	100	Addition of prerequisite material, explanation of the benefits of the material, integration of relevant science and art subjects, introduction to the use of the GeoGebra application, and more challenging practical exercises.
2	Pedagogical design and learning flow	3	75	
3	Assessment and evaluation	4	100	
4	Support for creativity (pedagogical perspective)	4	100	
5	Inclusivity, safety, and ethics	3	75	
6	Language, readability, and layout	4	100	
7	Practicality of implementation in the classroom	3	75	
Amount		25	625	
Average		3.57	92.85	

Table 7. Material Expert Validation Test

No.	Aspect	Score	Percentage	Short note
1	Alignment of curriculum and objectives	4	100	Differentiate colors on the XYZ axis, enlarge GeoGebra output, and add more example problems to make the material easier for students to understand.
2	Conceptual accuracy and mathematical truth	3	75	
3	Concept development and depth of material	4	100	
4	Problem solving and reasoning	3	75	
5	Quality of practice and assessment items	3	75	
6	Creativity support (material perspective)	4	100	
7	Digital content integrity (math specific)	3	75	
Total		23	600	
Average		3.28	85.71	

Table 8. STEAM Expert Validation Test

No.	Aspect	Score	Percentage	Short note
1	Authentic STEAM integration	3	75	A more detailed definition of STEAM, an explanation of the Engineering Design Process, a clearer perspective on STEAM, and better integration between STEAM components.
2	Inquiry, design, and engineering processes	3	75	
3	Utilization of technology (quality of digital learning)	2	50	
4	Integration of arts and development of creativity	3	75	
5	Creativity indicators (evidence in the product)	3	75	
6	Collaboration and communication	4	100	
7	The feasibility of scientific and engineering thinking for elementary school	3	75	
8	Implementation and assessment in STEAM	3	100	
Total		24	625	
Average		3	78.12	

From the validation process carried out by 3 experts, the average value of all aspects assessed was obtained; the validation test for education experts was 3.57 or 92.85%, the validation test for material experts was 3.28 or 85.71%, and the validation test for STEAM

experts was 3 or 78.12%. Based on the assessments of the three validators, the average value was 3.28 or 85.56%, which is in the very valid category.

Implementation Stage

In the practicality test stage, it was carried out by distributing STEAM-based digital mathematics teaching materials to users, in this case mathematics teachers and fifth-grade students at the Lab. School of Unismuh Elementary School. The teachers and students were asked to fill out the questionnaire provided to find out the responses of teachers and students regarding the teaching materials developed. The practicality test questionnaire included student response questionnaires in the form of aspects of Clarity of instructions & materials (easy to understand), Attractiveness of appearance & learning motivation, Involvement & relevance to learning activities (interactive, making active), and the accuracy of the language presented in the teaching materials.

Table 9. Practicality Test of Teachers and Students

No.	Practical Aspects	Score	Percentage	Short note
1	Clarity of instructions & materials (easy to understand)	3.4	85	Very easy to use, clear with a very attractive teaching material design and relevant to students' learning needs.
2	Attractive appearance & learning motivation	3.2	80	
3	Engagement & relevance to learning activities (interactive, making active)	3.2	80	
4	The accuracy of Indonesian language presented in teaching materials	3.4	85	
Total		13.2	330	
Average		3.3	82.5	

The practicality test, conducted with the involvement of mathematics teachers and students, yielded an average score of 3.3 or 82.5%, within the $70\% \leq P < 85\%$ range, categorized as practical. This indicates that the teaching materials are considered easy to use, clear, and relevant to students' learning needs.

Evaluation Stage

The effectiveness test with the implementation of the developed STEAM-based digital mathematics teaching materials is the final stage of this research and development activity. At this stage, product use and evaluation of the results of product use are carried out to determine the level or extent to which this teaching material works effectively, which is indicated by the fulfillment of students' creative thinking indicators (Fluency, Flexibility, and Originality) from students' answers to each question given during the post-test. In addition, statistically, a significant difference was seen in students' answers between the pre-test and post-test.

In terms of flow, the effectiveness testing process was carried out when teachers used digital mathematics teaching materials developed at the Unismuh School Lab., which began with the implementation of a pre-test to collect data related to students' creative thinking abilities which were reviewed from each student's answers based on indicators of creative thinking abilities. After that, the learning process began using the STEAM-based digital mathematics teaching materials that had been developed by the researcher, and after the use of the product took place according to schedule, the researcher then returned to collect data through the post-test process.

The results of the post-test were then used as comparative data in analyzing the effectiveness of the developed product. A summary of the assessment results of students' creativity for each indicator, both before and after the implementation or use of digital mathematics teaching materials, is presented below:

Table 10. Average values and N-gain

N	Mean Pre	Mean Post	N-gain	Category
15	2,799	3,399	0.500	Currently

Table 11. Average Value per indicator

Aspect	N	Mean Pre	Mean Post	Gain	N-gain	Category
Fluency	15	3.533	3.800	0.267	0.571	Moderate
Flexibility	15	2.600	3.600	1.000	0.714	High
Originality	15	2.200	2.800	0.600	0.333	Moderate

Table 12. t-test results

Aspect	Sig. (2-tailed) Wilcoxon	Sig. (2-tailed) Paired t-test
Fluency	0.206	0.217
Flexibility	0.004	<0.001
Originality	0.014	0.007

The analysis results show that STEAM-based digital mathematics teaching materials contribute to increasing student creativity. Descriptively, the average creativity score increased from 2.799 (pretest) to 3.399 (posttest). This increase is also supported by the class N-gain value of 0.500 (moderate category), which indicates an increase in educationally meaningful learning. Furthermore, the paired difference test showed a significant difference between the pretest and posttest (Sig. 2-tailed = 0.002 < 0.05), so it can be confirmed that the use of STEAM-based digital teaching materials has a real impact on increasing student creativity.

Based on the creativity indicator, the fluency indicator increased from 3,533 to 3,800 with an N-gain of 0.571 (moderate), but the significance test did not show a significant difference ($p = 0.206 > 0.05$). Pedagogically, this condition can be explained through two possibilities. First, the initial high fluency score indicates a ceiling effect, namely the room for improvement becomes narrow because students have approached the maximum score since the pretest. Second, STEAM-based learning—especially when emphasizing design/projects—often demands more in-depth solutions and selection of the best strategy, rather than simply generating as many ideas as possible. If the activities in the teaching materials are more oriented towards the accuracy of the process and the final product, then the quantity of ideas (fluency) can increase but not consistently enough to be statistically significant. The flexibility indicator showed the most prominent increase: the average rose from 2,600 to 3,600, with an N-gain of 0.714 (high) and a significant difference ($p = 0.004 < 0.05$). These findings are highly consistent with creativity theory, which defines flexibility as the ability to switch strategies, use multiple representations, and choose alternative approaches. In STEAM learning, students generally face contextual problems that cannot be solved with a single routine procedure.

The engineering process encourages students to conduct trial-evaluation-revision, encouraging them to try several methods and compare their effectiveness. The arts element reinforces the use of visual/aesthetic representations, which enriches the variety of strategies. Therefore, STEAM-based digital learning materials naturally facilitate flexible thinking—for example, through the exploration of various models, the use of technology to visualize concepts, and problem-solving activities that open up multiple solution paths. The originality indicator increased from 2,200 to 2,800, with an N-gain of 0.333 (moderate) and a significant difference ($p = 0.014 < 0.05$). Originality is related to the novelty of ideas and the tendency to produce unusual solutions. The significant increase in originality suggests that the developed learning materials have opened up space for the emergence of more unique ideas, especially because STEAM provides an authentic context and opportunities for cross-disciplinary integration. However, the "moderate" increase in originality is understandable, as novel ideas typically require a longer period of familiarization, broader exploratory experiences, and more open-ended tasks to encourage students to move beyond "safe" answer patterns. In other words, the teaching materials are already effective in triggering novelty, but reinforcement can be achieved through designing more challenging activities and providing students with greater freedom to develop solutions.

Conceptually, creativity in mathematics learning is related to divergent thinking skills—generating numerous, diverse, and unique ideas—which are commonly operationalized through indicators of fluency, flexibility, and originality (Guilford; Torrance). Learning environments that encourage exploration, multiple representations, and open-ended problem solving tend to strengthen these abilities. In the context of STEAM, the integration of science, technology, engineering, art, and mathematics places students in authentic problem-solving situations that require the iterative development of ideas and strategies (Yakman). Thus, the increase in creativity found is in line with the character of STEAM, which emphasizes the creative process in understanding concepts and solving problems.

CONCLUSION

This research develops STEAM-based digital mathematics teaching materials to enhance students' creativity. This research was conducted using the ADDIE development model, with the following stages: analysis, design, development, implementation, and evaluation. The needs analysis shows that students experience difficulties in understanding mathematical concepts, students' creativity in solving mathematics problems is still relatively low and there is a need for more interactive learning strategies and media that can help students understand concepts visually and contextually. The design of this teaching material is expected to encourage active student involvement and increase creativity and understanding in solving mathematical problems, especially in the material of spatial shapes.

Expert validation results obtained an average of 3.28 or 85.56%, in the "very valid" category. The practicality test showed that the teacher and student responses obtained an average value of 3.3 or 82.5%, in the interval of $70\% \leq P < 85\%$ with a practical category, this means that the teaching materials are considered easy to use, clear, and relevant to the learning needs of students. The effectiveness test showed that STEAM-based digital mathematics teaching materials contributed to increasing student creativity. Descriptively, the average creativity increased from 2.799 (pretest) to 3.399 (posttest). This increase was also supported by the class N-gain value of 0.500 (moderate category), which indicates an increase in educationally meaningful learning. Furthermore, the paired difference test showed a significant difference between the pretest and posttest (Sig. 2-tailed = $0.002 < 0.05$), so it can be confirmed that the use of STEAM-based digital teaching materials has a real impact on increasing student creativity.

RECOMMENDATION

Future research is recommended to expand the application of STEAM-based digital mathematics teaching materials to other mathematics topics and educational levels. This effort will enhance the empirical evidence on the adaptability and effectiveness of digital learning. STEAM-oriented learning in various contexts. Furthermore, the integration of advanced technologies such as augmented reality (AR) and artificial intelligence (AI) can further enhance interactivity and creativity in learning. Teacher professional development programs also need to be strengthened to enhance pedagogical and digital competencies in implementing STEAM-based learning. Collaborative efforts between teachers, educational technologists, and curriculum developers are crucial to ensuring the sustainability of innovation in mathematics education.

However, several potential barriers may impact the implementation and outcomes of similar studies, including teachers' limited technological skills, inadequate school infrastructure, and time constraints in integrating digital learning materials. Student engagement can also impact learning effectiveness. Therefore, systematic support, ongoing training, and adequate digital facilities are needed to minimize these challenges.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mutmainnah	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Sitti Fithriani Saleh	✓	✓	✓			✓		✓	✓	✓	✓	✓		
Abdul Halim Abdullah	✓		✓	✓			✓	✓		✓	✓		✓	✓
Jumrah					✓		✓		✓	✓		✓		✓
Nurwanda					✓	✓	✓					✓	✓	
Ahmadhani			✓			✓	✓			✓		✓	✓	

Conflict of Interest Statement

Authors state no conflict of interest

Informed Consent

We have obtained informed consent from all individuals included in this study.

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Appendix 1
LEMBAR SOAL – PRETEST
(Kreativitas Peserta Didik)

Mata Pelajaran	Matematika (Bangun Ruang)
Nama	
Kelas	
No. Absen	
Tanggal	

Petunjuk:

Kerjakan dengan jujur dan rapi.

Pada beberapa soal, kamu diminta memberi lebih dari satu cara/jawaban.

Gunakan gambar/sketsa jika diperlukan, dan beri label ukuran.

Gunakan $\pi = 3,14$ (jika ada soal bola).

Soal

1. Sebuah kubus memiliki sisi merah di bagian atas. Tuliskan dan/atau gambarkan minimal 3 cara berbeda memutar kubus sehingga sisi merah berada di depan.



Cara 1 (tuliskan langkah + sketsa):

Cara 2 (tuliskan langkah + sketsa):

Cara 3 (tuliskan langkah + sketsa):

Jika ada, cara lain:

Figure A1. Pre-test questions