

BUKTI KORESPONDENSI

ARTIKEL JURNAL INTERNASIONAL BEREPUTASI

Judul artikel : Fostering mathematical creativity and autonomy through a STEM-based digital learning space

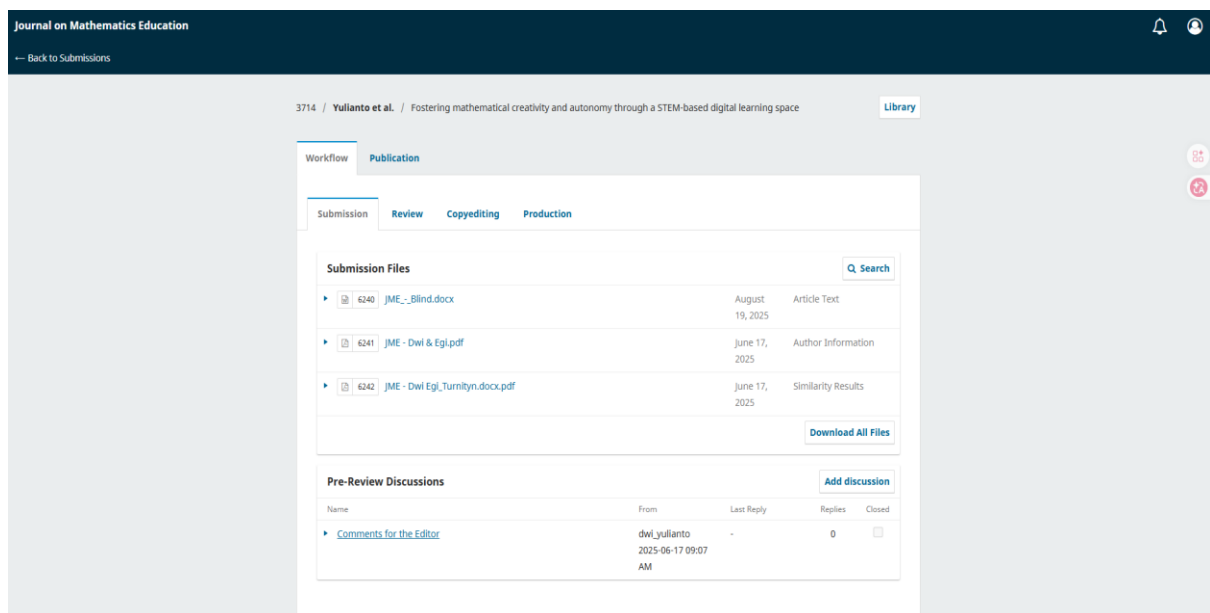
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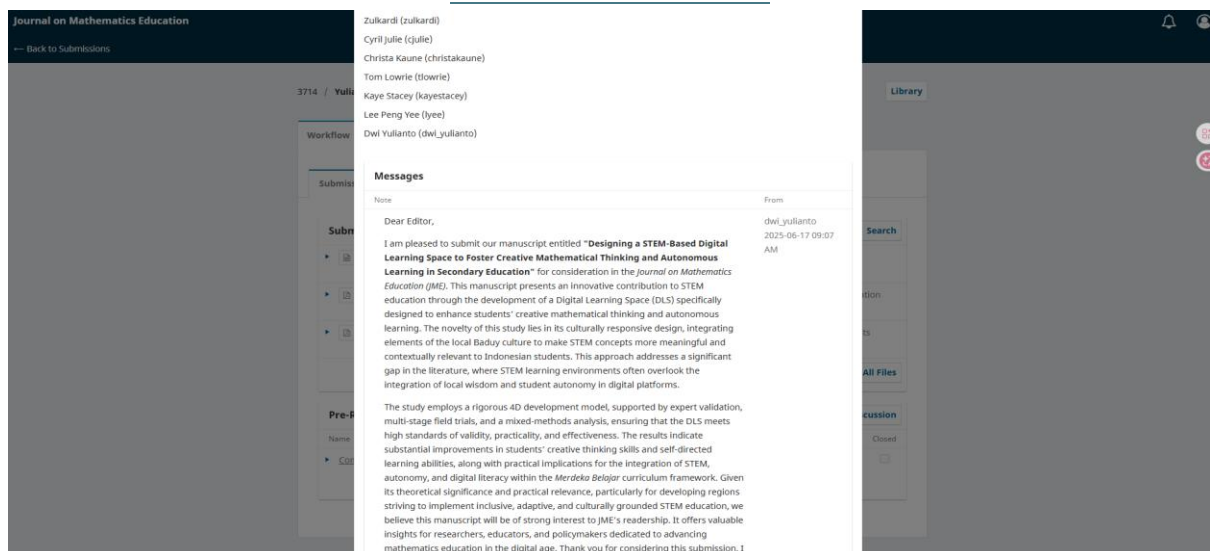
Penulis : Dwi Yulianto dan Egi Adha Juniawan

No.	Perihal	Tanggal	Lampiran Dokumen
1	Bukti konfirmasi submit artikel beserta artikel yang disubmit	17 Juni 2025	
2	Bukti konfirmasi review beserta hasil review pertama	30 September 2025	Lampiran 1
3	Bukti konfirmasi submit revisi pertama, respons kepada reviewer, beserta artikel hasil revisi yang disubmit kembali	1 Oktober 2025	Lampiran 2
4	Bukti konfirmasi review beserta hasil review kedua	30 September 2025	Lampiran 3
5	Bukti konfirmasi submit revisi kedua, respons kepada reviewer, beserta artikel hasil revisi yang disubmit kembali	1 Oktober 2025	
6	Bukti konfirmasi artikel diterima (<i>accepted</i>)		
7	Bukti konfirmasi artikel dipublikasikan secara daring (<i>published online</i>)		
8	Bukti Similarity		Lampiran 4

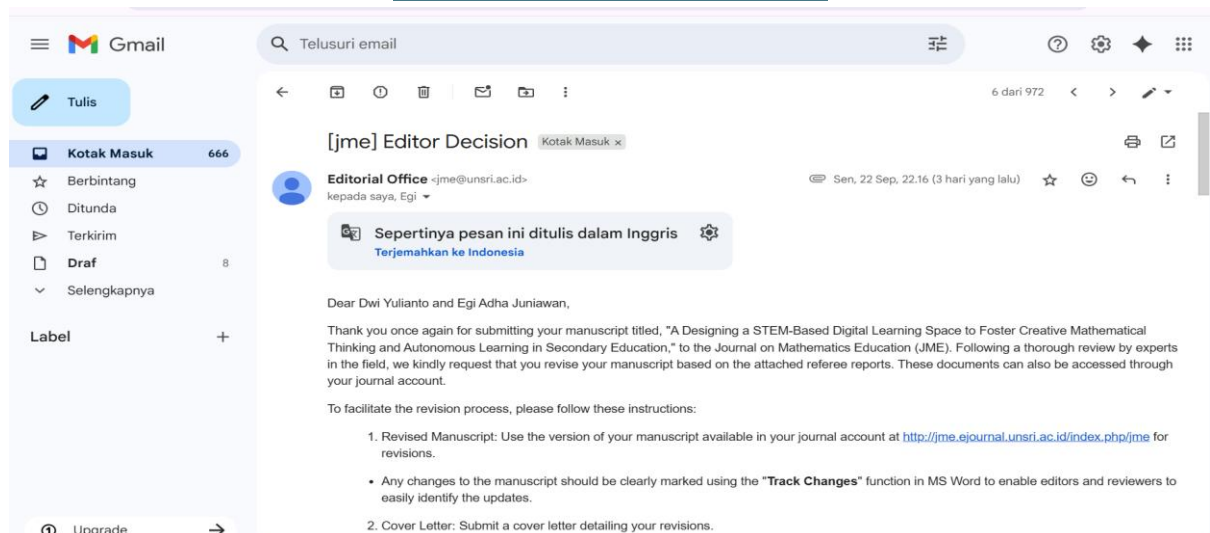
1. Bukti konfirmasi submit artikel beserta artikel yang disubmit

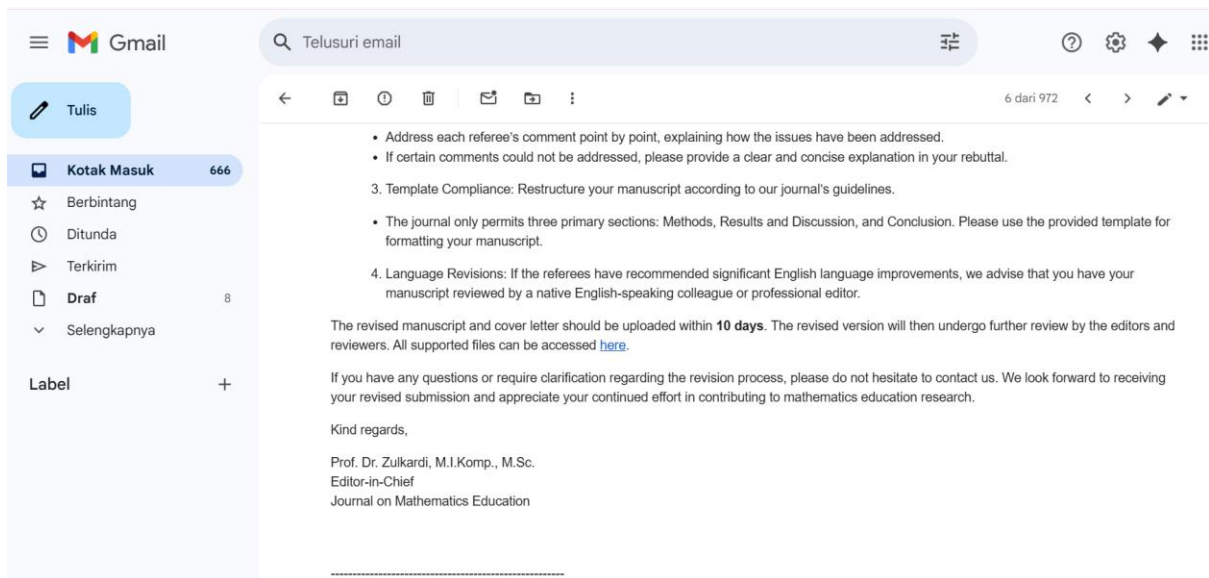


Comments for the Editor

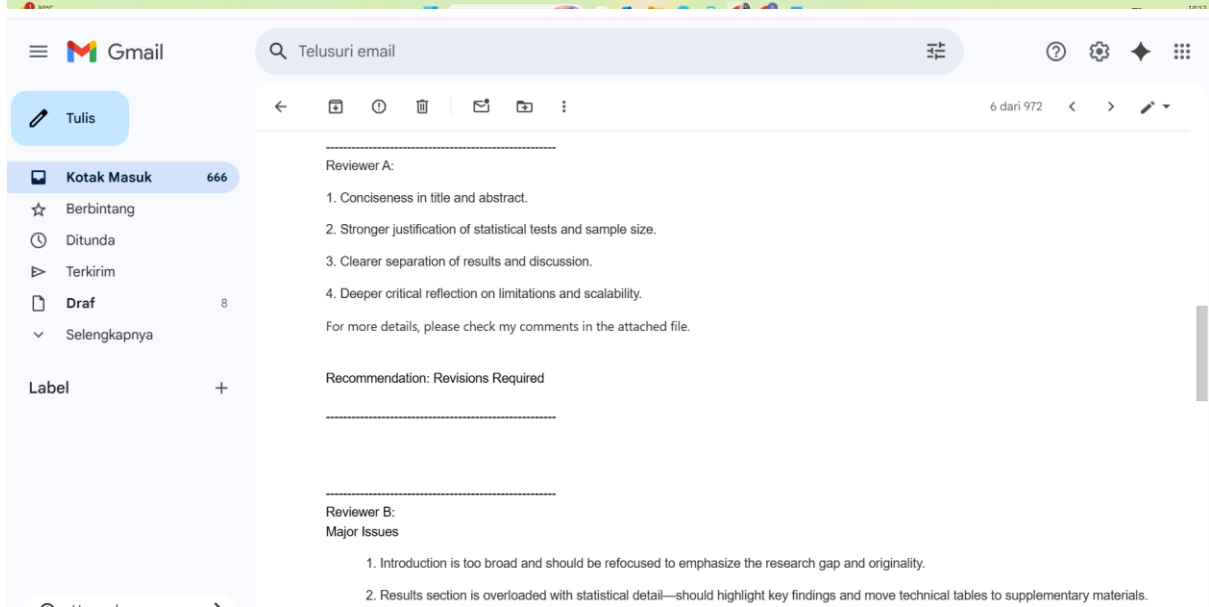
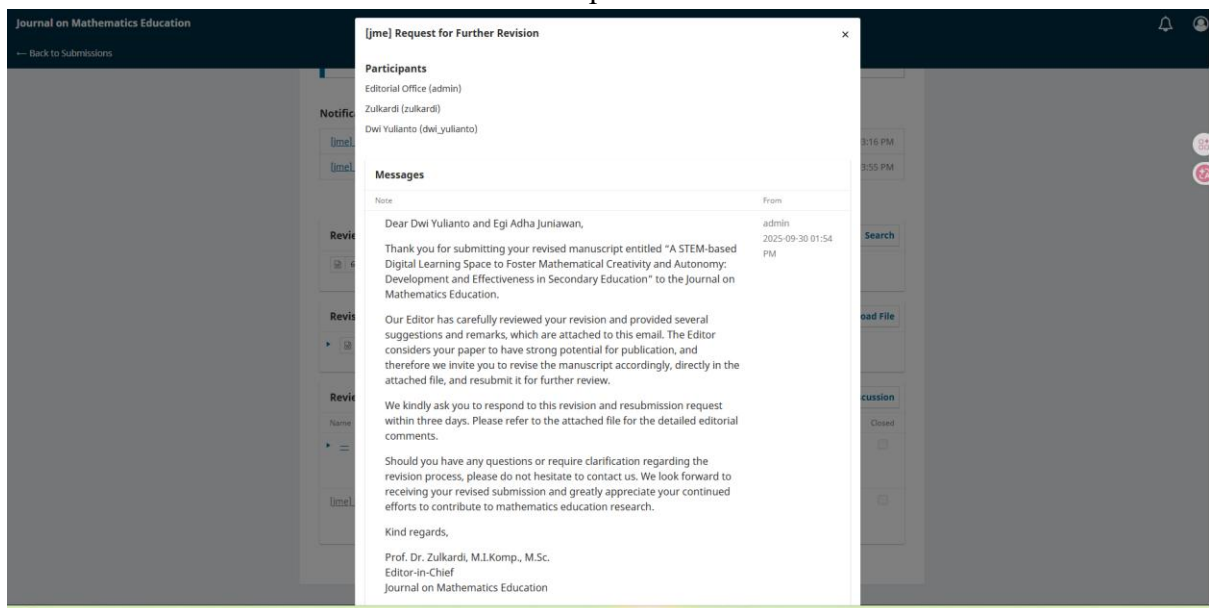


Konfirmasi Submit melalui Email





2. Bukti konfirmasi review beserta hasil review pertama



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Upgrade

Major Issues

1. Introduction is too broad and should be refocused to emphasize the research gap and originality.
2. Results section is overloaded with statistical detail—should highlight key findings and move technical tables to supplementary materials.
3. Discussion sometimes extrapolates beyond the evidence (policy/global claims).
4. Clarity and readability could be improved by simplifying sentences and removing redundancies.

Minor Issues

- Redundant citations (e.g., Conde et al. 2021 listed twice).
- Inconsistent DOI formatting in references.
- Figures and tables need tighter integration with text and clearer captions.
- Language polishing required to improve flow and accessibility.
- **Therefore:**
- Shorten and sharpen the introduction to foreground the research gap and novelty.
- Streamline the methods and results sections—move lengthy tables/technical details to appendices or supplementary files.
- Clarify the discussion to avoid overgeneralization and keep conclusions tightly linked to data."
- Revise writing for conciseness and clarity—simplify long sentences and improve readability.
- Correct reference list for duplicates and consistency.

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The study is methodologically sound and ethically compliant, with promising results. However, the paper is overly dense, the introduction and results sections are overloaded with detail, and some claims extend beyond the data.

Overall, I see strong potential, but the manuscript requires major revision for clarity, conciseness, and sharper alignment between findings and conclusions.

Recommendation: Revisions Required

[Journal on Mathematics Education](#)

3 Lampiran • Dipindai dengan Gmail

A-jme-review-as...

C-JME - Recapitu...

JME Author Pack

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Info Terbaru 2.833

Forum

Promosi 2.312

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[jme] Editor Decision

Jme Fkip Matematika

<jme@unsri.ac.id>

kepada saya, Dwi, Egi

20.54 (33 menit yang lalu)

Dear Dwi Yulianto and Egi Adha Juniawan,

Thank you for submitting your revised manuscript entitled "A STEM-based Digital Learning Space to Foster Mathematical Creativity and Autonomy: Development and Effectiveness in Secondary Education" to the Journal on Mathematics Education.

Our Editor has carefully reviewed your revision and provided several suggestions and remarks, which are attached to this email. The Editor considers your paper to have strong potential for publication, and therefore we invite you to revise the manuscript accordingly, directly in the attached file, and resubmit it for further review.

We kindly ask you to respond to this revision and resubmission request within three days. Please refer to the attached file for the detailed editorial comments.

Should you have any questions or require clarification regarding the revision process, please do not hesitate to contact us. We look forward to receiving your revised submission and greatly appreciate your continued efforts to contribute to mathematics education research.

Kind regards

3. Bukti konfirmasi submit revisi pertama, respons kepada reviewer, beserta artikel hasil revisi yang disubmit Kembali

This screenshot shows an email from Dwi Yulianto to Jme. The email is titled "Author Response" and is dated 13.18 (0 menit yang lalu). The content of the email is as follows:

Author Response

Dear Prof. Dr. Zulkardi,

We sincerely thank you and the editorial team for the valuable feedback on our manuscript entitled "A STEM-based Digital Learning Space to Foster Mathematical Creativity and Autonomy: Development and Effectiveness in Secondary Education."

We have carefully addressed all comments and suggestions provided by the Editor in the attached file. The manuscript has been revised accordingly to improve clarity, academic rigor, and alignment with the journal's standards. Specifically, we have:

1. Incorporated the requested revisions regarding the limitations, policy implications, and future research directions.
2. Refined the discussion structure to avoid reiterating results and to emphasize interpretation, relation to literature, and implications.
3. Revised tables, figures, and statistical reporting to ensure consistency and accuracy.
4. Updated the *Author Contribution Statement* according to the [JME] Authorship Form submission.

All revisions are highlighted in the resubmitted manuscript for easier review. We believe these improvements significantly strengthen the paper and align it more closely with the expectations of JME.

We greatly appreciate your guidance and the opportunity to revise our manuscript. Please kindly find our revised submission attached for your further consideration.

This screenshot shows an email from Jme Fkip Matematika to Dwi Yulianto and Egi Adha Juniawan. The email is dated Rab, 1 Okt, 22.55 (13 hari yang lalu). The content of the email is as follows:

Dear Dwi Yulianto and Egi Adha Juniawan,

We are pleased to inform you that your submission to the Journal on Mathematics Education, titled "Fostering mathematical creativity and autonomy through a STEM-based digital learning space," has been reviewed. After thorough evaluation, the editorial committee is delighted to accept your article for publication.

Please find attached the invoice for your manuscript. Your paper will now proceed to the production stage. Kindly refrain from submitting revised versions or updated figures unless specifically requested by the editorial team. You can expect to receive the page proofs within one to two weeks after your manuscript is forwarded to our production team. During this time, we kindly request you to provide proof of payment.

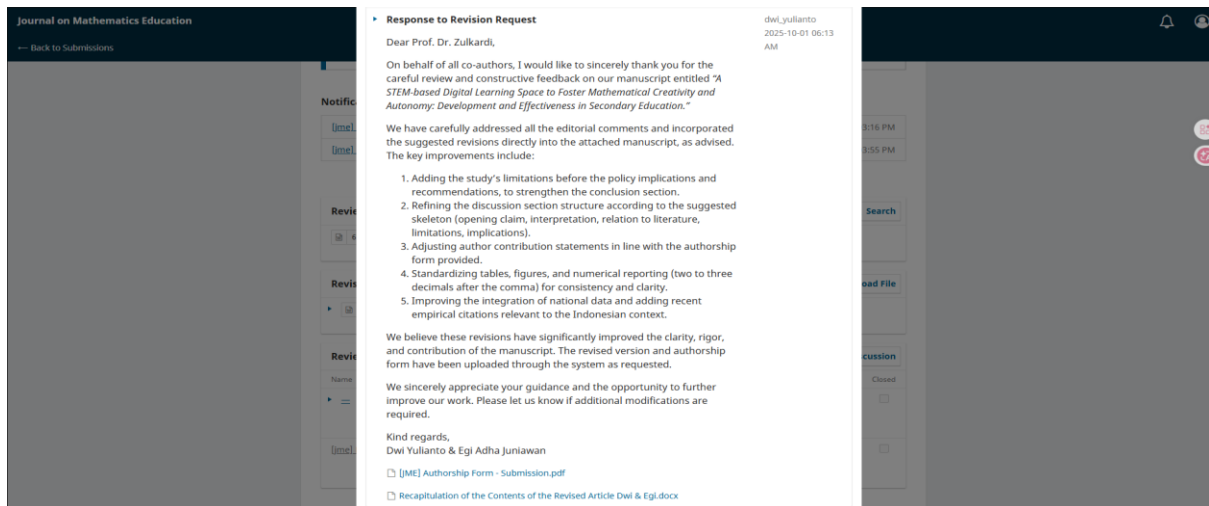
Should you have any questions or require further assistance, please do not hesitate to contact us.

Thank you for your valuable contribution to the journal. We deeply appreciate your cooperation and commitment to advancing mathematics education research.

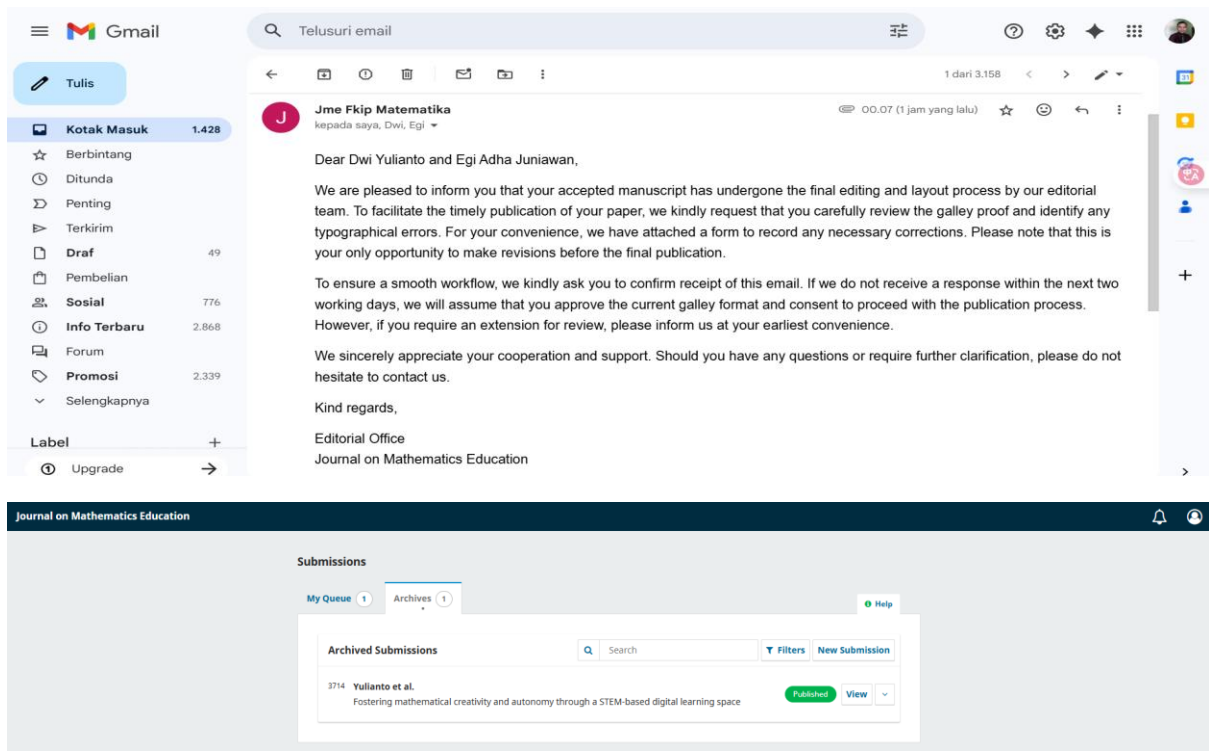
Kind regards,

Prof. Dr. Zulkardi, M.Ikomp., M.Sc.

This screenshot shows the submission dashboard for the Journal on Mathematics Education. The dashboard is titled "Journal on Mathematics Education" and has a "Back to Submissions" link. The main content area is divided into two tabs: "Workflow" and "Publication". The "Workflow" tab is currently selected, and it shows a "Round 1" status of "Submission accepted". Below this, there are "Notifications" and "Reviewer's Attachments" sections. The "Notifications" section shows two notifications: "Jme Editor Decision" dated 2025-09-22 03:16 PM and "Jme Editor Decision" dated 2025-10-01 03:55 PM. The "Reviewer's Attachments" section shows a list of attachments, including "Jme-review-assignment-3714-Article+Text-6650-2rev.docx" dated September 18, 2025. At the bottom, there is a "Revisions" section showing a list of revisions, including "17 - Dwi Yulianto - Reviewed by Editor.docx" dated October 1, 2025.



4. Bukti konfirmasi artikel diterima (*accepted*)



5. Bukti konfirmasi artikel dipublikasikan secara daring (*published online*)



Section Articles

Fostering mathematical creativity and autonomy through a STEM-based digital learning space

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Figure 2. STEM-DLS learning dashboard

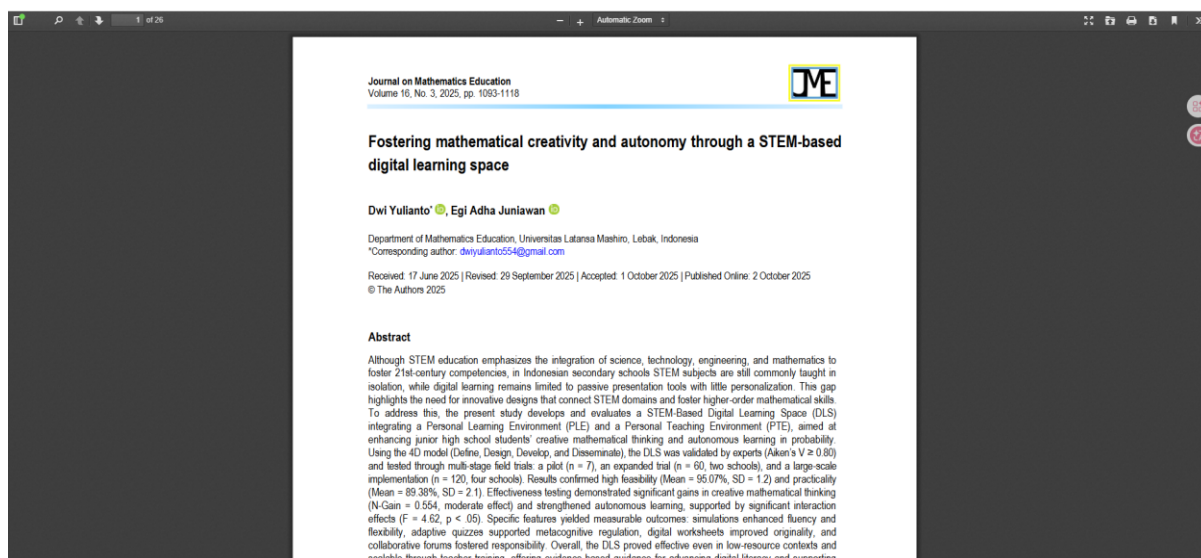
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Statistic

Abstract

Although STEM education emphasizes the integration of science, technology, engineering, and mathematics to foster 21st-century competencies, in Indonesian secondary schools STEM subjects are still commonly taught in isolation, while digital learning remains limited to passive presentation tools with little personalization. This gap highlights the need for innovative designs that connect STEM domains and foster higher-order mathematical skills. To address this, the present study develops and evaluates a STEM-Based Digital Learning Space (DLS) integrating a Personal Learning Environment (PLE) and a Personal Teaching Environment (PTE), aimed at enhancing junior high school students' creative mathematical thinking and autonomous learning in probability. Using the 4D model (Define, Design, Develop, and Disseminate), the DLS was validated by experts (Aiken's $V \geq 0.80$) and tested through multi-stage field trials: a pilot ($n = 7$), an expanded trial ($n = 60$, two schools), and a large-scale implementation ($n = 120$, four schools). Results confirmed high feasibility (Mean = 95.07%, SD = 1.2) and practicality (Mean = 89.38%, SD = 2.1). Effectiveness testing demonstrated significant gains in creative mathematical thinking (N-Gain = 0.554, moderate effect) and strengthened autonomous learning, supported by significant interaction effects ($F = 4.62$, $p < .05$). Specific features yielded measurable outcomes: simulations enhanced fluency and flexibility,





Designing a STEM-Based Digital Learning Space to Foster Creative Mathematical Thinking and Autonomous Learning in Secondary Education

Abstract

This study aims to develop and evaluate the effectiveness of a STEM-Based Digital Learning Space (DLS) designed to enhance junior high school students' creative mathematical thinking skills and autonomous learning. The DLS was developed in response to the limited interdisciplinary integration of science, technology, engineering, and mathematics in teaching, as well as the lack of access to contextualized and personalized digital learning environments. The development process followed the 4D model (Define, Design, Develop, Disseminate), accompanied by expert validation and multi-stage field testing. Expert validation results indicated that the DLS was highly feasible, while student practicality testing categorized the system as very practical. Effectiveness testing demonstrated a significant improvement in students' creative mathematical thinking abilities ($N\text{-Gain} = 0.554$, moderate category) and strengthened their autonomous learning. The DLS was designed as an ecosystem integrating both a Personal Learning Environment (PLE) and a Personal Teaching Environment (PTE), equipped with interactive features such as simulations, adaptive quizzes, digital worksheets, and collaborative forums. This innovation holds strong potential to support the transformation of digital mathematics learning at the secondary school level, aligning with the Deep Learning Curriculum and national digital literacy enhancement programs, particularly in regions with limited technological infrastructure.

Keywords: Autonomous Learning, Creative Mathematical Thinking, Digital Learning Space, Secondary Education, STEM-Based Learning.

In the era of the Industrial Revolution 4.0 and the post-COVID-19 period, educational challenges can no longer be addressed merely through partial technological adoption (González-Pérez & Ramírez-Montoya, 2022). A comprehensive pedagogical transformation is required to prepare a generation capable of adapting to the complexities of the digital age (Røe et al., 2022). In this context, creative mathematical thinking emerges as a critical 21st-century competency, particularly in response to automation and the explosion of data (Szabo et al., 2020; Yulianto et al., 2024). Unfortunately, digitalization in Indonesian education continues to face disparities in access and digital literacy (Li & Yu, 2022; Rawal, 2024; Samane-Cutipa et al., 2022). These gaps are exacerbated by procedural teaching systems that fail to sufficiently promote creativity and idea exploration (Yulianto et al., 2024), as reflected in the OECD (2023) report that ranks Indonesian students low in mathematical literacy, particularly on non-routine problems requiring flexible thinking.

Creative mathematical thinking, which involves the formulation, transformation, and flexible application of ideas in complex situations, serves as the foundation of 21st-century numeracy skills (Dilekçi & Karatay, 2023). This activity encompasses logical reasoning (Shuib et al., 2021) as well as the capacity to generate original and effective solutions (Rosengren et al., 2020). In mathematics education, creativity manifests through novel ideas, effective strategies, and interconnected solutions for solving non-routine problems. However, Indonesian students' performance in this domain remains low (Tanujaya et al., 2021), largely due to an instructional culture that limits contextual exploration (Prahmana et al., 2020). Therefore, STEM-based curricula and learning media are urgently needed to foster students' autonomy and creative exploration in addressing real-world problems (Nurintya & Agoestanto, 2022; Yuliardi et al., 2024).

Commented [Reviewer-1]: Clear but long (21+ words), begins with a process verb ("Designing") while the paper also reports evaluation and effectiveness testing. Reviewers expect the title to reflect design + evaluation and the context. Shorten and align with outcomes.

Commented [Reviewer-2]: A good aim, but lacking in design, sample, and context.

Commented [Reviewer-3]: Motivation is fine but generic, sounds like intro material. Replace with a specific and measurable gap.

Commented [Reviewer-4]: Good, but it is necessary to include who performed the validation (role), criteria (V Aiken threshold), and trial size per stage.

Commented [Reviewer-5]: What qualifiers? require numbers + a scale.

Commented [Reviewer-6]: Good design summary, consider linking each tool to measurable outcomes (creativity, autonomy).

Commented [Reviewer-7]: This claim is excessive and requires evidence. Still too general, and does not describe the specific implications

Commented [Reviewer-8]: Overly broad, keep only what directly motivates creative math + autonomy

Commented [Reviewer-9]: still too general. Mention specific transformations, such as project-based STEM learning with tasks integrated with culture + teacher-led arrangements through DLS.

Commented [Reviewer-10]: Good, but define the operational indicators you will actually assess (fluency, flexibility, originality, elaboration).

Commented [Reviewer-11]: Strong local reasoning, please cite national data more accurately or refer to recent studies on classroom learning practices. Add 1–2 specific empirical citations for Indonesia that are recent. Instead of presenting a long list of citations that are not relevant.

Commented [Reviewer-12]: Good, but ensure tight mapping from this theory to your rubric/items later.

Commented [Reviewer-13]: Needs data points (scores, ranks, year).



The core dimensions of creative thinking fluency, flexibility, originality, and elaboration are widely recognized through the Torrance Test of Creative Thinking (TTCT) framework, which has been adapted across various disciplines, including mathematics (Alabbasi et al., 2022; Suherman & Vidákovich, 2022). However, conventional approaches to assessing mathematical creativity remain generic and fail to reflect the discipline's specific demands for precision, logical structure, and multi-strategic exploration (Hjelte et al., 2020). Therefore, this study adapts the TTCT indicators within the context of probability learning: fluency as the ability to generate diverse experimental procedures and representations; flexibility as the formulation of alternative strategies based on probability data; originality in designing unconventional solutions; and elaboration through the development and justification of solutions using statistical arguments. These adjustments aim to capture the complexity of heuristic processes in solving mathematical probability problems (Yulianto et al., 2024).

Developing creative thinking skills requires a learning environment that fosters exploration, reflection, and the reconstruction of conceptual meaning (Junaedi et al., 2021; Zhou & Liu, 2024). In this context, the STEM approach offers an integrative framework that combines science, technology, engineering, and mathematics to address authentic problem-solving tasks (Fitriasari et al., 2024; Setiawati & Agoestanto, 2023). STEM not only enhances cognitive flexibility through multimodal representations (Hallström & Ankiewicz, 2023) but also fosters originality via digital design and experimentation (Nugraha et al., 2023). Studies by Yuliardi et al. (2024) and Stoyanov et al. (2022) have demonstrated that integrating a Digital Learning Space (DLS) within STEM education significantly improves students' autonomy, collaboration, and creativity.

Based on these findings, the development of a STEM-Based Digital Learning Space in this study was designed as a pedagogical intervention to cultivate students' creative thinking, autonomous learning, and critical reflection in solving data-driven mathematical problems (Yuliardi et al., 2024). This strategy is intended to contribute to the transformation of Indonesia's education system towards a more adaptive, innovative, and globally competitive model (Akhmetova et al., 2025; Cheng et al., 2023). In the digital disruption and automation era, STEM serves not merely as an interdisciplinary field but as an epistemic framework integrating conceptual knowledge with practical application through project-based learning, collaboration, and authentic problem-solving (Conde, Rodríguez-Sedano, et al., 2021; Nguyen et al., 2020). Countries such as Finland, the United States, Taiwan, and Malaysia have implemented national STEM policies that emphasize cross-disciplinary creativity, computational reasoning, and strategic reflection (Ha et al., 2020). At the global level, several universities have developed Self-Access Learning Centers (SALCs) such as those at Kanda University, ASLLC (EdUHK), and ELSAC (University of Auckland) to enhance academic autonomy. However, adoption in Indonesia remains limited (de Vink et al., 2023; Martín-Páez et al., 2019), hindered by low digital literacy, conventional instructional cultures, and inadequate STEM learning infrastructure. Yet, integrated STEM approaches inherently promote cross-disciplinary exploration and authentic problem-solving (Tramonti et al., 2024).

In Indonesia, although the "Merdeka Curriculum" and "Sekolah Penggerak" programs rhetorically advocate STEM-based education policies, their implementation in practice has not fully reflected this transformative approach (Jasiah et al., 2024). Learning models remain largely procedural and teacher-centered (Cheon et al., 2020), further constrained by low digital literacy among teachers, insufficient interdisciplinary training, and the scarcity of adaptive DLS platforms (Li & Yu, 2022; Rawal, 2024; Samane-Cutipa et al., 2022). Without systemic solutions, this gap risks widening the global competence divide faced by Indonesian students in meeting 21st-century demands. Therefore, STEM education in Indonesia must be reconceptualized as a pedagogical foundation that nurtures autonomy, cognitive

Commented [Reviewer-14]: TTCT is domain-general, justify its adaptation to mathematics (you do this later, bring it up front).

Commented [Reviewer-15]: Good direction. Add 1 example item and how scoring captures fluency/flexibility/originality.

Commented [Reviewer-16]: Several sentences are citation-heavy but evidence-light (e.g., multiple multi-country lists). Replace with fewer, higher-leverage sources + concrete statistics.

Broken citations across lines (e.g., "Studies by Yuliardi et al." / "(2024) and Stoyanov et al." / "(2022) ...") create sentence fragments, merge them into grammatical sentences.



flexibility, and creativity in authentic problem-solving. This strategy should include cross-subject integration, the enhancement of reflective pedagogical capacities among teachers (McGuire & O Broin, 2019; Romijn et al., 2021), and the development of STEM-based DLS platforms that empower students as solution designers (Hughes & Morrison, 2020). Through this approach, STEM education is expected to foster adaptive, self-directed learners capable of driving meaningful change (Yuliardi et al., 2024).

In the context of 21st-century education, autonomous learning has been recognized as a fundamental foundation for shaping resilient, reflective, and adaptive learners (González-Pérez & Ramírez-Montoya, 2022). Unlike traditional teacher-centered models, autonomous learning positions students as the primary agents in managing learning strategies, reflecting on achievements, and conducting self-assessment (Yuliardi et al., 2024). Technologies such as LMSs are expected to facilitate transformative self-directed learning, not merely serve as administrative tools (Athaya et al., 2021; Clark et al., 2021; *PISA 2022 Results (Volume I)*, 2023). Therefore, the design of digital pedagogy must shift towards STEM-based Digital Learning Spaces (DLS) that are open, contextual, and foster student agency (Aini et al., 2023; Conde, Rodríguez-Sedano, et al., 2021; Nguyen et al., 2020). However, its realization is still hindered by systemic factors such as rigid curricula, limited teacher digital competence, and unequal access to technology (Yulianto et al., 2024). Without comprehensive intervention, the synergistic potential of STEM, autonomous learning, and DLS risks becoming mere jargon without meaningful transformational impact in educational practice.

Digital Learning Spaces (DLS) are developed based on the principles of Networked Learning, emphasizing connectivity, collaborative knowledge construction, and active collaboration (Gourlay et al., 2021). DLS serves as infrastructure for both synchronous and asynchronous learning, aligned with the self-regulated learning framework that supports flexible access, goal setting, and learner autonomy (Dignath & Veenman, 2021; Sun & Chen, 2023). The DLS design also integrates the concepts of Personal Learning Environments (PLE) and Personal Teaching Environments (PTE), allowing for personalization and adaptive instructional design (Nan Censka et al., 2023; Tur et al., 2024). Collaborative forums and formative assessments within the DLS enhance students' cognitive presence (Maranna et al., 2022). However, the widely claimed accessibility and low-cost benefits of DLS require critical evaluation, especially in developing countries facing infrastructure, device, and digital literacy gaps (Gumbi et al., 2023). These disparities risk widening educational inequality, particularly among marginalized student groups. The effectiveness of DLS as a medium for flipped classrooms and inquiry-based learning also heavily depends on teacher professional development, supportive policies, and equitable digital infrastructure (Al-Said et al., 2023; Gourlay et al., 2021; Sosa Díaz et al., 2021).

Research on DLS in the STEM context should transcend mere access issues by fostering digital learning environments that encourage exploration, experimentation, and authentic problem-solving (Fitriasari et al., 2024; Setiawati & Agoestanto, 2023). The integration of STEM within DLS should not only deliver digital content but also create creative learning spaces that strengthen contextual mathematical reasoning and active participation (Johnston et al., 2022; Wan et al., 2021). Specifically, this study responds to the need for a digital learning environment that promotes creative mathematical thinking within local contexts. The STEM-Based Digital Learning Space (DLS) developed in this study is integrated with a problem-solving approach based on pedagogically and culturally adapted TIMSS-PISA content. This model addresses a gap in the literature concerning the integration of content design, local culture, and learner autonomy within digital platforms. The DLS is designed with a culturally responsive pedagogy that incorporates ethnomathematics and local wisdom into assessments, materials, and digital discussions. Interactive features such as adaptive feedback, open-ended



simulations, and collaborative spaces support the activation of self-regulated learning (SRL), divergent thinking, and conceptual generalization in authentic situations.

Unlike previous studies, this model offers a transformative approach that not only stimulates creative mathematical thinking but also builds contextual, independent, and inclusive digital literacy. Based on this background, the present study aims to answer two main research questions: (1) What are the characteristics of a valid and practical STEM-based DLS design that supports autonomous digital mathematics learning? (2) How does the DLS influence students' creative mathematical thinking skills in the context of self-directed learning?

METHODS

This study employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate) by Roman (2022) to develop a STEM-Based Digital Learning Space (DLS) integrated into both synchronous and asynchronous learning environments. This model was selected for its systematic, flexible, and iterative nature, allowing multi-stage validation and expert involvement from the early stages of development, crucial for producing a digital product that is valid, practical, and effective within the STEM education context. The final product consists of a web-based digital learning system equipped with interactive modules, probability simulations, discussion forums, and digital worksheets (LKPD) designed to enhance students' scientific literacy and creative mathematical thinking skills. The DLS design integrates two main functions: (1) Pedagogical and Technological Enhancement (PTE), emphasizing instructional management by teachers (account setup, multimedia integration, task management, and rubric-based evaluation), and (2) Personalized Learning Environment (PLE), promoting active student engagement through independent and collaborative activities, quizzes, reflection, and peer assessment based on task performance.

In the Define stage, a front-end analysis was conducted to map STEM learning needs in partner schools, along with a learner analysis to identify student characteristics, challenges, and learning requirements. The Design stage involved the development of evaluation instruments based on Torrance's (1974) indicators for creative mathematical thinking tests (fluency, flexibility, elaboration, originality, and connection-making) and Fisher et al.'s (2001) framework for the autonomous learning questionnaire (self-regulation, motivation control, initiative). Lightweight digital media were selected, and instructional materials were developed, integrating STEM content with technology. During the development stage, validation by content experts, media specialists, and initial user teachers was conducted using Aiken's V, with all items exceeding a value of 0.80. The trials followed a design-based research principle, encompassing a small-scale trial (7 students from Grade VIII at SMP Latansa 2), an expanded trial (60 students from SMP Latansa 2 and SMP Kun Karimma), and field testing (120 students from SMP Daar El Qolam 2 and 3, and SMP Latansa 1), purposively selected based on theoretical and contextual considerations.

Inclusion criteria included: (1) availability of adequate ICT infrastructure (computer labs and stable internet connections); (2) active involvement of mathematics teachers in technology-based learning; and (3) representation of school diversity based on accreditation status (A) and geographical location to evaluate practicality, engagement, and product effectiveness. Each stage was accompanied by teacher training and observations conducted by a trained evaluation team. At the Disseminate stage, the developed product was distributed through accredited scientific publications, national teacher training workshops, and intellectual property rights (IPR) applications to strengthen the product's

Commented [Reviewer-17]: Good. Add design label used for effectiveness (quasi-experimental?).

Commented [Reviewer-18]: Good. Cite design-based research if it guided iterations.

Commented [Reviewer-19]: Good. Add auth control, data logging, privacy.

Commented [Reviewer-20]: Sample selection criteria are clear, but demographic characteristics (gender, age) are not fully reported.



legitimacy. These efforts aimed to build a sustainable digital learning ecosystem through teacher learning communities and integration with the Merdeka Mengajar platform. Through this design, the STEM-DLS is expected to promote contextual, adaptive, and reflective learning while supporting the Merdeka Belajar policy and the national digital education transformation agenda.

Instruments and Validity

Students' creative mathematical thinking skills were assessed using pre-test and post-test instruments based on five core indicators: fluency, flexibility, elaboration, originality, and connection-making, as proposed by Torrance (1974). The test consisted of five open-ended essay questions, validated by three mathematics education experts, yielding an Aiken's V coefficient of 0.85, indicating high content validity. Internal reliability was confirmed with Cronbach's alpha ($\alpha = 0.81$), demonstrating good consistency. Students' autonomous learning was measured using a 30-item questionnaire based on the Self-Directed Learning Readiness model (Fisher et al., 2001), encompassing learning initiative, self-regulation, and metacognitive awareness. Responses were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), with an internal reliability coefficient of $\alpha = 0.873$. Construct validity was verified through exploratory factor analysis ($KMO > 0.8$), supporting the appropriateness of the three-factor model. In addition to these measurement instruments, the content validity and practicality of the STEM-Based Digital Learning Space (DLS) platform were evaluated by subject matter experts, digital media specialists, and STEM education experts using a standardized evaluation rubric and a student practicality questionnaire.

Data Collection and Analysis

Data were collected using a mixed-methods approach (Cahill & Bostic, 2025) to evaluate the effectiveness and user experience of the STEM-DLS. Qualitative data, in the form of multimodal documentation transcripts (photos, videos, audio recordings), were analyzed thematically (Braun & Clarke, 2006) to explore students' mathematical reasoning during the assembly, experimentation, and presentation phases. Quantitative analysis included content validity testing (Aiken's V), practicality evaluation (descriptive statistics), and effectiveness assessment (N-Gain, paired and independent t-tests, one-way ANOVA), as well as MANOVA to examine the effectiveness of the STEM-DLS across multiple variables. The STEM-DLS product was validated by three experts: an educational technology specialist, a mathematics expert, and a mathematics teacher as a pedagogical evaluator. Validation was conducted using a 5-point Likert scale covering content substance, alignment with core competencies, STEM integration, instructional design quality, assessment, and collaborative features. The mean validation scores determined the product's feasibility, categorized as invalid, less valid, fairly valid, valid, and highly valid. The product was deemed feasible if it achieved at least the "valid" or "highly valid" category; otherwise, revisions were made accordingly. In terms of practicality, students evaluated the DLS based on usability, clarity, readability, and time adequacy. A mean score of $\geq 70\%$ indicated practicality; scores below this threshold required improvements based on user feedback.

RESULTS AND DISCUSSION

Results

In the Define stage, participatory front-end and learner analyses were conducted at SMP Latansa Mashiro to map students' pedagogical needs and characteristics. The analysis revealed that learning in

Commented [Reviewer-21]: Strong validity/reliability reporting (Aiken's V, Cronbach's α). However, the construct validity explanation is brief — EFA results are only summarized ($KMO > 0.8$) without factor loadings or variance explained.

Commented [Reviewer-22]: Statistical analysis methods are mentioned but not justified (e.g., why MANOVA vs. ANCOVA).

Commented [Reviewer-23]: Well-organized tables (pre-post means, t-test, ANOVA). However, results section sometimes mixes interpretation (discussion) — e.g., "These findings confirm..." should be moved to Discussion.

Figures are referenced but not always described narratively (e.g., Figure 4–6 should be explicitly connected to outcomes).

Keep Results purely descriptive. Move causal interpretation ("confirm effectiveness") to Discussion.

Add visualizations (bar charts of N-Gain, ANOVA interaction plots) for clarity.



the school remained compartmentalized across disciplines (Science, Mathematics, ICT), technology use was limited to passive presentation media, and students' digital literacy was low, with most unfamiliar with LMS platforms or exploratory applications (see Table 1).

Table 1. Summary of Front-End and Learner Analysis Findings

Aspect	Key Findings	Implications for Solution Design
STEM Integration	Learning remains sectoral; no explicit integration across disciplines (Science, Mathematics, Technology).	Design project-based learning scenarios that integrate concepts from multiple disciplines.
Technology Utilization	Teachers rarely use supporting applications other than PowerPoint; no interactive digital media or simulations are employed.	Develop a Digital Learning Space that emphasizes exploratory and interactive visualization.
Student Digital Literacy	72.2% of students are only proficient with basic applications (WhatsApp, YouTube); unfamiliar with LMS platforms, GeoGebra, or other exploratory tools.	Provide gradual, adaptive digital media training tailored to students' initial skill levels.
Learning Autonomy	61.1% of students struggle with independent learning; they require intensive teacher guidance.	Integrate scaffolding into the digital task design to enable progressive student autonomy.
Technical Constraints	58.3% of students lack stable internet access at home; 25% own only low-spec smartphones.	Design lightweight learning media accessible offline or semi-offline (e.g., interactive HTML, locally stored videos).
Student Creative Potential	Only 16.7% of students exhibit tendencies towards creative thinking (e.g., asking critical questions, offering alternative solutions).	Apply strategies to stimulate creative thinking through real-world problem contexts and provide open exploration spaces.

At the Design stage, an initial prototype of the STEM-Based Digital Learning Space (STEM-DLS) was developed based on the framework of the Personal Teaching Environment (PTE) and Personal Learning Environment (PLE) (Figure 1). Four main components were designed: (1) Assessment instruments, consisting of a mathematical creative thinking test based on the indicators of fluency, flexibility, elaboration, originality, and connection-making (Alabbasi et al., 2022), along with an autonomous learning questionnaire referring to the dimensions of self-regulation, initiative, and metacognitive awareness (Fisher et al., 2001; Gu et al., 2023); (2) Digital media, using lightweight HTML and locally produced videos to support exploratory STEM principles and accommodate students' limited device access; (3) Integrated teaching materials, connecting science, mathematics, and ICT in a project-based learning scenario; and (4) The DLS design, which distinguishes between teachers' roles (PTE) and students' independent and collaborative activities (PLE). Key platform features include discussion forums, assignment reflection spaces, interactive quizzes, and peer assessment, all of which promote learner autonomy. The entire design was validated by two instructional design experts and one STEM content expert, who confirmed its feasibility for further implementation. The STEM-DLS platform prototype is accessible at <https://kalana.my.id>, as illustrated in Figure 1.



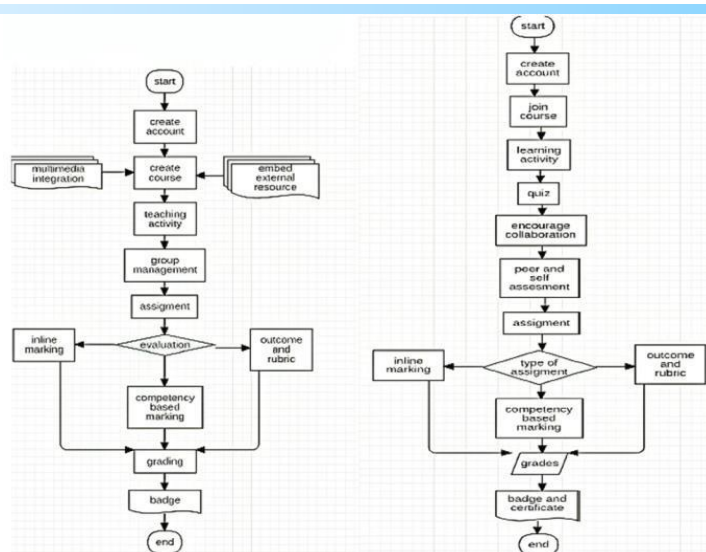


Figure 1. Flow diagram of PTE and PLE (Yuliardi et al., 2024)

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The development phase of the STEM-DLS aimed to ensure content validity, pedagogical suitability, and practical applicability within a digital learning context. Validation was conducted by two experts in educational technology and mathematics, as well as a mathematics teacher serving as a pedagogical evaluator. The validation instrument consisted of 20 items covering content substance, relevance to core competencies, and the integration of STEM components. The entire validation process was supported by a panel discussion using a triangulated consensus approach to align perspectives between academic experts and field practitioners. Therefore, the developed DLS product meets both substantive and technical feasibility criteria for implementation in digital STEM learning (see Tables 2 and 3).

Table 2. Expert Validation Results – Content

Assessed Aspect	Description	AV	Validity Category
Content Quality and Objectives	Alignment with learning objectives and student competencies	3.90	Valid
Instructional Design	Structure, delivery strategy, and material sequencing	4.00	Valid
Learning Design	Activity planning, student engagement, and scenario development	4.05	Valid
Evaluation and Feedback	Clarity of assessment instruments and effectiveness of feedback	3.86	Valid
Discussion and Collaboration Features	Ease of information sharing and online discussion facilities	3.95	Valid
Average Validity	Overall mean score from content experts	4.35	Practical

Table 3. Expert Validation Results – Media

Assessed Aspect	Description	AV	Validity Category
DLS Web Appearance	Layout clarity, visual aesthetics, readability, and user	4.20	Good



Assessed Aspect	Description	AV	Validity Category
DLS Menu Design	interface navigation Menu structure, icons, ease of access, and completeness of digital navigation	3.80	Good
Audio-Visual Clarity and Interactivity	Media sound/image quality, system response to user interaction, and user engagement	4.25	Good
Programming Appropriateness and Functionality	Technical performance, cross-device compatibility, and system reliability in practice	4.20	Good
Average Validity	Aggregate score from all media validation aspects	4.11	Practical

Development Results of STEM-DLS Features

The development of the STEM-DLS was carried out through collaboration among the academic team, web developers, teachers, and students to ensure both pedagogical relevance and contextual suitability for partner schools. The design of the DLS integrates international best practices, such as Project-Based Learning and TIMSS/PISA frameworks, while being adapted to local constraints, including low-specification devices, visual preferences, and limited digital literacy. Therefore, the platform was designed to be modular, lightweight, and supportive of asynchronous access to enhance inclusivity. The STEM-DLS features include interactive simulations, a progress dashboard, digital student worksheets, and a Collaborative Learning Hub, all aimed at fostering 4C skills (Creativity, Critical Thinking, Communication, Collaboration) as well as self-directed learning through a self-regulated learning approach. In addition to STEM-based content, the DLS is equipped with automated formative assessments, adaptive feedback, and performance tracking via learning analytics, enabling teachers to conduct real-time, data-driven assessments.

Table 4. Summary of Key Features of the STEM-DLS

Feature	Main Function	Benefits for Teachers/Students
Learning Dashboard	Provides learning guidance, content navigation, and student progress tracking.	Supports independent learning management; helps teachers monitor students' progress efficiently.
Interactive Simulations & Videos	Presents STEM concepts visually and multimodally.	Enhances contextual and applied understanding of abstract concepts.
Digital Student Worksheets & Project Upload	Serves as a medium for task completion and student project documentation.	Encourages project-based learning and the development of digital portfolios.
Automated Formative Assessment	Offers interactive quizzes with feedback and alternative solutions.	Delivers instant feedback; provides teachers with performance-based assessment data.
Collaborative Learning Hub	Acts as a discussion forum and a space for sharing learning outcomes.	Facilitates collaboration, reflection, and idea exchange among users.
Resource Center (STEM Gallery)	Hosts a gallery of projects, videos, and context-based assignments.	Enhances knowledge transfer and inspiration from real learning environments.

These features were developed following the principles of connected learning to support contextual education in the digital era. Formative validation and limited student trials were conducted



iteratively to refine the design and functionality. As part of the STEM-DLS, seven units of digital Student Worksheets were designed and validated by content experts. The content validation was carried out by two university lecturers specializing in educational technology and mathematics, as well as a mathematics teacher who served as a pedagogical evaluator, assessing the format, language, content, and illustrations. The results indicated that all assessed aspects achieved the "Very Valid" category, with an average score of 95.07% (see Table 5). In terms of practicality, the DLS was evaluated by students using a practicality questionnaire covering ease of access, clarity of presentation, readability of information, and appropriateness of time allocation. All aspects scored above 70%, with an average of 89.38%, classified as "Very Practical" (Table 6).

Table 5. Results of Student Worksheet Validation Analysis

Validator Rating Average	Face Validity	Content Validity	Construct Validity	Validation Average
Student Worksheet – 1	96.35%	93.06%	96.21%	95.21%
Student Worksheet – 2	95.83%	92.36%	96.21%	94.80%
Student Worksheet – 3	95.83%	92.36%	95.45%	94.55%
Student Worksheet – 4	95.83%	93.75%	96.21%	95.26%
Student Worksheet – 5	96.88%	93.06%	94.70%	94.88%
Student Worksheet – 6	96.35%	93.75%	97.73%	95.94%
Student Worksheet – 7	95.31%	93.06%	96.21%	94.86%
Average	96.05%	93.06%	96.10%	95.07%

Category	Very Valid	Very Valid	Very Valid	Very Valid
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Table 6. Practicality of STEM-Based DLS Based on Student Assessment

Practicality Aspects	1	2	3	4	5	6	7	Average	Category
Ease of Access and Navigation	92.78	95.00	90.83	92.78	90.83	90.83	89.17	91.75	Very Practical
Clarity of Information and STEM Content	91.67	90.67	88.67	87.67	87.67	85.00	87.00	88.34	Very Practical
Presentation Readability of Text and Digital Visualization	88.33	89.00	89.33	90.00	90.67	91.33	88.33	89.57	Very Practical
Appropriateness of Feature Usage	88.33	89.17	87.50	87.50	86.67	87.50	88.33	87.86	Very Practical
Time Allocation									
Overall Practicality Average	90.28	90.96	89.08	89.49	88.96	88.67	88.21	89.38	Very Practical

STEM Task Description

This program aims to enhance secondary school students' creative mathematical thinking through STEM learning rooted in the local culture of the Baduy community. Preliminary observations revealed that many students struggle with data interpretation, constructing numerical arguments, and applying concepts of probability and ratio in real-life contexts. To address these challenges, a series of thematic activities was developed, integrating mathematical concepts (data, scale, probability), science (weather



observation, energy), technology (basic LMS, simulations), and engineering (designing simple tools). These activities are organized into seven main topics, each reflecting elements of Baduy daily life, such as traditional games, weaving patterns, house structures, and local natural resources. Every task incorporates Torrance's dimensions of creativity fluency, flexibility, originality, and elaboration through open-ended problem-solving exercises.

Table 7. STEM Learning Plan Based on Baduy Local Culture

Mathematics Topic	Creative Thinking Indicators	STEM Components	Digital Learning Media
Patterns and Sequences in Baduy Weaving Motifs	Fluency, Elaboration	M, A, T	Weaving motif images, pattern exploration videos, and interactive pattern simulations in LMS
Ratios and Scale: Baduy Traditional Village Map	Flexibility, Originality	M, T, E	Digital village maps, drone videos, digital measurement apps, and building scale simulations
Data and Statistics: Traditional Energy Survey of Baduy Houses	Fluency, Flexibility, Elaboration	M, S, T	Digital questionnaires, interactive graphs, LMS for survey data input and visualization
Probability: Traditional Baduy Games Experiment	Fluency, Originality, Elaboration	M, S, T	Experiment videos, simple spin wheel simulations, data-based experiment dashboards
Plane and Solid Figures: Baduy Traditional House Architecture	Originality, Elaboration	M, A, T	3D house models, area and volume simulations, local architectural animations
Cartesian Coordinates: Locating Baduy Natural Resources	Flexibility, Elaboration	M, S, T	Interactive coordinate maps, position and distance exercises, and digital mapping tools
Final Project: Designing a Simple Traditional Weather Monitoring Tool	Elaboration, Originality, Flexibility	S, T, E, M	Digital weather tool simulations, local rainfall observation videos, and an LMS for experiment documentation

Note: M = Mathematics (concepts and calculations); T = Technology (digital tools, calculators, LMS, simulations); S = Science (observation and real experiments); E = Engineering (design of simple technological solutions).

To strengthen the integration of mathematical concepts and STEM principles in real-world contexts, the final project was designed to address the needs of the local community, specifically farmers in the Baduy region who face difficulties in predicting weather patterns for subsistence farming. This project challenges students to design and implement a simple weather data collection tool using an engineering-for-social-context approach, fully incorporating Science, Technology, Engineering, and Mathematics (STEM) components. Unlike conventional experiment-based methods, this project emphasizes problem-based learning, focusing on designing practical solutions for local environmental issues. The project follows six structured stages (see Table 7) aimed at fostering creative thinking skills, elaboration, originality, flexibility, fluency, as well as developing students' social responsibility by designing solutions aligned with community needs. Learning activities are conducted both synchronously and asynchronously using an open-source LMS, supported by videos, simulations, and digital collaboration. Students are encouraged to design, build, and test prototypes of mini weather monitoring tools, present data through graphs, and provide interpretations relevant to local agricultural practices. This project not only integrates subjects such as Science, Mathematics, and ICT but also



embodies the values of *Merdeka Belajar* and the *Pancasila Student Profile* by promoting exploration, independence, and social contribution. The detailed project stages are presented in Table 7.

Table 7. Final STEM Project Design: Simple Weather Data Collection Tool

STEM Phase	Task Description	Explanation	Guidelines	Duration
Asking Essential Questions	Identifying community problems and formulating research questions	Students explore farmers' needs (e.g., difficulties in predicting weather changes) and formulate a research question: "How can we measure and predict weather simply?"	Use local farmer interview videos, LMS discussion forums, and inquiry guides based on community needs.	2 lessons @ 50 minutes (synchronous)
Designing a Prototype Tool	Designing a simple weather monitoring tool	Students discuss and design a tool by selecting the type of weather data to collect (temperature, humidity, rainfall) and determining methods for data visualization and documentation.	Provide sensor tutorial videos, weather instrument simulations, and digital design templates via LMS. Emphasize measurement principles and interdisciplinary STEM connections.	3 lessons @ 50 minutes (synchronous & asynchronous)
Scheduling and Task Division	Project management within teams	Students create a project work plan, assign roles (designer, data recorder, analyst), and establish activity flow and data collection schedules.	Utilize LMS planner templates, teamwork rubrics, and collaborative forum discussions. Encourage accountability among team members.	1 lesson @ 50 minutes (synchronous)
Building and Testing the Tool	Construction and testing of a mini weather monitoring tool	Students build a simple tool (e.g., a manual ombrometer), record daily data for five days, and compare their results with simulation or digital weather forecasts.	Use data recording sheets, simple data loggers, and LMS platforms to compare actual data with simulations (e.g., online BMKG forecasts).	4 lessons @ 50 minutes (asynchronous)
Analyzing and Presenting Data	Data interpretation and visualization	Collected data is analyzed using graphs and narratives. Students connect findings to local agricultural phenomena and practical implications.	Provide digital table templates, Google Sheets spreadsheets, and trend analysis rubrics. Encourage discussions linking data insights to real-life farming challenges.	2 lessons @ 50 minutes (synchronous)
Reflection and Presentation	Delivering project outcomes and self-evaluation	Students prepare reports, create digital presentations, and reflect on their learning experience and encountered technical	Use LMS video recorders for documentation, presentation rubrics, and Zoom/Google Meet for project exposure sessions with classmates and	2 lessons @ 50 minutes (synchronous)



STEM Phase	Task Description	Explanation	Guidelines	Duration
		challenges.	mentors.	

Phase 1: Facilitating Meaningful Questions in a Local STEM Context

This phase aims to foster students' scientific curiosity and divergent thinking through a community-based problem-based learning approach centered on real issues faced by Baduy farmers, such as planting season uncertainty and extreme weather conditions. Students are encouraged to explore these problems through contextual videos and guided discussions, with the teacher acting as a learning coach who connects scientific concepts with local wisdom. Through this process, students formulate exploratory questions to design simple, locally sourced weather prediction tools. The success of this phase is evaluated using an exploratory question rubric that assesses relevance to applied science, originality, and the feasibility of tool development, in order to build cross-disciplinary understanding rooted in the local context. Examples of the exploratory questions formulated by students include: "How can we create a simple yet accurate tool for predicting weather for farmers?" and "Is it possible to build a temperature and humidity measuring device using local materials?"



Figure 2. Learning Coach



Figure 3. Students Conducting Literature Review

Phase 2. Designing the Prototype

In this phase, students, teachers, and local farmer groups collaboratively designed a simple climate monitoring prototype based on the Internet of Things (IoT) to assist Baduy farmers in adapting to shifting planting patterns caused by climate change. The students developed a data logger using temperature (DHT11), humidity, and rainfall (rain gauge) sensors integrated with Arduino, which was tested for seven days to record environmental data. The prototype was then upgraded into a Raspberry Pi-based system, enabling real-time weather data monitoring and visualization through a Python GUI interface, with data stored in CSV format on a local server without requiring an internet connection (see Figure 4).

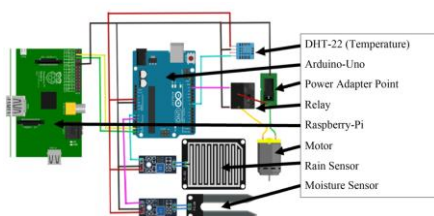


Figure 4. Connectivity view.



Figure 5. Demo photo of the project



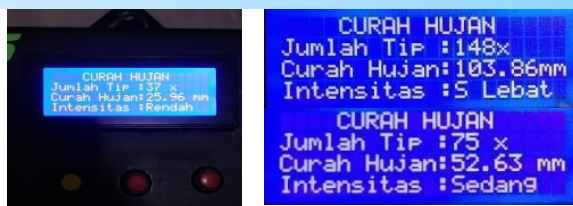


Figure 6. Output results of the project

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Stage 3: Project Scheduling

In a 50-minute synchronous learning session, students are guided to develop a structured project work plan and distribute roles based on each team member's competencies and interests. They utilize digital tools such as the local LMS, Google Calendar (for structured physical scheduling), and online discussion platforms like WhatsApp or LMS forums. The success of this stage is evaluated using three main instruments: (1) a Project Planning Rubric developed based on indicators of time management effectiveness and role distribution; (2) an Activity Log Tracker that automatically monitors individual digital contributions via the LMS; and (3) a Team Reflection Sheet, designed following the Pancasila Student Profile reflection guidelines issued by the Indonesian Ministry of Education and Culture. System Usage Procedure by Indigenous Farmers: 1) The system automatically activates at 5:00 AM and 4:00 PM to collect data; 2) Sensors detect temperature, humidity, and rainfall levels; 3) Raspberry Pi stores and processes data into daily graphical visualizations (simple icons: hot, humid, heavy rain); 4) Farmers read a small LCD screen displaying weather status and simple warnings ("Planting delayed," "Heavy rain alert"); and 5) Training is provided by students and teachers to explain how to interpret weather patterns and their impact on the local rice cultivation cycle.

Stage 4: Project Monitoring and Evaluation

This stage ensures the technical quality and learning impact of the student-constructed weather monitoring device. Teachers and students serve as evaluators using rubrics based on design originality, measurement accuracy, scientific validity, and local contextual relevance. A five-day field test compares the device's readings with official data from the Meteorology, Climatology, and Geophysics Agency (BMKG) to assess validity and reliability. Evaluation results are then used as the basis for design improvement, facilitated by mentors.

Stage 5: Data Analysis and Dissemination

After five days of weather data collection, students process the observations using spreadsheets to visualize trends in temperature, humidity, and rainfall. This activity enhances data literacy and contextual understanding through a STEM-based scientific inquiry approach. Students formulate simple hypotheses on the impact of weather conditions on agriculture and engage in reflective discussions under teacher guidance. This phase contributes to strengthening community scientific literacy and adaptive resilience to local climate change. A key activity is stimulating students to develop and test hypotheses regarding the effects of weather patterns on planting cycles, soil fertility, and crop yields. Teachers facilitate reflective discussions using analytical questions such as: "How can this data help farmers make planting decisions?" or "What are the limitations of this data for short-term predictions?" The processed data is presented in simple infographics designed to be easily understood by community



members with limited educational backgrounds. These infographics are then presented by students in small video forums uploaded to the LMS.

Effectiveness of STEM-DLS

After completing all stages of development and implementation, the next step was to evaluate the effectiveness of the STEM-DLS using a quasi-experimental design at the field level. Based on the results of the independent sample t-test presented in Table 8, a significant difference was found in creative thinking abilities between students in the experimental and control groups, indicating a moderate to large practical effect. **These findings confirm** that the STEM-DLS learning model is demonstrably more effective than conventional approaches in stimulating creative thinking, particularly through the integration of visual exploration, contextual projects, and digital scaffolding.

Table 8. Autonomy Levels and Creative Thinking Before and After in the Control Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	$t_{emp.}$	Before	After	$t_{emp.}$
High	Self-initiation	4.111	4.455	2.533	4.022	4.388	2.402
	Goal orientation	4.233	4.600	2.642	4.100	4.478	2.318
	Persistence	3.988	4.300	2.200	3.877	4.188	2.011
	Responsibility	4.211	4.622	2.881	4.078	4.500	2.540
	Decision-making	4.089	4.500	2.700	3.955	4.388	2.380
Moderate	Self-initiation	3.788	4.100	2.200	3.689	4.022	2.089
	Goal orientation	3.955	4.344	2.478	3.822	4.256	2.204
	Persistence	3.700	4.044	2.100	3.566	3.900	1.922
	Responsibility	3.800	4.222	2.820	3.755	4.211	2.322
	Decision-making	3.789	4.178	2.511	3.688	4.089	2.144
Low	Self-initiation	3.411	3.800	2.000	3.388	3.700	1.901
	Goal orientation	3.544	3.900	2.211	3.422	3.833	2.100
	Persistence	3.422	3.700	1.889	3.311	3.600	1.800
	Responsibility	3.655	3.978	2.000	3.588	3.911	2.045
	Decision-making	3.611	3.944	2.022	3.489	3.822	2.033
Creative Thinking Level	Indicators Thinking Level	Boys			Girls		
		Before	After	$t_{emp.}$	Before	After	$t_{emp.}$
High	Fluency	1.322	1.544	2.111	1.200	1.422	2.015
	Flexibility	0.722	0.933	2.066	0.855	1.066	2.100
	Originality	2.100	2.400	2.220	2.566	2.822	1.966
	Elaboration	1.366	1.622	2.144	2.200	2.466	2.111
	Connection-making	1.533	1.789	2.089	1.644	1.922	2.022
Moderate	Fluency	1.078	1.300	2.010	0.988	1.200	1.885
	Flexibility	0.633	0.844	2.033	0.744	0.955	2.044
	Originality	1.855	2.122	2.150	2.422	2.655	1.933
	Elaboration	1.200	1.456	2.244	2.100	2.356	2.088
	Connection-making	1.444	1.678	2.033	1.522	1.744	2.011
Low	Fluency	0.889	1.066	2.089	0.855	1.044	2.012
	Flexibility	0.422	0.633	2.066	0.622	0.811	2.000
	Originality	1.433	1.678	2.033	2.211	2.433	1.889
	Elaboration	1.000	1.211	2.011	1.944	2.177	2.022
	Connection-making	1.233	1.455	2.077	1.311	1.522	1.955

Table 9. Autonomy Levels and Creative Thinking Before and After in the Experimental Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	$t_{emp.}$	Before	After	$t_{emp.}$
High	Self-initiation	4.133	4.722	3.122	4.089	4.678	3.055
	Goal orientation	4.200	4.789	3.300	4.122	4.733	3.188



Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t_{emp-}	Before	After	t_{emp-}
Moderate	Persistence	4.011	4.611	3.122	3.911	4.500	3.044
	Responsibility	4.255	4.855	3.233	4.144	4.755	3.211
	Decision-making	4.144	4.800	3.344	4.022	4.688	3.278
	Self-initiation	3.822	4.444	3.144	3.722	4.366	3.100
	Goal orientation	3.977	4.600	3.266	3.855	4.544	3.189
	Persistence	3.755	4.333	3.000	3.622	4.255	2.944
	Responsibility	3.866	4.522	3.144	3.811	4.466	3.111
	Decision-making	3.833	4.478	3.188	3.755	4.400	3.077
	Self-initiation	3.433	4.011	2.933	3.400	3.977	2.855
	Goal orientation	3.577	4.144	2.988	3.444	4.111	2.911
Low	Persistence	3.433	4.000	2.800	3.322	3.911	2.733
	Responsibility	3.688	4.244	2.944	3.622	4.200	2.866
	Decision-making	3.633	4.222	3.022	3.511	4.122	2.900
Creative Thinking Level	Indicators Thinking Level	Boys			Girls		
		Before	After	t_{emp-}	Before	After	t_{emp-}
High	Fluency	1.344	1.700	2.455	1.244	1.644	2.333
	Flexibility	0.755	1.144	2.566	0.900	1.300	2.488
	Originality	2.188	2.722	2.611	2.633	3.044	2.444
	Elaboration	1.411	1.877	2.488	2.255	2.733	2.600
	Connection-making	1.577	2.033	2.533	1.677	2.100	2.511
Moderate	Fluency	1.100	1.544	2.366	1.000	1.466	2.233
	Flexibility	0.655	1.044	2.500	0.766	1.144	2.411
	Originality	1.900	2.433	2.577	2.466	2.977	2.388
	Elaboration	1.222	1.700	2.611	2.144	2.677	2.544
	Connection-making	1.488	1.933	2.544	1.555	2.000	2.466
Low	Fluency	0.911	1.366	2.433	0.877	1.322	2.355
	Flexibility	0.444	0.877	2.488	0.655	1.044	2.344
	Originality	1.477	2.011	2.611	2.233	2.744	2.477
	Elaboration	1.033	1.511	2.555	2.000	2.511	2.500
	Connection-making	1.266	1.755	2.500	1.344	1.833	2.455

The results indicate that the STEM-DLS intervention contributed positively to enhancing students' learning autonomy and creative thinking skills compared to the control class. To assess the extent of this learning model's impact on students' cognitive achievements, a comparative analysis of pretest, posttest, and N-Gain scores in mathematical creative thinking was conducted, as presented in Table 10.

Table 10. Mean Scores of Pretest, Posttest, and N-Gain in Mathematical Creative Thinking Ability

Group	N	Pretest Mean	Posttest Mean	N-Gain ($\langle g \rangle$)	Effectiveness Interpretation
Experimental (STEM-DLS)	60	53.12	75.46	0.554	Moderate (Effective)
Control (Conventional)	60	52.78	63.29	0.223	Low (Less Effective)
Difference	—	—	+12.17	+0.331	—

The difference in N-Gain scores between the experimental and control groups indicates that the implementation of STEM-DLS was more effective in improving students' mathematical creative thinking abilities. To further examine the interaction effect between the learning model and students' autonomy levels, a Two-Way ANOVA was conducted, with the results shown in Table 11.

Table 11. Two-Way ANOVA (Autonomy Level $\times$ Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.450	5	0.490	37.690	0.000



Intercept	40.320	1	40.320	3102.31	0.000
Autonomy Level	1.750	2	0.875	67.310	0.000
Learning Model	0.580	1	0.580	44.620	0.000
Autonomy Level * Learning Model	0.120	2	0.060	4.620	0.012
Error	1.500	114	0.013		
Total	44.270	120			
Corrected Total	3.950	119			

The Two-Way ANOVA results reveal a significant interaction between students' autonomy levels and the learning model on their autonomy scores. To identify which groups differed significantly, a post hoc Tukey HSD test was performed, as presented in Table 12.

Table 12. Tukey HSD Test – Learning Autonomy Level

(I) Autonomy Level	(J) Autonomy Level	Mean Difference (I-J)	Std. Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.348*	0.033	0.000	Significant: Low < Moderate
Low	High	-0.601*	0.033	0.000	Significant: Low < High
Moderate	High	-0.253*	0.033	0.000	Significant: Moderate < High

The Tukey HSD test confirms that higher levels of learning autonomy correspond to higher learning achievements, particularly when applying the STEM-DLS model. These findings highlight the critical role of students' autonomy readiness in maximizing the effectiveness of STEM-based instruction. To complement these findings, the next analysis focuses on the interaction between creative thinking ability levels and the learning model (see Table 13).

Table 13. Two-Way ANOVA (Creative Thinking Level × Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.750	5	0.550	26.190	0.000
Intercept	51.200	1	51.200	2438.10	0.000
Creative Thinking Level	2.100	2	1.050	50.000	0.000
Learning Model	0.460	1	0.460	21.905	0.000
Creative Thinking × Learning Model	0.190	2	0.095	4.524	0.013
Error	2.400	114	0.021		
Total	56.350	120			
Corrected Total	5.150	119			

The results of the Two-Way ANOVA test revealed a significant interaction between students' levels of creative thinking ability and the learning model employed. These findings indicate that the impact of the STEM-DLS model varies across different categories of students' creative thinking skills. To determine the specific differences between groups, a post-hoc Tukey HSD test was conducted, as presented in Table 14.

Table 14. Tukey HSD Test on Creative Thinking

(I) Creative Thinking Level	(J) Creative Thinking Level	Mean Difference (I-J)	Standard Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.175	0.028	0.000	Significant: Low < Moderate
	High	-0.279	0.028	0.000	Significant: Low < High
Moderate	Low	0.175	0.028	0.000	Significant: Moderate > Low
	High	-0.104	0.028	0.001	Significant: Moderate < High
High	Low	0.279	0.028	0.000	Significant: High > Low
	Moderate	0.104	0.028	0.001	Significant: High > Moderate



The results of the Tukey HSD test confirmed significant differences in creative thinking abilities among the three levels of creativity. Students in the high creativity group demonstrated substantially higher performance compared to those in the moderate and low creativity groups. These findings provide a critical basis for supporting the dissemination and broader replication of the STEM-DLS model as outlined in the subsequent phase. The fourth phase of this study focused on a structured dissemination strategy to expand the impact of the STEM-DLS innovation adaptively and sustainably. This strategy encompassed four main pillars: academic legitimacy, independent replication, intellectual property rights legalization, and the activation of learning communities. First, scientific articles related to the conceptual framework and design of STEM-DLS were submitted as a means of academic validation and outreach. Second, a national training program involving 42 teachers from various regions of Lebak and Pandeglang resulted in a replication readiness rate of 78.6%, with two non-research schools beginning to implement portions of the modules. The effectiveness of dissemination was evaluated through three key indicators: (1) adoption by six non-research subject teachers, supported by lesson plans and video documentation; (2) the establishment of an independent Teacher Learning Community with a monthly reflection agenda; and (3) transformation of instructional practices as evidenced by project portfolios and increased use of interdisciplinary interactive digital media. These findings suggest that an adaptive, data-driven dissemination strategy can lay the groundwork for a participatory, contextual, and potentially nationwide replicable digital learning ecosystem.

Discussion

The development of the STEM-Based Digital Learning Space (DLS) successfully addressed the limitations of conventional LMS platforms in partner schools, particularly in terms of flexibility, visualization, and student empowerment. Figure 7 illustrates one of the STEM-DLS products, which was designed based on local needs through a participatory front-end analysis involving teachers and students, in line with the concept of a collaborative digital ecosystem.

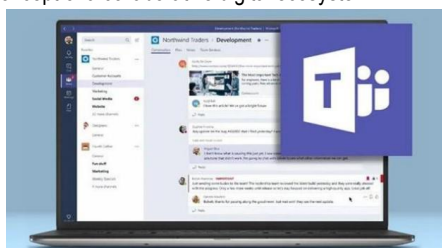


Figure 7 presents the online STEM-DLS platform, which can be accessed at <https://kalana.my.id>.

The project-based STEM learning stages were applied to foster students' creative mathematical thinking skills, starting from the *Essential Question* phase, which enhances fluency and flexibility, to the *Design a Plan* phase, which develops originality and elaboration, and the *Schedule & Monitor* phase, which promotes autonomous learning and independent project management. In the *Assess the Outcome* phase, students sharpen their data literacy skills through experimental result analysis and theoretical reflection. Initial implementation demonstrated a significant increase in student participation and improvement in creative mathematical thinking skills, as measured by various TTCT indicators. These findings align with the main objective of this study, which was to develop an effective STEM-DLS model for enhancing students' mathematical creativity and autonomous learning.

The STEM-DLS innovation developed in this study successfully addressed the shortcomings of

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Expand discussion on limitations, scalability, and potential bias (Hawthorne effect, selection bias due to purposive sampling). Compare effect sizes to previous similar studies.



conventional LMS platforms in supporting contextual and collaborative learning (Nurintya & Agoestanto, 2022). The DLS features innovative elements such as STEM project videos, a shared practice space, and interactive discussions, enabling teachers and students from various regions to access and replicate this learning model. Validation results in terms of practicality, validity, and effectiveness indicate that the DLS significantly enhances learning quality, student engagement, and teacher creativity. Its key strengths include easy web access, a user-friendly interface, contextual STEM content integration, and interactive quizzes with automated feedback. These findings are consistent with those of Lin et al. (2017) and Yuliardi et al. (2024), who emphasized the effectiveness of DLS in promoting interaction and learning outcomes. However, as noted by Saputro & Tri. (2019), the success of DLS also depends on teacher readiness, the enhancement of digital literacy, and the reinforcement of interactive pedagogy. Therefore, the DLS implementation was accompanied by intensive training and the development of teacher communities of practice to ensure sustainable, transformative impact.

This study reinforces the theoretical framework of STEM integration through digital technology by developing an adaptive and contextual Digital Learning Space (DLS) model. This DLS innovation broadens the STEM learning framework by emphasizing the integration of science, technology, creativity development, digital literacy, and autonomous learning. The DLS prototype is flexible and can be replicated by teachers through a co-design approach to support project-based learning models. Practically, the DLS provides tangible benefits for teachers by offering an open, modular, and collaborative digital learning platform, supported by teacher training and learning communities for broader regional replication. For policymakers, these findings serve as a valuable reference for accelerating digital transformation in education, aligned with the Merdeka Belajar policy and SDG Goal 4 on quality education. The study's limitations lie in the relatively small sample size ($N = 120$) and limited geographical representation, restricting the generalizability of the findings. Future research is recommended to involve more diverse samples across educational levels and regions and to test the effectiveness of the DLS model in various STEM project contexts. Infrastructure limitations and unequal internet access also present challenges that require policy support in the form of minimum technology provision in schools and teacher training to optimize the use of DLS as a sustainable digital learning ecosystem.

CONCLUSION

The development of the STEM-Based Digital Learning Space (STEM-DLS) using the 4D model has successfully addressed the need for adaptive digital learning media to overcome the limitations of conventional LMS platforms in fostering student autonomy and creative learning. The DLS has been proven valid, practical, and effective in enhancing students' self-directed learning and creative mathematical thinking through the integration of contextual learning principles, STEM syntax, and interactive digital features. Effectiveness testing revealed that the DLS promotes active student engagement, strengthens digital literacy, and facilitates collaboration among educational stakeholders. With its accessibility and flexibility, the DLS holds strong potential for widespread adoption to support the development of an inclusive and sustainable digital learning ecosystem, aligned with the 'Merdeka Belajar' educational policy.

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add implications and contributions, as well as opportunities for future research



Acknowledgments

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Declarations

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- Funding Statement : This research was funded by the Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia.
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- Additional Information : Additional information is available for this paper.

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A STEM-Based Digital Learning Space to Foster Mathematical Creativity and Autonomy: Development and Effectiveness in Secondary Education

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Abstract

This study develops and evaluates a STEM-Based Digital Learning Space (DLS) designed to enhance junior high school students' creative mathematical thinking and autonomous learning with a focus on probability. The research employs the 4D model (Define, Design, Develop, Disseminate) and addresses a specific gap in Indonesian secondary schools, where STEM subjects are commonly taught in isolation and digital learning is often limited to passive presentation tools with minimal personalization. The DLS was validated by two instructional design experts, one STEM content specialist, and two mathematics teachers, with all items meeting Aiken's V threshold of 0.80 or higher. Multi-stage field trials were conducted: (a) a small-scale pilot (n = 7, Grade VIII), (b) an expanded trial (n = 60 across two schools), and (c) a large-scale implementation (n = 120 across four schools with varying accreditation levels). Validation results categorized the system as "Very Feasible" (M = 95.07%, SD = 1.2), while student practicality testing rated it as "Very Practical" (M = 89.38%, SD = 2.1). Effectiveness testing using a quasi-experimental design demonstrated significant improvement in creative mathematical thinking (N-Gain = 0.554, moderate effect) and strengthened autonomous learning, with a Two-Way ANOVA confirming significant interaction effects between autonomy levels and the model (F = 4.62, p < .05). The DLS integrates both a Personal Learning Environment (PLE) and a Personal Teaching Environment (PTE), with measurable outcomes directly linked to its features: simulations enhanced fluency and flexibility, adaptive quizzes supported metacognitive regulation, digital worksheets improved elaboration and originality, and collaborative forums fostered decision-making and responsibility. Beyond statistical improvements, the DLS proved effective in schools with limited ICT infrastructure, and dissemination through national teacher training involving 42 participants achieved a replication readiness rate of 78.6%. Overall, these findings provide evidence-based guidance for advancing digital literacy and support the *Merdeka Belajar* policy through the development of a sustainable and equitable STEM learning ecosystem in Indonesia.

Keywords: Autonomous Learning, Creative Mathematical Thinking, Digital Learning Space, Secondary Education, STEM-Based Learning.

The OECD (2023) reports that Indonesian students perform poorly in mathematical literacy, particularly on non-routine tasks requiring flexible reasoning, underscoring the urgent need to strengthen creative mathematical thinking and learner autonomy. Despite the *Merdeka Belajar* reforms, secondary classrooms remain largely rote-based with limited emphasis on problem-solving and creativity (OECD, 2023). Research highlights that the effectiveness of digital learning depends on teacher readiness and institutional capacity (Chang et al., 2025), while classroom observations in Banten reveal that mathematics instruction is still textbook-driven with minimal STEM integration (Tambunan & Yang, 2022). To address these gaps, this study develops and evaluates a project-based STEM Digital Learning Space (DLS) that integrates culturally grounded tasks such as Baduy weaving and weather-monitoring projects within a teacher-led Personal Teaching Environment (PTE) (Yuliardi et al., 2024). Mathematical creativity

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Commented [DY3]: A good aim, but lacking in design, sample, and context.

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Commented [DY5]: Motivation is fine but generic, sounds like intro material. Replace with a specific and measurable gap.

Commented [DY6R5]: revised

Commented [DY7]: Good, but it is necessary to include who performed the validation (role), criteria (V Aiken threshold), and trial size per stage.

Commented [DY8R7]: revised

Commented [DY9]: The sample and trial stages are described

Commented [DY10R9]: revised

Commented [DY11]: What qualifiers? require numbers + a scale.

Commented [DY12R11]: revised

Commented [DY13]: Quantitative data and corresponding scales are provided.

Commented [DY14R13]: revised

Commented [DY15]: Good design summary, consider linking each tool to measurable outcomes (creativity, autonomy).

Commented [DY16R15]: revised

Commented [DY17]: This claim is excessive and requires evidence. Still too general, and does not describe the specific implications

Commented [DY18R17]: revised

Commented [DY19]: Overly broad, keep only what directly motivates creative math + autonomy

Commented [DY20R19]: revised

Commented [DY21]: still too general. Mention specific transformations, such as project-based STEM learning with tasks integrated with culture + teacher-led arrangements through DLS.

Commented [DY22R21]: revised

Commented [DY23]: still too general. Mention specific transformations, such as project-based STEM learning with tasks integrated with culture + teacher-led arrangements through DLS.

Commented [DY24R23]: revised



is measured through fluency, flexibility, originality, and elaboration, while learner autonomy is assessed via self-regulation, initiative, and metacognitive awareness (Yuliardi et al., 2024; Hidajat, 2022). Findings indicate that the DLS effectively enhances both creativity and autonomy, offering a scalable, context-sensitive model for secondary education, particularly in schools with limited ICT infrastructure.

Indonesia's international assessment results reveal persistent deficiencies in mathematical literacy: in 2022, only 18% of 15-year-olds achieved PISA's minimum proficiency (Level 2), far below the OECD average (OECD, 2023), while PISA 2018 reported just 28% reaching basic to intermediate levels (OECD, 2019). Despite wide recognition of this issue, few studies have systematically targeted both creative mathematical thinking, the generation, transformation, and flexible application of ideas in complex, non-routine tasks, and learner autonomy within a validated, task-based framework. This study addresses this gap by mapping Torrance-style creativity dimensions onto rubrics (Yoon, 2017): fluency (distinct solution moves), flexibility (diverse strategies), originality (novelty of responses), and elaboration (solution depth, representational richness, and justification). Learner autonomy is measured using validated subscales of self-regulation, initiative, and metacognitive awareness. All instruments underwent expert validation (Aiken's $V > 0.80$) and inter-rater reliability checks ($ICC \geq 0.75$; López-Angulo et al., 2024), enabling robust pre- and post-intervention comparisons through normalized gain, effect sizes, and interaction tests (Coletta & Steinert, 2020). By explicitly linking constructs to measurement, this study provides reliable evidence of interventions that simultaneously enhance mathematical creativity and learner autonomy, filling a gap rarely addressed in prior research.

Although the Torrance Tests of Creative Thinking (TTCT) are widely used to assess general creativity, they do not fully capture the distinct features of mathematical thinking, such as precision, logical consistency, and multi-strategy reasoning (Meier et al., 2021). To bridge this gap, this study adapts the TTCT framework to mathematical problem-solving, aligning fluency, flexibility, originality, and elaboration with domain-specific demands (Meier et al., 2024; Suherman & Vidákovich, 2022). For example, one culturally embedded task asks students to estimate rainfall probability in the Baduy region, prompting them to generate multiple valid procedures (fluency), apply diverse strategies such as analytical models, simulations, and heuristics (flexibility), propose novel approaches (originality), and provide in-depth justifications with representations and error analyses (elaboration) (Lu et al., 2025; Grajzel et al., 2023). Scoring rubrics are further aligned with international frameworks, drawing from PISA 2018 problem-solving dimensions for fluency and flexibility (OECD, 2019) and PISA 2022 creative thinking for originality and elaboration (OECD, 2023). This integration produces a domain-specific, internationally benchmarked assessment framework that more accurately evaluates mathematical creativity (Yulianto et al., 2024; López-Angulo et al., 2024).

Creative mathematical thinking develops optimally in learning environments that encourage exploration, reflection, and conceptual reconstruction (Junaedi et al., 2021). Yet in Indonesia, STEM pedagogy remains constrained by procedural instruction, textbook dependency, and digital readiness gaps: only 65% of secondary schools have stable internet access, and fewer than 40% of students own a personal computer (Revina et al., 2023; Chai et al., 2020). To address these challenges, this study designs a STEM-based DLS aimed at fostering mathematical creativity, learner autonomy, and critical reflection through data-driven tasks (Yuliardi et al., 2024; González-Mujico, 2024). Effectiveness is evaluated using adapted Torrance indicators (fluency, flexibility, originality, elaboration) and validated learner autonomy scales, resulting in a scalable rubric framework applicable even in contexts with limited ICT infrastructure (López-Angulo et al., 2024). The study makes a dual contribution: providing a practical digital tool and a methodological approach for strengthening equitable, creativity-focused STEM

Commented [DY25]: Good, but define the operational indicators you will actually assess (fluency, flexibility, originality, elaboration).

Commented [DY26R25]: revised

Commented [DY27]: Needs data points (scores, ranks, year).

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Commented [DY29]: Good, but ensure tight mapping from this theory to your rubric/items later.

Commented [DY30R29]: revised

Commented [DY31]: TTCT is domain-general, justify its adaptation to mathematics (you do this later, bring it up front)

Commented [DY32R31]: revised

Commented [DY33]: Good direction. Add 1 example item and how scoring captures fluency/flexibility/originality.

Commented [DY34R33]: revised



education in secondary schools. Offline/semi-offline compatibility and support for low-specification devices ensure inclusivity for diverse Indonesian contexts.

In Indonesia, initiatives such as the *Merdeka Curriculum* and *Sekolah Penggerak* promote STEM-oriented education (Jasiah et al., 2024), yet classroom practice remains procedural and teacher-centered (Cheon et al., 2020). Key challenges include low teacher digital literacy, insufficient interdisciplinary training, and a lack of adaptive digital learning platforms (Li & Yu, 2022; Rawal, 2024). Without systemic reform, these gaps risk widening global competence disparities. Effective STEM education requires a pedagogical shift that nurtures autonomy, cognitive flexibility, and creativity through authentic problem-solving, cross-disciplinary integration, and reflective teaching practices (McGuire & O Broin, 2019; Romijn et al., 2021). This shift must be supported by STEM-based DLS that empower students as solution designers (Hughes & Morrison, 2020; Yuliardi et al., 2024).

Autonomous learning is essential in 21st-century education, positioning students as active agents in managing learning strategies, reflecting on progress, and conducting self-assessment (González-Pérez & Ramírez-Montoya, 2022; Yuliardi et al., 2024). Digital tools should facilitate transformative, self-directed learning rather than serve merely administrative functions (Athaya et al., 2021). Accordingly, STEM-based DLS must be open, contextual, and promote learner agency (Aini et al., 2023; Conde et al., 2021; Nguyen et al., 2020). However, rigid curricula, unequal access, and limited teacher competence remain significant barriers (Yulianto et al., 2024). Without systemic intervention, STEM, autonomy, and DLS risk remaining rhetorical concepts without practical impact.

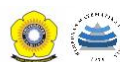
Grounded in Networked Learning principles, DLS emphasizes connectivity, collaboration, and active knowledge construction (Gourlay et al., 2021). They support both synchronous and asynchronous learning, aligned with self-regulated learning frameworks that enable flexible access, goal setting, and learner autonomy (Dignath & Veenman, 2021; Sun & Chen, 2023). By integrating Personal Learning Environments (PLE) and Personal Teaching Environments (PTE), DLS allows for personalization and adaptive instruction (Nan Cenka et al., 2023). Collaborative forums and formative assessments further enhance cognitive presence (Maranna et al., 2022). However, claims of DLS accessibility and low cost must be critically examined in developing countries where infrastructure, device ownership, and digital literacy gaps persist, exacerbating educational inequities (Gumbi et al., 2023). Effective DLS implementation depends not only on teacher professional development but also on supportive policies and equitable digital infrastructure (Al-Said et al., 2023).

Research on STEM-DLS should extend beyond issues of access to cultivate environments that promote exploration, experimentation, and authentic problem-solving (Fitriasari et al., 2024; Setiawati & Agoestanto, 2023). STEM content within DLS should not only deliver digital materials but also foster creativity and contextual mathematical reasoning (Johnston et al., 2022). This study addresses that need by developing a STEM-based DLS aligned with TIMSS-PISA frameworks, integrating local culture and ethnomathematics into materials, assessments, and digital discussions. Features such as adaptive feedback, open-ended simulations, and collaborative spaces support self-regulated learning, divergent thinking, and conceptual generalization. Unlike prior models, this DLS promotes both creative mathematical thinking and inclusive, context-aware digital literacy. The study pursues two main research questions: (1) What are the characteristics of a valid and practical STEM-based DLS that supports autonomous digital mathematics learning? (2) How does the DLS influence students' creative mathematical thinking within self-directed learning?

Commented [DY35]: Several sentences are citation-heavy but evidence-light (e.g., multiple multi-country lists). Replace with fewer, higher-leverage sources + concrete statistics.

Broken citations across lines (e.g., "Studies by Yuliardi et al." / "(2024) ...") create sentence fragments, merge them into grammatical sentences.

Commented [DY36R35]: revised



METHODS

Research Design

This study employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate) to develop a STEM-based Digital Learning Space (DLS) for secondary mathematics. Guided by design-based research principles (Brown, 1992), the process involved iterative prototyping, expert validation, classroom trials, and systematic revisions. To evaluate effectiveness, a quasi-experimental non-equivalent control group pretest–posttest design was implemented (experimental = 60; control = 60), following a pilot study ($n = 7$) and an expanded trial ($n = 60$). A larger field test ($n = 120$) across multiple schools assessed feasibility, practicality, and external validity. The DLS integrated a pedagogical and technological enhancement (PTE) dashboard for teachers, rubric-based assessments, and orchestration tools, alongside a personalized learning environment (PLE) featuring adaptive quizzes, collaborative workspaces, and reflective tools.

Schools were included based on three criteria: (1) availability of basic ICT infrastructure (≥ 10 devices, stable internet, or local server), (2) teacher commitment to technology integration, and (3) representation across diverse accreditation levels and school settings. Role-based authentication, secure communication protocols, and anonymized activity logs ensured data security. Ethical safeguards included informed consent from students and parents/guardians, Institutional Review Board (IRB) approval (University Latansa Mashiro, No. 29/E-5/UNILAM/2025), and data minimization practices. Demographic data were reported across three phases. The pilot involved 7 Grade VIII students (57% male; M age = 13.4, $SD = 0.5$) at SMP Latansa 2. The expanded trial included 60 Grade VII students (47% male; M age = 13.1, $SD = 0.6$) from SMP Latansa 2 and SMP Kun Karimma. The field test comprised 120 Grade VII students (48% male; M age = 12.8, $SD = 0.5$) from SMP Daar El Qolam 2 & 3 and SMP Latansa 1, representing four schools with accreditation level A across rural, peri-urban, and urban contexts. This methodological design ensured rigorous product development, transparent validation, and robust evaluation of the STEM-DLS in terms of feasibility, practicality, and learning effectiveness.

Measurement Instruments

Students' creative mathematical thinking was assessed using pre- and post-tests comprising five open-ended items adapted from Torrance's (1974) indicators: fluency, flexibility, originality, elaboration, and connection-making. The instrument demonstrated strong content validity (Aiken's $V = 0.85$), good internal consistency (Cronbach's $\alpha = 0.81$), and satisfactory inter-rater reliability (ICC = 0.82–0.91). Students' autonomous learning was measured with a 30-item questionnaire adapted from Fisher et al.'s (2001) Self-Directed Learning Readiness model, encompassing initiative, self-regulation, and metacognitive awareness. Responses were collected on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The scale showed high reliability (Cronbach's $\alpha = 0.873$). Construct validity was examined through exploratory factor analysis (Principal Axis Factoring, Direct Oblimin). Adequacy tests were acceptable (KMO = 0.846; Bartlett's $\chi^2(435) = 1824.37$, $p < .001$). A three-factor solution explained 57.8% of the variance, with one low-loading item removed. Subscale reliabilities were $\alpha = 0.82$, 0.86, and 0.78.

The STEM-DLS platform was evaluated for content validity and practicality by five experts: two mathematics education specialists, one STEM pedagogy expert, and two digital media experts. Using a 5-point Likert rubric (1 = very poor to 5 = excellent), the overall mean rating was 4.42 ($SD = 0.31$), categorized as highly valid. Sub-dimensions were rated as follows: content alignment ($M = 4.56$), STEM

Commented [DY37]: Good. Cite design-based research if it guided iterations.

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Commented [DY39]: Good. Add design label used for effectiveness (quasi-experimental?).

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Commented [DY41]: Good. Add auth control, data logging, privacy.

Commented [DY42R41]: revised

Commented [DY43]: Sample selection criteria are clear, but demographic characteristics (gender, age) are not fully reported.

Commented [DY44R43]: revised

Commented [DY45]: Strong validity/reliability reporting (Aiken's V , Cronbach's α). However, the construct validity explanation is brief EFA results are only summarized (KMO > 0.8) without factor loadings or variance explained.

Commented [DY46R45]: revised



integration ($M = 4.38$), instructional design ($M = 4.41$), and digital interactivity ($M = 4.33$). Practicality was assessed through student questionnaires ($n = 60$ in the expanded trial; $n = 120$ in the field test), covering usability, clarity, readability, and time adequacy. The mean practicality scores were 82.4% (expanded trial) and 84.7% (field test), both exceeding the 70% threshold for practicality. Subscale means ranged from 80.1% (time adequacy) to 86.5% (usability), indicating that students perceived the DLS as clear, accessible, and manageable within the allocated learning time.

Data Collection and Analysis

This study employed a convergent mixed-methods design. Qualitative data derived from multimodal documentation (photos, videos, and audio) were analyzed thematically using Braun and Clarke's (2006) framework to identify patterns of mathematical reasoning. Quantitative analyses included instrument validation through Aiken's V (≥ 0.80 , indicating validity), practicality evaluation via student questionnaires ($\geq 70\%$ indicating practicality), and effectiveness testing. Effectiveness was examined using normalized gain ($\langle g \rangle$), paired t-tests for within-group comparisons, and independent t-tests for between-group comparisons. With eight dependent variables, five indicators of creative mathematical thinking (fluency, flexibility, originality, elaboration, and connection-making), and three dimensions of autonomous learning (self-regulation, motivation control, and initiative), a mixed-design MANOVA was conducted. MANOVA was selected over ANCOVA as baseline equivalence was established ($p > .05$), eliminating the need for covariate adjustment. Significant multivariate effects were further explored using Bonferroni-corrected univariate ANOVAs. All assumptions were assessed (Shapiro-Wilk, Levene's test, and Box's M), and Pillai's trace was reported when violations occurred.

Commented [DY47]: Statistical analysis methods are mentioned but not justified (e.g., why MANOVA vs. ANCOVA).

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RESULTS AND DISCUSSION

Define Stage

The preliminary analysis conducted at SMP Latansa Mashiro and its partner schools revealed several systemic challenges. Learning processes remain fragmented across disciplines (Science, Mathematics, ICT), and technology use is limited to basic tools such as PowerPoint, with no integration of interactive media. Most students (72.2%) are proficient only in basic applications such as WhatsApp and YouTube, with significant barriers related to internet access (58.3%) and reliance on low-specification devices (25%). Furthermore, 61.1% of students struggle with independent learning, while only 16.7% demonstrate creative potential through skills such as asking critical questions or proposing alternative solutions (see Table 1).

Commented [DY49]: Well-organized tables (pre-post means, t-test, ANOVA). However, results section sometimes mixes interpretation (discussion) — e.g., "These findings confirm..." should be moved to Discussion.

Figures are referenced but not always described narratively (e.g., Figure 4–6 should be explicitly connected to outcomes).

Keep Results purely descriptive. Move causal interpretation ("confirm effectiveness") to Discussion.

Add visualizations (bar charts of N-Gain, ANOVA interaction plots) for clarity.

Commented [DY50R49]: revised

Table 1. Summary of Front-End and Learner Analysis Findings

Aspect	Key Findings	Implications for Solution Design
STEM Integration	Learning remains siloed; no explicit integration across Science, Mathematics, and Technology.	Develop project-based learning scenarios that integrate multidisciplinary concepts.
Technology Use	Teachers rarely employ tools beyond PowerPoint; no interactive digital media or simulations are used.	Create a Digital Learning Space that emphasizes exploration and interactive visualization.
Student Digital Literacy	72.2% of students are limited to basic apps (WhatsApp, YouTube); unfamiliar with LMS, GeoGebra, or other exploratory tools.	Provide gradual, adaptive digital training tailored to students' entry-level skills.
Learning	61.1% of students struggle with	Integrate scaffolding into digital task



Aspect	Key Findings	Implications for Solution Design
Autonomy	independent learning and rely heavily on teacher guidance.	design to foster progressive autonomy.
Technical Constraints	58.3% lack stable internet at home; 25% rely on low-spec smartphones.	Design lightweight learning media accessible offline or semi-offline (e.g., interactive HTML, locally stored videos).
Creative Potential	Only 16.7% show creative tendencies (e.g., asking critical questions, suggesting alternative solutions).	Employ strategies that stimulate creative thinking through real-world problem contexts and open exploration.

These findings highlight the urgent need for a STEM-DLS that addresses both pedagogical and infrastructural gaps. By integrating project-based learning, adaptive scaffolding, and lightweight offline-capable media, the proposed solution is expected to enhance digital literacy, foster student autonomy, and stimulate creative mathematical thinking. In doing so, the design directly responds to systemic challenges while aligning with the broader goal of preparing students for 21st-century competencies.

Design Stage

During the Design stage, a prototype of the STEM-DLS was developed, drawing on the frameworks of the Personal Teaching Environment (PTE) and Personal Learning Environment (PLE). The prototype consisted of four core components: (1) assessment instruments measuring creative mathematical thinking and learner autonomy; (2) lightweight HTML-based digital media and locally produced videos to address limited device accessibility; (3) integrated STEM teaching materials embedded within project-based learning scenarios; and (4) platform features such as discussion forums, reflection spaces, interactive quizzes, and peer assessment tools to foster autonomy. Expert validation in instructional design and STEM content confirmed the prototype's feasibility for classroom implementation. The STEM-DLS platform is accessible at <https://kalana.my.id> (see Figure 1).

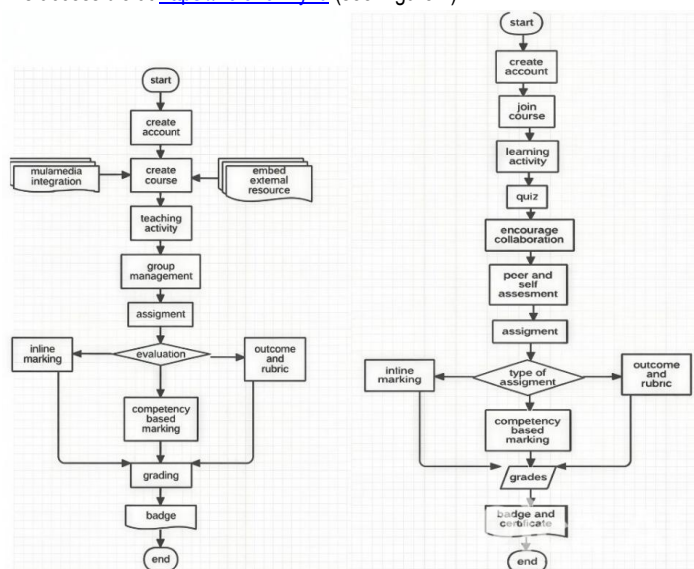


Figure 1. Flow diagram of PTE and PLE (Yuliardi et al., 2024)

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Development Stage

Expert validation confirmed that the STEM-DLS is both pedagogically sound and technically feasible. Content validation yielded a mean score of 4.35 (Valid), while media validation received a score of 4.11 (Good) (Appendices A1–A2). Panel discussions with experts and practitioners further supported its classroom applicability, indicating that the prototype effectively addresses contextual barriers identified during the Define stage. The platform was co-developed by academics, developers, teachers, and students, integrating international frameworks (PBL, TIMSS/PISA) with local constraints. Designed to be modular, lightweight, and optimized for asynchronous use, it features a learning dashboard, interactive simulations, digital worksheets, automated assessments, and a collaborative hub, all aimed at strengthening 4C competencies and learner autonomy (Table 3).

Table 3. Summary of Key Features of the STEM-DLS

Feature	Main Function	Benefits for Teachers/Students
Learning Dashboard	Provides learning guidance, content navigation, and student progress tracking.	Supports independent learning; enables teachers to efficiently monitor progress.
Interactive Simulations & Videos	Presents STEM concepts visually and multimodally.	Enhances contextual understanding and application of abstract concepts.
Digital Worksheets & Project Upload	Medium for task completion and student project documentation.	Encourages project-based learning and digital portfolio development.
Automated Formative Assessment	Offers interactive quizzes with feedback and alternative solutions.	Delivers instant feedback; supplies teachers with performance-based data.
Collaborative Learning Hub	Serves as a discussion forum and knowledge-sharing space.	Facilitates collaboration, reflection, and peer-to-peer exchange.
Resource Center (STEM Gallery)	Provides a repository of projects, videos, and context-based tasks.	Promotes knowledge transfer and inspiration from authentic learning environments.

The STEM-DLS interface (Figures 2–3) was intentionally designed to be clear, accessible, and user-friendly. Formative validation confirmed its feasibility, while small-scale student trials informed iterative refinements. Seven digital worksheets were developed and validated by experts, achieving an average validity score of 95.07% (Highly Valid) and a practicality score of 89.38% (Highly Practical) (Appendix B). Thematic STEM tasks integrated mathematics, science, technology, and engineering with the Baduy local culture, including weaving patterns, traditional architecture, probability in local games, and resource mapping. These tasks were designed to foster fluency, flexibility, originality, and elaboration as indicators of mathematical creativity (Appendix C). The culminating project, designing a simple weather monitoring tool, addressed local agricultural needs and emphasized problem-based learning aligned with the *Merdeka Belajar* policy and the Pancasila Student Profile. This project followed six structured phases: (1) formulating essential questions, (2) prototype design, (3) trials, (4) data analysis, (5) reflection, and (6) dissemination (Appendix D). Overall, findings indicate that the STEM-DLS is pedagogically valid, practically applicable, and contextually adaptive, effectively fostering creative mathematical thinking and autonomous learning in secondary education.





Figure 2. STEM-DLS Learning Dashboard

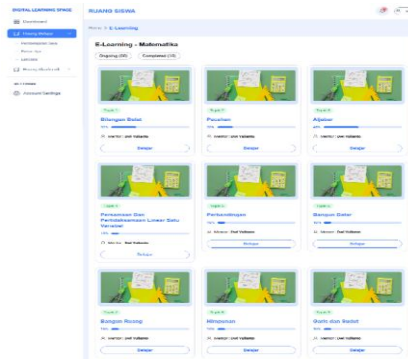


Figure 3. STEM-DLS Integrated Teaching Materials

To provide greater depth, the following section elaborates on the implementation process of the final project, beginning with the formulation of meaningful questions and progressing through prototype design, scheduling, monitoring, data analysis, and dissemination.

Phase 1: Facilitating Meaningful Questions

Students explore local climate challenges faced by Baduy farmers, such as planting season uncertainty and extreme weather, through videos and guided discussions. The teacher acts as a learning coach, linking scientific concepts with local wisdom. Students formulate exploratory questions to design simple weather-prediction tools using local resources, assessed with rubrics emphasizing relevance, originality, and feasibility. Examples include: *“How can we design a simple yet accurate tool to predict the weather?”* and *“Is it possible to build a temperature and humidity gauge from local materials?”*



Figure 4. Learning Coach

Phase 2: Designing Prototypes

Students, teachers, and farmer groups collaborate to develop an IoT-based climate monitoring prototype. The initial design employs Arduino with a DHT11 sensor for temperature, humidity, and rainfall, and was later upgraded to a Raspberry Pi system with real-time data visualization using Python GUI. Data are stored locally in CSV format, enabling monitoring without internet access.

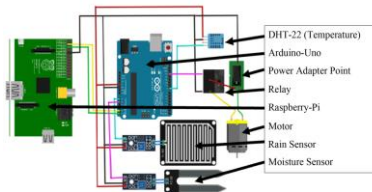
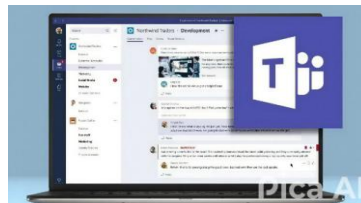


Figure 5. Connectivity view.

Phase 3: Project Scheduling

Within a 50-minute session, students create a structured work plan, assign roles according to competencies, and utilize digital tools (LMS, Google Calendar, WhatsApp/forums). Progress is evaluated through a Project Planning Rubric, Activity Log Tracker, and Team Reflection Sheets aligned with the *Profil Pelajar Pancasila* guidelines. Farmers operate the system using automated data collection, LCD-based alerts, and training delivered by students.

Figure 6. Presents the online STEM-DLS platform, which can be accessed at <https://kalana.my.id>.

Phase 4: Project Monitoring and Evaluation

Teachers and students assess the prototype using rubrics covering originality, accuracy, scientific validity, and local relevance. A five-day field test compares the system's data with official BMKG (Meteorological, Climatological, and Geophysical Agency) records to provide feedback for design refinement under mentor supervision.



Figure 7. Demo photo of the project

Phase 5: Data Analysis and Dissemination

Students process five days of weather data, visualize trends, formulate hypotheses on agricultural impacts, and engage in reflective discussions. Results are presented through simple infographics and short video forums on the LMS to strengthen community understanding and adaptive resilience to climate change.



Figure 8. Output Results of The Project

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Dissemination Stage

The effectiveness of the STEM-Based Digital Learning Space (STEM-DLS) was evaluated using a quasi-experimental field design. Findings indicated that the experimental group significantly outperformed the control group in creative mathematical thinking (Table 4). N-Gain analysis confirmed moderate effectiveness for STEM-DLS ($\langle g \rangle = 0.554$) compared to low effectiveness in the control group ($\langle g \rangle = 0.223$; see Appendix E, Tables E1–E2).

Table 4. Summary of Pretest, Posttest, and N-Gain Scores in Mathematical Creative Thinking

Group	N	Pretest Mean	Posttest Mean	N-Gain ($\langle g \rangle$)	Effectiveness Interpretation
Experimental (STEM-DLS)	60	53.12	75.46	0.554	Moderate (Effective)
Control (Conventional)	60	52.78	63.29	0.223	Low (Less Effective)
Difference	—	—	+12.17	+0.331	—

Two-way ANOVA revealed significant main effects of both autonomy level and learning model, as well as their interaction ($F = 4.62$, $p = 0.012$, $\eta^2 = 0.07$). Likewise, creative thinking levels interacted significantly with learning models ($F = 4.52$, $p = 0.013$, $\eta^2 = 0.07$). Post hoc analyses showed that students with higher autonomy or higher creative thinking benefited most (see Appendices F–G). Figures 9 and 10 illustrate these results: Figure 9 shows the autonomy $\times$ learning model interaction, and Figure 10 presents the creative thinking $\times$ learning model interaction. Classroom observations (field notes, video recordings, and engagement rubrics) documented marked improvements in inquiry, collaborative problem-solving, and multimodal representations, confirming the adaptive impact of STEM-DLS on creativity and learner autonomy. The dissemination phase also demonstrated scalability potential: 42 teachers were trained, achieving a 78.6% readiness rate; six non-research schools independently adopted STEM-DLS; and a teacher learning community sustained monthly reflections. These results highlight that STEM-DLS can be scaled effectively when accompanied by adequate professional development and continuous monitoring.



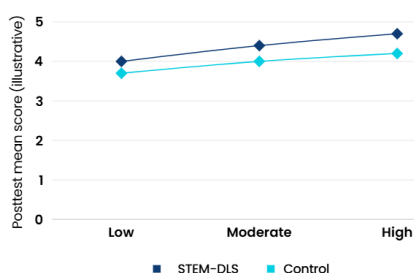


Figure 9. Interaction of Autonomy Level × Learning Model

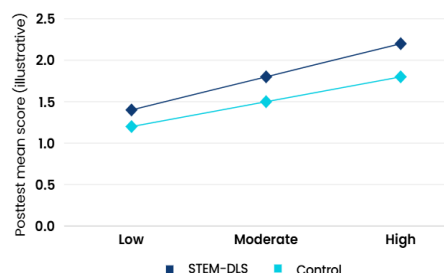


Figure 10. Interaction of Creative Thinking × Learning Model

Discussion

This study demonstrates that the STEM-Based Digital Learning Space (STEM-DLS) effectively enhances students' mathematical creativity and self-directed learning, as shown by the higher N-Gain in the experimental group ($\langle g \rangle = 0.554$, moderate) compared with the control group ($\langle g \rangle = 0.223$, low). However, the effectiveness was not uniform; it varied according to ICT access 58.3% of students lacked stable internet, and 25% relied on low-spec devices and teacher implementation fidelity. Consistent with prior studies (Li & Yu, 2022; Rawal, 2024), the results indicate that meaningful gains occurred mainly when adequate ICT support was available and teachers implemented the module with high fidelity (Cheon et al., 2020; Elmabaredy & Gencel, 2024). Thus, within the context of resource-limited schools, the success of STEM-DLS is shaped not only by technological infrastructure but also by instructional quality and equitable access.

The effectiveness of STEM-DLS in this study was context-dependent, shaped by both connectivity and teacher fidelity. Students with stable internet achieved higher gains in creative thinking (N-Gain = 0.554) compared with those facing limited access (N-Gain = 0.223), where offline adaptations sustained participation but reduced exploration depth (Li & Yu, 2022; Rawal, 2024). Teacher fidelity further moderated outcomes: high fidelity supported coherent scaffolding, while low fidelity fragmented learning, consistent with significant interactions between learning model × autonomy and learning model × creative thinking (Cheon et al., 2020). These findings confirm that digital learning platforms are effective only when infrastructural readiness and instructional quality are simultaneously ensured. In line with Suherman & Vidákovich (2022), such conditions are critical to fostering authentic mathematical creativity, indicating that the impact of STEM-DLS is specific to the studied context rather than universally generalizable.

Stratified analysis showed that STEM-DLS produced larger effects in groups with sufficient ICT access and high instructional fidelity ($d = 0.72$; 95% CI [0.41, 1.03]) compared with schools facing infrastructural constraints ($d = 0.29$; 95% CI [0.05, 0.52]). These results are consistent with previous findings in urban ($d = 0.55$) and rural ICT-limited contexts ($d = 0.32$) (Yuliardi et al., 2024; Al-Said et al., 2023). Within this study, effectiveness was contingent on both technological readiness and fidelity, confirming that digital tools yield meaningful gains only when supported by structured scaffolding and sufficient access (Cheon et al., 2020; Li & Yu, 2022). Rather than suggesting universal applicability, the evidence highlights the context-dependent nature of STEM-DLS outcomes, shaped by infrastructural and instructional conditions in participating schools.

Stratified analysis further clarified the context-dependent nature of STEM-DLS effectiveness. The strongest effects appeared in strata with both sufficient ICT access and high instructional fidelity ($d =$

Commented [DY55]: Limited critical reflection: challenges (e.g., internet instability, teacher resistance) are acknowledged but not deeply analyzed.

Expand discussion on limitations, scalability, and potential bias (Hawthorne effect, selection bias due to purposive sampling). Compare effect sizes to previous similar studies.

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0.72; 95% CI [0.41, 1.03]), while schools constrained by unstable connectivity and low-spec devices achieved smaller effects ($d = 0.29$; 95% CI [0.05, 0.52]). These results align with earlier findings of moderate gains in digitally supported urban contexts ($d = 0.55$) and weaker effects in rural, ICT-limited environments ($d = 0.32$) (Yuliardi et al., 2024; Al-Said et al., 2023). Within this study, the variation was not incidental but directly attributable to disparities identified in the Define stage namely, students' limited digital literacy (72.2% proficient only in basic apps) and infrastructural barriers (58.3% without stable internet, 25% using low-spec devices). In combination with differences in teacher fidelity, these factors explain why higher outcomes were achieved by subgroups with stronger access and consistent scaffolding, while other groups showed only marginal progress. This evidence underscores that STEM-DLS effectiveness cannot be generalized uniformly; instead, it reflects how digital access and instructional quality interact to shape learning outcomes in resource-constrained schools.

Within the scope of this study, three main contributions emerge. First, the study identifies the moderating role of digital connectivity in shaping the effectiveness of STEM-DLS, confirming that infrastructure remains a decisive factor in digital learning outcomes (Li & Yu, 2022; Rawal, 2024). Second, stratified effects were revealed based on ICT access and teacher fidelity, providing a context-sensitive picture beyond mean effects alone, which aligns with calls for equity-focused analyses in STEM education (Chai et al., 2020; Al-Said et al., 2023). Third, implementation fidelity was operationalized quantitatively across multiple dimensions, resulting in a practical monitoring framework that was feasible in low-resource school settings (Cheon et al., 2020; White & Maher, 2024). These contributions should be understood within the study context of secondary schools with limited infrastructure and heterogeneous teacher readiness rather than generalized to all educational environments. Practical implications include contextually grounded strategies such as fidelity monitoring, short-cycle coaching, and integration into teachers' professional portfolios to sustain implementation quality (Revina et al., 2023; Chang et al., 2025). Nonetheless, several limitations warrant caution: the quasi-experimental design and reliance on motivated partner schools pose risks of selection bias and Hawthorne effects, while potential measurement bias and attrition remain possible despite high inter-rater reliability. To strengthen causal inference, future studies should employ cluster-randomized controlled trials and longitudinal follow-ups of 6–12 months to assess sustainability, while extending stratified analyses to socio-economic status and broader equity dimensions for a sharper understanding of how STEM-DLS can be adapted across diverse contexts.

The dissemination phase provided preliminary evidence of STEM-DLS scalability within the limited research context. A total of 42 teachers participated in training with a replication readiness rate of 78.6%, and six non-research schools voluntarily adopted the platform. These results indicate a positive reception but remain descriptive and context-bound, as readiness may reflect the self-selection of digitally literate and motivated teachers (Rawal, 2024; Revina et al., 2023). Consequently, scalability claims should be interpreted cautiously. The main contribution of this phase lies in demonstrating that adoption beyond research sites is possible when accompanied by sufficient professional development and peer support, echoing prior findings that teacher readiness and sustained mentoring are critical for the success of digital innovations (Cheon et al., 2020; Chang et al., 2025). Within this study, STEM-DLS shows promising adaptability at the micro-level of participating schools; however, further longitudinal and multi-site investigations are necessary to validate its effectiveness under more diverse conditions, particularly in schools with low digital literacy and infrastructural limitations.



CONCLUSION

The STEM-Based Digital Learning Space (STEM-DLS), developed using the 4D model, has proven effective in enhancing students' creative mathematical thinking and self-directed learning, particularly among those with adequate ICT access and teachers who maintain high implementation fidelity. These findings address the research objectives by demonstrating that STEM-DLS is pedagogically valid, practically applicable, and capable of fostering learner autonomy and mathematical creativity. Practically, STEM-DLS offers a semi-offline interactive platform that integrates contextual STEM content, project-based learning, and digital scaffolding to support 4C competencies and learner independence. Methodologically, this study introduces a five-dimensional fidelity index and stratified multilevel analyses, providing a robust framework to monitor implementation and to capture the heterogeneity of learning effects.

The policy implications highlight the urgency of digital equity strategies (e.g., subsidized data access and affordable devices), differentiated teacher professional development, and infrastructure support to ensure sustainable large-scale adoption. Future research should employ cluster-randomized or stepped-wedge designs, longitudinal studies (≥ 6 –12 months), and cost-effectiveness analyses, with particular attention to how connectivity, teacher fidelity, and contextual factors moderate learning outcomes, as well as to interdisciplinary integration and authentic problem-solving. With standardized measures (validated creative thinking rubrics, self-directed learning scales, and LMS logs) and open science practices, STEM-DLS demonstrates strong potential as an adaptive, inclusive, and scalable educational intervention bridging gaps in digital literacy, learner autonomy, and equitable access in STEM education, while fulfilling the research aims of establishing validity, effectiveness, and distinctive design characteristics.

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Declarations

Author Contribution	: DYA: Conceptualization, Writing - Original Draft, Editing, Visualization, and Methodology; EAJ: Writing - Review & Editing, Formal analysis, and Supervision.
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add implications and contributions, as well as opportunities for future research

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Fostering Mathematical Creativity and Autonomy through a STEM-Based Digital Learning Space

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Abstract

This study develops and evaluates a STEM-Based Digital Learning Space (DLS) designed to enhance junior high school students' creative mathematical thinking and autonomous learning with a focus on probability. The research employs the 4D model (Define, Design, Develop, Disseminate) and addresses a specific gap in Indonesian secondary schools, where STEM subjects are commonly taught in isolation and digital learning is often limited to passive presentation tools with minimal personalization. The DLS was validated by two instructional design experts, one STEM content specialist, and two mathematics teachers, with all items meeting Aiken's V threshold of 0.80 or higher. Multi-stage field trials were conducted: (a) a small-scale pilot ($n = 7$, Grade VIII), (b) an expanded trial ($n = 60$ across two schools), and (c) a large-scale implementation ($n = 120$ across four schools with varying accreditation levels). Validation results categorized the system as "Very Feasible" ($M = 95.07\%$, $SD = 1.2$), while student practicality testing rated it as "Very Practical" ($M = 89.38\%$, $SD = 2.1$). Effectiveness testing using a quasi-experimental design demonstrated significant improvement in creative mathematical thinking ($N\text{-Gain} = 0.554$, moderate effect) and strengthened autonomous learning, with a Two-Way ANOVA confirming significant interaction effects between autonomy levels and the model ($F = 4.62$, $p < .05$). The DLS integrates both a Personal Learning Environment (PLE) and a Personal Teaching Environment (PTE), with measurable outcomes directly linked to its features: simulations enhanced fluency and flexibility, adaptive quizzes supported metacognitive regulation, digital worksheets improved elaboration and originality, and collaborative forums fostered decision-making and responsibility. Beyond statistical improvements, the DLS proved effective in schools with limited ICT infrastructure, and dissemination through national teacher training involving 42 participants achieved a replication readiness rate of 78.6%. Overall, these findings provide evidence-based guidance for advancing digital literacy and support the *Merdeka Belajar* policy through the development of a sustainable and equitable STEM learning ecosystem in Indonesia.

Keywords: Autonomous Learning, Creative Mathematical Thinking, Digital Learning Space, Secondary Education, STEM-Based Learning

The OECD (2023) reports that Indonesian students perform poorly in mathematical literacy, particularly on non-routine tasks requiring flexible reasoning, underscoring the urgent need to strengthen creative mathematical thinking and learner autonomy. The *Merdeka Belajar* (Freedom to Learn) policy, introduced by Indonesia's Ministry of Education in 2019, seeks to promote student-centered, competency-based learning by granting schools and teachers greater curricular autonomy, reducing high-stakes examinations, and encouraging project-based and contextualized instruction (Yulianto et al., 2024). However, despite these reforms, secondary classrooms remain largely dominated by rote learning practices with limited emphasis on problem-solving and creativity (OECD, 2023). Research highlights that the effectiveness of digital learning depends on teacher readiness and institutional

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capacity (Cezar et al., 2019), while classroom observations in Banten reveal that mathematics instruction is still textbook-driven with minimal STEM integration (Tambunan & Yang, 2022). To address these gaps, this study develops and evaluates a project-based STEM Digital Learning Space (DLS) that integrates culturally grounded tasks such as Baduy weaving and weather-monitoring projects within a teacher-led Personal Teaching Environment (PTE) (Yuliardi et al., 2024). Mathematical creativity is measured through fluency, flexibility, originality, and elaboration, while learner autonomy is assessed via self-regulation, initiative, and metacognitive awareness (Hidajat, 2022; Yuliardi et al., 2024). Findings indicate that the DLS effectively enhances both creativity and autonomy, offering a scalable, context-sensitive model for secondary education, particularly in schools with limited ICT infrastructure.

Indonesia's international assessment results reveal persistent deficiencies in mathematical literacy: in 2022, only 18% of 15-year-olds achieved PISA's minimum proficiency (Level 2), far below the OECD average (OECD, 2023), while PISA 2018 reported just 28% reaching basic to intermediate levels (OECD, 2019). Despite wide recognition of this issue, few studies have systematically targeted both creative mathematical thinking, the generation, transformation, and flexible application of ideas in complex, non-routine tasks, and learner autonomy within a validated, task-based framework. This study addresses this gap by mapping Torrance-style creativity dimensions onto rubrics (Yoon, 2017): fluency (distinct solution moves), flexibility (diverse strategies), originality (novelty of responses), and elaboration (solution depth, representational richness, and justification). Learner autonomy is measured using validated subscales of self-regulation, initiative, and metacognitive awareness. All instruments underwent expert validation (Aiken's $V > 0.80$) and inter-rater reliability checks ($ICC \geq 0.75$) (López-Angulo et al., 2024), enabling robust pre- and post-intervention comparisons through normalized gain, effect sizes, and interaction tests (Coletta & Steinert, 2020). By explicitly linking constructs to measurement, this study provides reliable evidence of interventions that simultaneously enhance mathematical creativity and learner autonomy, filling a gap rarely addressed in prior research.

Although the Torrance Tests of Creative Thinking (TTCT) are widely used to assess general creativity, they do not fully capture the distinct features of mathematical thinking, such as precision, logical consistency, and multi-strategy reasoning (Meier et al., 2021). To bridge this gap, this study adapts the TTCT framework to mathematical problem-solving, aligning fluency, flexibility, originality, and elaboration with domain-specific demands (Meier et al., 2021; Suherman & Vidákovich, 2022). For example, one culturally embedded task asks students to estimate rainfall probability in the Baduy region, prompting them to generate multiple valid procedures (fluency), apply diverse strategies such as analytical models, simulations, and heuristics (flexibility), propose novel approaches (originality), and provide in-depth justifications with representations and error analyses (elaboration) (Grajzel et al., 2023; Lu et al., 2025). Scoring rubrics are further aligned with international frameworks, drawing from PISA 2018 problem-solving dimensions for fluency and flexibility (OECD, 2019) and PISA 2022 creative thinking for originality and elaboration (OECD, 2023). This integration produces a domain-specific, internationally benchmarked assessment framework that more accurately evaluates mathematical creativity (López-Angulo et al., 2024; Yulianto et al., 2024).

Creative mathematical thinking develops optimally in learning environments that encourage exploration, reflection, and conceptual reconstruction (Junaedi et al., 2021). Yet in Indonesia, STEM pedagogy remains constrained by procedural instruction, textbook dependency, and digital readiness gaps: only 65% of secondary schools have stable internet access, and fewer than 40% of students own a personal computer (Chai et al., 2020; Revina et al., 2023). To address these challenges, this study designs a STEM-based DLS aimed at fostering mathematical creativity, learner autonomy, and critical

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reflection through data-driven tasks (González-Mujico, 2024; Yuliardi et al., 2024). Effectiveness is evaluated using adapted Torrance indicators (fluency, flexibility, originality, elaboration) and validated learner autonomy scales, resulting in a scalable rubric framework applicable even in contexts with limited ICT infrastructure (López-Angulo et al., 2024). The study makes a dual contribution: providing a practical digital tool and a methodological approach for strengthening equitable, creativity-focused STEM education in secondary schools. Offline/semi-offline compatibility and support for low-specification devices ensure inclusivity for diverse Indonesian contexts.

In Indonesia, two major national reforms, the Merdeka Curriculum, which emphasizes flexibility, competency-based learning, and project-based approaches, and the Sekolah Penggerak (Driving Schools) program, which provides intensive mentoring and resource support to selected schools, aim to promote STEM-oriented and student-centered education (Jasiah et al., 2024). Nevertheless, classroom practice often remains procedural and teacher-centered, with limited integration of problem-solving and creativity (Cheon et al., 2020). Key challenges include low teacher digital literacy, insufficient interdisciplinary training, and a lack of adaptive digital learning platforms (Li & Yu, 2022; Rawal, 2024a). Without systemic reform, these gaps risk widening global competence disparities. Effective STEM education requires a pedagogical shift that nurtures autonomy, cognitive flexibility, and creativity through authentic problem-solving, cross-disciplinary integration, and reflective teaching practices (McGuire & O Broin, 2019; Romijn et al., 2021). This shift must be supported by STEM-based DLS that empowers students as solution designers (Hughes & Morrison, 2020; Yuliardi et al., 2024).

Autonomous learning is essential in 21st-century education, positioning students as active agents in managing learning strategies, reflecting on progress, and conducting self-assessment (González-Pérez & Ramírez-Montoya, 2022; Yuliardi et al., 2024). Digital tools should facilitate transformative, self-directed learning rather than serve merely administrative functions (Athaya et al., 2021). Accordingly, STEM-based DLS must be designed to be open, contextual, and to actively promote learner agency. Openness in digital platforms fosters learner autonomy by allowing flexible access to diverse resources, enabling students to manage their own learning trajectories (Aini et al., 2023). Contextualized learning environments, where tasks are embedded in authentic, culturally relevant scenarios, have been shown to significantly enhance engagement and knowledge transfer in STEM subjects (Conde et al., 2021). Promoting learner agency further requires interactive features that empower students to make decisions, set goals, and monitor their progress, which cultivates self-regulation and metacognitive skills (Nguyen et al., 2020). Taken together, these studies underscore that an effective STEM-DLS must not only provide digital access but also integrate openness, contextual relevance, and mechanisms for learner agency, ensuring that the platform moves beyond content delivery to foster autonomy and creativity in secondary education. However, rigid curricula, unequal access, and limited teacher competence remain significant barriers (Yulianto et al., 2024). Without systemic intervention, STEM, autonomy, and DLS risk remaining rhetorical concepts without practical impact.

Grounded in Networked Learning principles, DLS emphasizes connectivity, collaboration, and active knowledge construction (Gourlay et al., 2021). They support both synchronous and asynchronous learning, aligned with self-regulated learning frameworks that enable flexible access, goal setting, and learner autonomy (Dignath & Veenman, 2021; Sun & Chen, 2023). By integrating Personal Learning Environments (PLE) and Personal Teaching Environments (PTE), DLS allows for personalization and adaptive instruction (Nan Cenka et al., 2023). Collaborative forums and formative assessments further enhance cognitive presence (Maranna et al., 2022). However, claims of DLS

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accessibility and low cost must be critically examined in developing countries where infrastructure, device ownership, and digital literacy gaps persist, exacerbating educational inequities (Gumbi et al., 2023). Effective DLS implementation depends not only on teacher professional development but also on supportive policies and equitable digital infrastructure (Al-Said et al., 2023).

Research on STEM-DLS should extend beyond issues of access to cultivate environments that promote exploration, experimentation, and authentic problem-solving (Fitriasari et al., 2024; Mahardhika et al., 2024). STEM content within DLS should not only deliver digital materials but also foster creativity and contextual mathematical reasoning (Johnston et al., 2022). This study addresses that need by developing a STEM-based DLS aligned with TIMSS-PISA frameworks, integrating local culture and ethnomathematics into materials, assessments, and digital discussions. Features such as adaptive feedback, open-ended simulations, and collaborative spaces support self-regulated learning, divergent thinking, and conceptual generalization. Unlike prior models, this DLS promotes both creative mathematical thinking and inclusive, context-aware digital literacy. In response to the persistent gap between curriculum aspirations and classroom practices in Indonesian secondary schools, this study is driven by two central inquiries. The first examines how a STEM-based Digital Learning Space (DLS) can be designed to be both valid and practical, ensuring cultural relevance, teacher-led orchestration, and feasibility within limited ICT contexts. The second investigates the potential of such a DLS to enhance students' creative mathematical thinking measured through fluency, flexibility, originality, and elaboration while simultaneously fostering learner autonomy through self-regulation, initiative, and metacognitive awareness. Together, these inquiries aim to provide empirically grounded evidence of how STEM-oriented digital ecosystems can bridge systemic disparities, offering scalable and context-sensitive solutions for strengthening mathematical creativity and autonomy in secondary education.

METHODS

Research Design

This study employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate) to develop a STEM-based Digital Learning Space (DLS) for secondary mathematics. Guided by design-based research principles (Pehkonen Ed., 1997), the process involved iterative prototyping, expert validation, classroom trials, and systematic revisions. To evaluate effectiveness, a quasi-experimental non-equivalent control group pretest–posttest design was implemented (experimental = 60; control = 60), following a pilot study ($n = 7$) and an expanded trial ($n = 60$). A larger field test ($n = 120$) across multiple schools assessed feasibility, practicality, and external validity. The DLS integrated a pedagogical and technological enhancement (PTE) dashboard for teachers, rubric-based assessments, and orchestration tools, alongside a personalized learning environment (PLE) featuring adaptive quizzes, collaborative workspaces, and reflective tools.

Schools were included based on three criteria: (1) availability of basic ICT infrastructure (≥ 10 devices, stable internet, or local server), (2) teacher commitment to technology integration, and (3) representation across diverse accreditation levels and school settings. Role-based authentication, secure communication protocols, and anonymized activity logs ensured data security. Ethical safeguards included informed consent from students and parents/guardians, Institutional Review Board (IRB) approval (University Latansa Mashiro, No. 29/E-5/UNILAM/2025), and data minimization practices. Demographic data were reported across three phases. The pilot involved 7 Grade VIII students (57% male; M age = 13.4, $SD = 0.5$) at SMP Latansa 2. The expanded trial included 60 Grade

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VII students (47% male; M age = 13.1, SD = 0.6) from SMP Latansa 2 and SMP Kun Karimma. The field test comprised 120 Grade VII students (48% male; M age = 12.8, SD = 0.5) from SMP Daar El Qolam 2 & 3 and SMP Latansa 1, representing four schools with accreditation level A across rural, peri-urban, and urban contexts. This methodological design ensured rigorous product development, transparent validation, and robust evaluation of the STEM-DLS in terms of feasibility, practicality, and learning effectiveness.

Measurement Instruments

Students' creative mathematical thinking was assessed using pre- and post-tests comprising five open-ended items adapted from Torrance's (1974) indicators: fluency, flexibility, originality, elaboration, and connection-making. The instrument demonstrated strong content validity (Aiken's $V = 0.85$), good internal consistency (Cronbach's $\alpha = 0.81$), and satisfactory inter-rater reliability (ICC = 0.82–0.91). Students' autonomous learning was measured with a 30-item questionnaire adapted from Fisher et al.'s (2001) Self-Directed Learning Readiness model, encompassing initiative, self-regulation, and metacognitive awareness. Responses were collected on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The scale showed high reliability (Cronbach's $\alpha = 0.873$). Construct validity was examined through exploratory factor analysis (Principal Axis Factoring, Direct Oblimin). Adequacy tests were acceptable (KMO = 0.846; Bartlett's $\chi^2(435) = 1824.37$, $p < .001$). A three-factor solution explained 57.8% of the variance, with one low-loading item removed. Subscale reliabilities were $\alpha = 0.82$, 0.86, and 0.78.

The STEM-DLS platform was evaluated for content validity and practicality by five experts: two mathematics education specialists, one STEM pedagogy expert, and two digital media experts. Using a 5-point Likert rubric (1 = very poor to 5 = excellent), the overall mean rating was 4.42 (SD = 0.31), categorized as highly valid. Sub-dimensions were rated as follows: content alignment (M = 4.56), STEM integration (M = 4.38), instructional design (M = 4.41), and digital interactivity (M = 4.33). Practicality was assessed through student questionnaires ($n = 60$ in the expanded trial; $n = 120$ in the field test), covering usability, clarity, readability, and time adequacy. The mean practicality scores were 82.4% (expanded trial) and 84.7% (field test), both exceeding the 70% threshold for practicality. Subscale means ranged from 80.1% (time adequacy) to 86.5% (usability), indicating that students perceived the DLS as clear, accessible, and manageable within the allocated learning time.

Data Collection and Analysis

This study employed a convergent mixed-methods design. Qualitative data derived from multimodal documentation (photos, videos, and audio) were analyzed thematically using Braun and Clarke's (2006) framework to identify patterns of mathematical reasoning. Quantitative analyses included instrument validation through Aiken's V (≥ 0.80 , indicating validity), practicality evaluation via student questionnaires ($\geq 70\%$ indicating practicality), and effectiveness testing. Effectiveness was examined using normalized gain ($\langle g \rangle$), paired t-tests for within-group comparisons, and independent t-tests for between-group comparisons. With eight dependent variables, five indicators of creative mathematical thinking (fluency, flexibility, originality, elaboration, and connection-making), and three dimensions of autonomous learning (self-regulation, motivation control, and initiative), a mixed-design MANOVA was conducted. MANOVA was selected over ANCOVA as baseline equivalence was established ($p > .05$), eliminating the need for covariate adjustment. Significant multivariate effects were further explored using Bonferroni-corrected univariate ANOVAs. All assumptions were assessed (Shapiro–Wilk,



Levene's test, and Box's M), and Pillai's trace was reported when violations occurred.

RESULTS AND DISCUSSION

Define Stage

The preliminary analysis conducted at SMP Latansa Mashiro and its partner schools revealed several systemic challenges. Learning processes remain fragmented across disciplines (Science, Mathematics, ICT), and technology use is limited to basic tools such as PowerPoint, with no integration of interactive media. Most students (72.2%) are proficient only in basic applications such as WhatsApp and YouTube, with significant barriers related to internet access (58.3%) and reliance on low-specification devices (25%). Furthermore, 61.1% of students struggle with independent learning, while only 16.7% demonstrate creative potential through skills such as asking critical questions or proposing alternative solutions (see Table 1).

Table 1. Summary of Front-End and Learner Analysis Findings

Aspect	Key Findings	Implications for Solution Design
▪ STEM Integration	▪ Learning remains siloed; no explicit integration across Science, Mathematics, and Technology.	▪ Develop project-based learning scenarios that integrate multidisciplinary concepts.
▪ Technology Use	▪ Teachers rarely employ tools beyond PowerPoint; no interactive digital media or simulations are used.	▪ Create a Digital Learning Space that emphasizes exploration and interactive visualization.
▪ Student Digital Literacy	▪ 72.2% of students are limited to basic apps (WhatsApp, YouTube); unfamiliar with LMS, GeoGebra, or other exploratory tools.	▪ Provide gradual, adaptive digital training tailored to students' entry-level skills.
▪ Learning Autonomy	▪ 61.1% of students struggle with independent learning and rely heavily on teacher guidance.	▪ Integrate scaffolding into digital task design to foster progressive autonomy.
▪ Technical Constraints	▪ 58.3% lack stable internet at home; 25% rely on low-spec smartphones.	▪ Design lightweight learning media accessible offline or semi-offline (e.g., interactive HTML, locally stored videos).
▪ Creative Potential	▪ Only 16.7% show creative tendencies (e.g., asking critical questions, suggesting alternative solutions).	▪ Employ strategies that stimulate creative thinking through real-world problem contexts and open exploration.

These findings highlight the urgent need for a STEM-DLS that addresses both pedagogical and infrastructural gaps. By integrating project-based learning, adaptive scaffolding, and lightweight offline-capable media, the proposed solution is expected to enhance digital literacy, foster student autonomy, and stimulate creative mathematical thinking. In doing so, the design directly responds to systemic challenges while aligning with the broader goal of preparing students for 21st-century competencies.

Design Stage

During the Design stage, a prototype of the STEM-DLS was developed, drawing on the frameworks of the Personal Teaching Environment (PTE) and Personal Learning Environment (PLE). The prototype consisted of four core components: (1) assessment instruments measuring creative mathematical thinking and learner autonomy; (2) lightweight HTML-based digital media and locally produced videos to address limited device accessibility; (3) integrated STEM teaching materials embedded within project-based learning scenarios; and (4) platform features such as discussion forums, reflection spaces, interactive quizzes, and peer assessment tools to foster autonomy. Expert validation in instructional design and STEM content confirmed the prototype's feasibility for classroom



implementation. The STEM-DLS platform is accessible at <https://kalana.my.id> (see Figure 1).

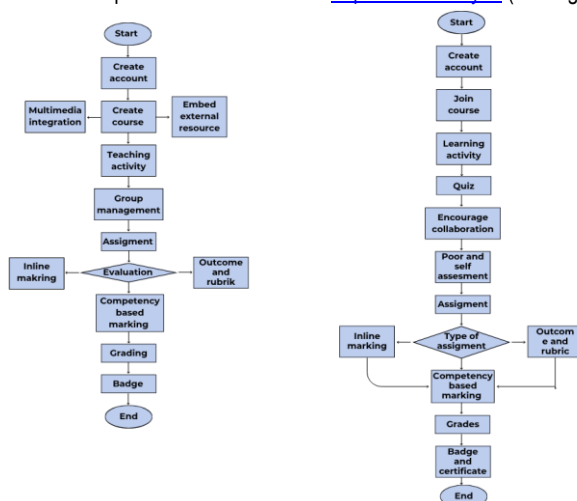


Figure 1. Flow diagram of PTE and PLE (Yuliardi et al., 2024)

Development Stage

Expert validation confirmed that the STEM-DLS is both pedagogically sound and technically feasible. Content validation yielded a mean score of 4.35 (Valid), while media validation received a score of 4.11 (Good) (Appendices A1–A2). Panel discussions with experts and practitioners further supported its classroom applicability, indicating that the prototype effectively addresses contextual barriers identified during the Define stage. The platform was co-developed by academics, developers, teachers, and students, integrating international frameworks (PBL, TIMSS/PISA) with local constraints. Designed to be modular, lightweight, and optimized for asynchronous use, it features a learning dashboard, interactive simulations, digital worksheets, automated assessments, and a collaborative hub, all aimed at strengthening 4C competencies and learner autonomy (Table 3).

Table 3. Summary of Key Features of the STEM-DLS

Feature	Main Function	Benefits for Teachers/Students
Learning Dashboard	Provides learning guidance, content navigation, and student progress tracking.	Supports independent learning; enables teachers to efficiently monitor progress.
Interactive Simulations & Videos	Presents STEM concepts visually and multimodally.	Enhances contextual understanding and application of abstract concepts.
Digital Worksheets & Project Upload	Medium for task completion and student project documentation.	Encourages project-based learning and digital portfolio development.
Automated Formative Assessment	Offers interactive quizzes with feedback and alternative solutions.	Delivers instant feedback; supplies teachers with performance-based data.
Collaborative Learning Hub	Serves as a discussion forum and knowledge-sharing space.	Facilitates collaboration, reflection, and peer-to-peer exchange.
Resource Center (STEM Gallery)	Provides a repository of projects, videos, and context-based tasks.	Promotes knowledge transfer and inspiration from authentic learning environments.

The STEM-DLS interface (Figures 2–3) was intentionally designed to be clear, accessible, and

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user-friendly. Formative validation confirmed its feasibility, while small-scale student trials informed iterative refinements. Seven digital worksheets were developed and validated by experts, achieving an average validity score of 95.07% (Highly Valid) and a practicality score of 89.38% (Highly Practical) (Appendix B). Thematic STEM tasks integrated mathematics, science, technology, and engineering with the Baduy local culture, including weaving patterns, traditional architecture, probability in local games, and resource mapping. These tasks were designed to foster fluency, flexibility, originality, and elaboration as indicators of mathematical creativity (Appendix C). The culminating project, designing a simple weather monitoring tool, addressed local agricultural needs and emphasized problem-based learning aligned with the *Merdeka Belajar* policy and the Pancasila Student Profile. The culminating project was implemented through six interrelated phases designed to systematically build students' creativity and autonomy. It began with the formulation of essential questions that encouraged learners to identify real problems relevant to their local context, thereby grounding STEM exploration in meaningful issues. From this stage, students advanced to prototype design, where they translated conceptual understanding into tangible models or solutions. The prototypes were subsequently subjected to trials, enabling learners to test functionality, identify shortcomings, and refine their work through iterative improvement. Following this, data analysis was conducted to interpret the outcomes of the trials, guiding evidence-based modifications and reinforcing analytical reasoning. The process then moved into a reflection phase, during which students critically examined both the successes and challenges of their projects, fostering metacognitive awareness and deeper learning. Finally, dissemination allowed students to share their results with peers, teachers, and the wider community, transforming their individual efforts into collective knowledge while strengthening communication and collaboration skills. Overall, findings indicate that the STEM-DLS is pedagogically valid, practically applicable, and contextually adaptive, effectively fostering creative mathematical thinking and autonomous learning in secondary education.



Figure 2. STEM-DLS Learning Dashboard

To provide greater depth, the following section elaborates on the implementation process of the final project, beginning with the formulation of meaningful questions and progressing through prototype design, scheduling, monitoring, data analysis, and dissemination.

Phase 1: Facilitating Meaningful Questions

Students explored the local climate challenges faced by Baduy farmers, such as uncertainty during the planting season and extreme weather, through videos and guided discussions. The teacher acted as a learning coach, linking scientific concepts with local wisdom. Students then formulated exploratory

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questions to design simple weather-prediction tools using local resources. These were assessed using rubrics that emphasized relevance, originality, and feasibility. For instance, they asked: “How can we design a simple yet accurate tool to predict the weather?” and “Is it possible to build a temperature and humidity gauge from local materials?”. As illustrated in Figure 3, the teacher functioned as a learning coach, facilitating students’ ability to pose meaningful exploratory questions.



Figure 3. Learning Coach

Phase 2: Designing Prototypes

In this phase, students collaborated with teachers and local farmer groups to develop an IoT-based climate monitoring prototype. The initial design employed Arduino with a DHT11 sensor for temperature, humidity, and rainfall, and was later upgraded to a Raspberry Pi system with real-time data visualization using a Python GUI. Data were stored locally in CSV format, enabling monitoring without internet access, thus ensuring contextual relevance for rural settings. The connectivity and workflow of this IoT-based prototype are presented in Figure 4.

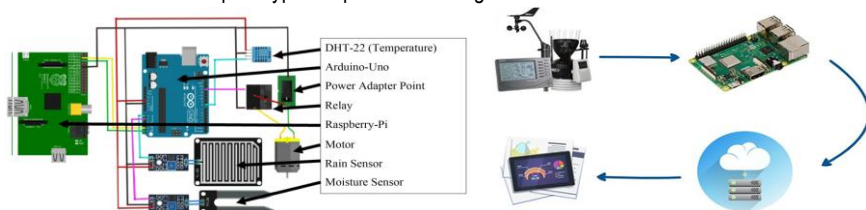


Figure 4. Connectivity view.

Phase 3: Project Scheduling

Within a 50-minute session, students developed a structured work plan, assigned roles based on individual competencies, and utilized digital tools such as LMS, Google Calendar, and WhatsApp/forums for coordination. Progress was evaluated using a Project Planning Rubric, Activity Log Tracker, and Team Reflection Sheets, aligned with the *Profil Pelajar Pancasila* guidelines. Farmers then operated the system using automated data collection, LCD-based alerts, and training delivered by students. The interface of the online STEM-DLS platform is shown in Figure 5.

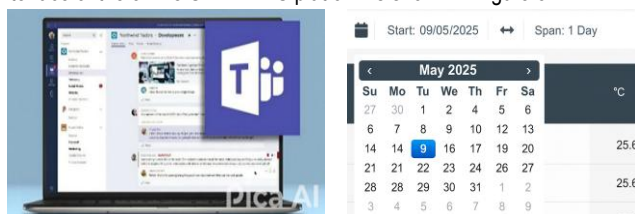


Figure 5. Presents the online STEM-DLS platform, accessible at <https://kalana.my.id>

Phase 4: Project Monitoring and Evaluation

Teachers and students assessed the prototype using rubrics covering originality, accuracy, scientific



validity, and local relevance. A five-day field test compared the system's data with official BMKG (Meteorological, Climatological, and Geophysical Agency) records, providing valuable feedback for iterative refinement under mentor supervision. A demonstration of the project prototype during classroom implementation is displayed in Figure 6.

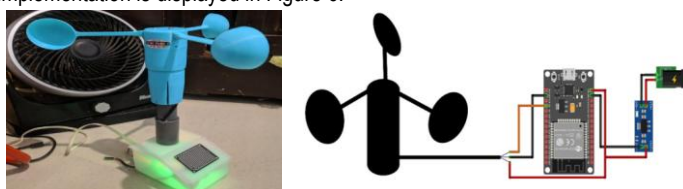


Figure 6. Demo photo of the project

Phase 5: Data Analysis and Dissemination

Students analyzed five days of weather data, visualized trends, formulated hypotheses regarding agricultural impacts, and engaged in reflective group discussions. The results were disseminated through infographics and short video forums on the LMS to strengthen community awareness and adaptive resilience toward climate change. The output of this dissemination process is presented in Figure 7.



Figure 7. Output Results of The Project

Dissemination Stage

The effectiveness of the STEM-Based Digital Learning Space (STEM-DLS) was evaluated using a quasi-experimental field design. Findings indicated that the experimental group significantly outperformed the control group in creative mathematical thinking (Table 4). N-Gain analysis confirmed moderate effectiveness for STEM-DLS ($\langle g \rangle = 0.554$) compared to low effectiveness in the control group ($\langle g \rangle = 0.223$).

Table 4. Summary of Pretest, Posttest, and N-Gain Scores in Mathematical Creative Thinking

Group	N	Pretest Mean	Posttest Mean	N-Gain ($\langle g \rangle$)	Effectiveness Interpretation
Experimental (STEM-DLS)	60	53.12	75.46	0.554	Moderate (Effective)
Control (Conventional)	60	52.78	63.29	0.223	Low (Less Effective)
Difference	—	—	+12.17	+0.331	—

Two-way ANOVA revealed significant main effects of both autonomy level and learning model, as well as their interaction ($F = 4.62$, $p = 0.012$, $\eta^2 = 0.07$). Likewise, creative thinking levels interacted significantly with learning models ($F = 4.52$, $p = 0.013$, $\eta^2 = 0.07$). Post hoc analyses showed that students with higher autonomy or higher creative thinking benefited most (see Appendices D). To better illustrate these findings, Figure 8 presents the interaction effect between autonomy level and learning model, while Figure 9 depicts the interaction between creative thinking and learning model. Both figures clearly demonstrate that the STEM-DLS condition amplifies the benefits for students with higher autonomy and creative thinking, confirming its adaptive role in fostering learner-centered outcomes.

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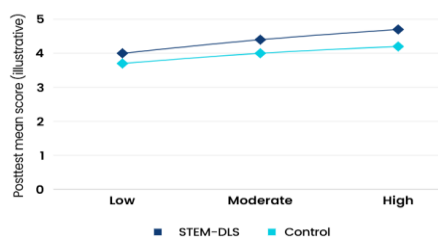


Figure 8. Interaction of Autonomy Level × Learning Model

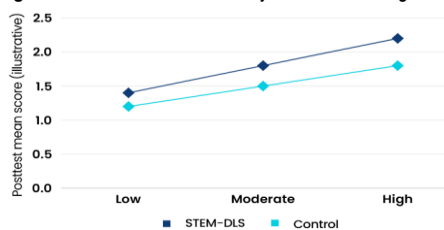


Figure 9. Interaction of Creative Thinking × Learning Model

Classroom observations (field notes, video recordings, and engagement rubrics) further support these quantitative findings, documenting marked improvements in inquiry, collaborative problem-solving, and multimodal representations. These results confirm the adaptive impact of STEM-DLS on both creativity and learner autonomy. Moreover, the dissemination phase demonstrated scalability potential: 42 teachers were trained, achieving a 78.6% readiness rate; six non-research schools independently adopted STEM-DLS; and a teacher learning community sustained monthly reflections. This evidence suggests that STEM-DLS can be scaled effectively when supported by professional development and continuous monitoring.

Discussion

This study demonstrates that the STEM-Based Digital Learning Space (STEM-DLS) effectively enhances students' mathematical creativity and self-directed learning, as shown by the higher N-Gain in the experimental group ($\langle g \rangle = 0.554$, moderate) compared with the control group ($\langle g \rangle = 0.223$, low). However, the effectiveness was not uniform; it varied according to ICT access 58.3% of students lacked stable internet, and 25% relied on low-spec devices and teacher implementation fidelity. Consistent with prior studies (J. Li et al., 2020; Rawal, 2024a), the results indicate that meaningful gains occurred mainly when adequate ICT support was available and teachers implemented the module with high fidelity (Cheon et al., 2020; Elmabaredy & Gencel, 2024). Thus, within the context of resource-limited schools, the success of STEM-DLS is shaped not only by technological infrastructure but also by instructional quality and equitable access.

The effectiveness of STEM-DLS in this study was context-dependent, shaped by both connectivity and teacher fidelity. Students with stable internet achieved higher gains in creative thinking (N-Gain = 0.554) compared with those facing limited access (N-Gain = 0.223), where offline adaptations sustained participation but reduced exploration depth (M. Li & Yu, 2022; Rawal, 2024b). Teacher fidelity further moderated outcomes: high fidelity supported coherent scaffolding, while low fidelity fragmented learning, consistent with significant interactions between learning model × autonomy and learning model × creative thinking (Cheon et al., 2020). These findings confirm that digital learning platforms are effective only when infrastructural readiness and instructional quality are simultaneously



ensured. In line with Suherman & Vidákovich (2022), such conditions are critical to fostering authentic mathematical creativity, indicating that the impact of STEM-DLS is specific to the studied context rather than universally generalizable.

Stratified analysis showed that STEM-DLS produced larger effects in groups with sufficient ICT access and high instructional fidelity ($d = 0.72$; 95% CI [0.41, 1.03]) compared with schools facing infrastructural constraints ($d = 0.29$; 95% CI [0.05, 0.52]). These results are consistent with previous findings in urban ($d = 0.55$) and rural ICT-limited contexts ($d = 0.32$) (Al-Said et al., 2023; Yuliardi et al., 2024). Within this study, effectiveness was contingent on both technological readiness and fidelity, confirming that digital tools yield meaningful gains only when supported by structured scaffolding and sufficient access (Cheon et al., 2020; Li & Yu, 2022). Rather than suggesting universal applicability, the evidence highlights the context-dependent nature of STEM-DLS outcomes, shaped by infrastructural and instructional conditions in participating schools.

Stratified analysis further clarified the context-dependent nature of STEM-DLS effectiveness. The strongest effects appeared in strata with both sufficient ICT access and high instructional fidelity ($d = 0.72$; 95% CI [0.41, 1.03]), while schools constrained by unstable connectivity and low-spec devices achieved smaller effects ($d = 0.29$; 95% CI [0.05, 0.52]). These results align with earlier findings of moderate gains in digitally supported urban contexts ($d = 0.55$) and weaker effects in rural, ICT-limited environments ($d = 0.32$) (Al-Said et al., 2023; Yuliardi et al., 2024). Within this study, the variation was not incidental but directly attributable to disparities identified in the Define stage, namely, students' limited digital literacy (72.2% proficient only in basic apps) and infrastructural barriers (58.3% without stable internet, 25% using low-spec devices). In combination with differences in teacher fidelity, these factors explain why higher outcomes were achieved by subgroups with stronger access and consistent scaffolding, while other groups showed only marginal progress. This evidence underscores that STEM-DLS effectiveness cannot be generalized uniformly; instead, it reflects how digital access and instructional quality interact to shape learning outcomes in resource-constrained schools.

Within the scope of this study, three main contributions emerge. First, the study identifies the moderating role of digital connectivity in shaping the effectiveness of STEM-DLS, confirming that infrastructure remains a decisive factor in digital learning outcomes (Li & Yu, 2022; Rawal, 2024a). Second, stratified effects were revealed based on ICT access and teacher fidelity, providing a context-sensitive picture beyond mean effects alone, which aligns with calls for equity-focused analyses in STEM education (Al-Said et al., 2023; Chai et al., 2020). Third, implementation fidelity was operationalized quantitatively across multiple dimensions, resulting in a practical monitoring framework that was feasible in low-resource school settings (Cheon et al., 2020; Fontaine et al., 2020). These contributions should be understood within the study context of secondary schools with limited infrastructure and heterogeneous teacher readiness rather than generalized to all educational environments. Practical implications include contextually grounded strategies such as fidelity monitoring, short-cycle coaching, and integration into teachers' professional portfolios to sustain implementation quality (Cezar et al., 2019; Revina et al., 2023). Nonetheless, several limitations warrant caution: the quasi-experimental design and reliance on motivated partner schools pose risks of selection bias and Hawthorne effects, while potential measurement bias and attrition remain possible despite high inter-rater reliability. To strengthen causal inference, future studies should employ cluster-randomized controlled trials and longitudinal follow-ups of 6–12 months to assess sustainability, while extending stratified analyses to socio-economic status and broader equity dimensions for a sharper understanding of how STEM-DLS can be adapted across diverse contexts.



The dissemination phase provided preliminary evidence of STEM-DLS scalability within the limited research context. A total of 42 teachers participated in training with a replication readiness rate of 78.6%, and six non-research schools voluntarily adopted the platform. These results indicate a positive reception but remain descriptive and context-bound, as readiness may reflect the self-selection of digitally literate and motivated teachers (Rawal, 2024a; Revina et al., 2023). Consequently, scalability claims should be interpreted cautiously. The main contribution of this phase lies in demonstrating that adoption beyond research sites is possible when accompanied by sufficient professional development and peer support, echoing prior findings that teacher readiness and sustained mentoring are critical for the success of digital innovations (Cezar et al., 2019; Cheon et al., 2020). Within this study, STEM-DLS shows promising adaptability at the micro-level of participating schools; however, further longitudinal and multi-site investigations are necessary to validate its effectiveness under more diverse conditions, particularly in schools with low digital literacy and infrastructural limitations.

CONCLUSION

The STEM-Based Digital Learning Space (STEM-DLS), developed using the 4D model, has proven effective in enhancing students' creative mathematical thinking and self-directed learning, particularly among those with adequate ICT access and teachers who maintain high implementation fidelity. These findings address the research objectives by demonstrating that STEM-DLS is pedagogically valid, practically applicable, and capable of fostering learner autonomy and mathematical creativity. Practically, STEM-DLS offers a semi-offline interactive platform that integrates contextual STEM content, project-based learning, and digital scaffolding to support 4C competencies and learner independence. Methodologically, this study introduces a five-dimensional fidelity index and stratified multilevel analyses, providing a robust framework to monitor implementation and to capture the heterogeneity of learning effects.

This study has several limitations that should be acknowledged. The quasi-experimental design with purposive sampling of supportive partner schools restricts generalizability to broader contexts. ICT constraints, 58.3% of students without stable internet and 25% using low-spec devices, moderated the intervention's impact. Teacher fidelity also varied across classes, introducing potential implementation bias despite the use of a fidelity index. Moreover, the intervention was limited to one semester, preventing assessment of long-term sustainability. Finally, contextual variables such as socioeconomic disparities and cultural alignment were not fully examined.

The policy implications highlight the urgency of digital equity strategies (e.g., subsidized data access and affordable devices), differentiated teacher professional development, and infrastructure support to ensure sustainable large-scale adoption. Future research should employ cluster-randomized or stepped-wedge designs, longitudinal studies (≥ 6 –12 months), and cost-effectiveness analyses, with particular attention to how connectivity, teacher fidelity, and contextual factors moderate learning outcomes, as well as to interdisciplinary integration and authentic problem-solving. With standardized measures (validated creative thinking rubrics, self-directed learning scales, and LMS logs) and open science practices, STEM-DLS demonstrates strong potential as an adaptive, inclusive, and scalable educational intervention bridging gaps in digital literacy, learner autonomy, and equitable access in STEM education, while fulfilling the research aims of establishing validity, effectiveness, and distinctive design characteristics.

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Appendices

Table A1. Expert Validation Results – Content

Assessed Aspect	Description	AV	Validity Category
Content Quality and Objectives	Alignment with learning objectives and student competencies	3.90	Valid
Instructional Design	Structure, delivery strategy, and material sequencing	4.00	Valid
Learning Design	Activity planning, student engagement, and scenario development	4.05	Valid
Evaluation and Feedback	Clarity of assessment instruments and effectiveness of feedback	3.86	Valid
Discussion and Collaboration Features	Ease of information sharing and online discussion facilities	3.95	Valid
Average Validity	Overall mean score from content experts	4.35	Practical

Table A2. Expert Validation Results – Media

Assessed Aspect	Description	AV	Validity Category
DLS Web Appearance	Layout clarity, visual aesthetics, readability, and user interface navigation	4.20	Good
DLS Menu Design	Menu structure, icons, ease of access, and completeness of digital navigation	3.80	Good
Audio-Visual Clarity and Interactivity	Media sound/image quality, system response to user interaction, and user engagement	4.25	Good
Programming Appropriateness and Functionality	Technical performance, cross-device compatibility, and system reliability in practice	4.20	Good
Average Validity	Aggregate score from all media validation aspects	4.11	Practical

Table B. Results of Student Worksheet Validation Analysis

Validator Rating Average	Face Validity	Content Validity	Construct Validity	Validation Average
Student Worksheet – 1	96.35%	93.06%	96.21%	95.21%
Student Worksheet – 2	95.83%	92.36%	96.21%	94.80%
Student Worksheet – 3	95.83%	92.36%	95.45%	94.55%
Student Worksheet – 4	95.83%	93.75%	96.21%	95.26%
Student Worksheet – 5	96.88%	93.06%	94.70%	94.88%
Student Worksheet – 6	96.35%	93.75%	97.73%	95.94%
Student Worksheet – 7	95.31%	93.06%	96.21%	94.86%
Average	96.05%	93.06%	96.10%	95.07%
Category	Very Valid	Very Valid	Very Valid	Very Valid

Table C. Practicality of STEM-Based DLS Based on Student Assessment

Practicality Aspects	1	2	3	4	5	6	7	Average	Category
Ease of Access and Navigation	92.78	95.00	90.83	92.78	90.83	90.83	89.17	91.75	Very Practical
Clarity of Information and STEM Content Presentation	91.67	90.67	88.67	87.67	87.67	85.00	87.00	88.34	Very Practical
Readability of Text and Digital Visualization	88.33	89.00	89.33	90.00	90.67	91.33	88.33	89.57	Very Practical
Appropriateness of Feature Usage Time Allocation	88.33	89.17	87.50	87.50	86.67	87.50	88.33	87.86	Very Practical
Overall Practicality Average	90.28	90.96	89.08	89.49	88.96	88.67	88.21	89.38	Very Practical

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Table D1. Autonomy Levels and Creative Thinking Before and After in the Control Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t _{emp.}	Before	After	t _{emp.}
High	Self-initiation	4.111	4.455	2.533	4.022	4.388	2.402
	Goal orientation	4.233	4.600	2.642	4.100	4.478	2.318
	Persistence	3.988	4.300	2.200	3.877	4.188	2.011
	Responsibility	4.211	4.622	2.881	4.078	4.500	2.540
	Decision-making	4.089	4.500	2.700	3.955	4.388	2.380
Moderate	Self-initiation	3.788	4.100	2.200	3.689	4.022	2.089
	Goal orientation	3.955	4.344	2.478	3.822	4.256	2.204
	Persistence	3.700	4.044	2.100	3.566	3.900	1.922
	Responsibility	3.800	4.222	2.820	3.755	4.211	2.322
	Decision-making	3.789	4.178	2.511	3.688	4.089	2.144
Low	Self-initiation	3.411	3.800	2.000	3.388	3.700	1.901
	Goal orientation	3.544	3.900	2.211	3.422	3.833	2.100
	Persistence	3.422	3.700	1.889	3.311	3.600	1.800
	Responsibility	3.655	3.978	2.000	3.588	3.911	2.045
	Decision-making	3.611	3.944	2.022	3.489	3.822	2.033
Creative Thinking Level	Indicators Thinking Level	Boys			Girls		
		Before	After	t _{emp.}	Before	After	t _{emp.}
High	Fluency	1.322	1.544	2.111	1.200	1.422	2.015
	Flexibility	0.722	0.933	2.066	0.855	1.066	2.100
	Originality	2.100	2.400	2.220	2.566	2.822	1.966
	Elaboration	1.366	1.622	2.144	2.200	2.466	2.111
	Connection-making	1.533	1.789	2.089	1.644	1.922	2.022
Moderate	Fluency	1.078	1.300	2.010	0.988	1.200	1.885
	Flexibility	0.633	0.844	2.033	0.744	0.955	2.044
	Originality	1.855	2.122	2.150	2.422	2.655	1.933
	Elaboration	1.200	1.456	2.244	2.100	2.356	2.088
	Connection-making	1.444	1.678	2.033	1.522	1.744	2.011
Low	Fluency	0.889	1.066	2.089	0.855	1.044	2.012
	Flexibility	0.422	0.633	2.066	0.622	0.811	2.000
	Originality	1.433	1.678	2.033	2.211	2.433	1.889
	Elaboration	1.000	1.211	2.011	1.944	2.177	2.022
	Connection-making	1.233	1.455	2.077	1.311	1.522	1.955

Table D2. Autonomy Levels and Creative Thinking Before and After in the Experimental Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t _{emp.}	Before	After	t _{emp.}
High	Self-initiation	4.133	4.722	3.122	4.089	4.678	3.055
	Goal orientation	4.200	4.789	3.300	4.122	4.733	3.188
	Persistence	4.011	4.611	3.122	3.911	4.500	3.044
	Responsibility	4.255	4.855	3.233	4.144	4.755	3.211
	Decision-making	4.144	4.800	3.344	4.022	4.688	3.278
Moderate	Self-initiation	3.822	4.444	3.144	3.722	4.366	3.100
	Goal orientation	3.977	4.600	3.266	3.855	4.544	3.189
	Persistence	3.755	4.333	3.000	3.622	4.255	2.944
	Responsibility	3.866	4.522	3.144	3.811	4.466	3.111
	Decision-making	3.833	4.478	3.188	3.755	4.400	3.077
Low	Self-initiation	3.433	4.011	2.933	3.400	3.977	2.855
	Goal orientation	3.577	4.144	2.988	3.444	4.111	2.911
	Persistence	3.433	4.000	2.800	3.322	3.911	2.733
	Responsibility	3.688	4.244	2.944	3.622	4.200	2.866
	Decision-making	3.633	4.222	3.022	3.511	4.122	2.900
Creative Thinking Level	Indicators Thinking Level	Boys			Girls		
		Before	After	t _{emp.}	Before	After	t _{emp.}
High	Fluency	1.344	1.700	2.455	1.244	1.644	2.333
	Flexibility	0.755	1.144	2.566	0.900	1.300	2.488
	Originality	2.188	2.722	2.611	2.633	3.044	2.444
	Elaboration	1.411	1.877	2.488	2.255	2.733	2.600



Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t _{emp.}	Before	After	t _{emp.}
Moderate	Connection-making	1.577	2.033	2.533	1.677	2.100	2.511
	Fluency	1.100	1.544	2.366	1.000	1.466	2.233
	Flexibility	0.655	1.044	2.500	0.766	1.144	2.411
	Originality	1.900	2.433	2.577	2.466	2.977	2.388
	Elaboration	1.222	1.700	2.611	2.144	2.677	2.544
Low	Connection-making	1.488	1.933	2.544	1.555	2.000	2.466
	Fluency	0.911	1.366	2.433	0.877	1.322	2.355
	Flexibility	0.444	0.877	2.488	0.655	1.044	2.344
	Originality	1.477	2.011	2.611	2.233	2.744	2.477
	Elaboration	1.033	1.511	2.555	2.000	2.511	2.500
	Connection-making	1.266	1.755	2.500	1.344	1.833	2.455

Table D3. Two-Way ANOVA (Autonomy Level × Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.450	5	0.490	37.690	0.000
Intercept	40.320	1	40.320	3102.31	0.000
Autonomy Level	1.750	2	0.875	67.310	0.000
Learning Model	0.580	1	0.580	44.620	0.000
Autonomy Level * Learning Model	0.120	2	0.060	4.620	0.012
Error	1.500	114	0.013		
Total	44.270	120			
Corrected Total	3.950	119			

Table D4. Tukey HSD Test – Learning Autonomy Level

(I) Autonomy Level	(J) Autonomy Level	Mean Difference (I-J)	Std. Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.348*	0.033	0.000	Significant: Low < Moderate
Low	High	-0.601*	0.033	0.000	Significant: Low < High
Moderate	High	-0.253*	0.033	0.000	Significant: Moderate < High

Table D5. Two-Way ANOVA (Creative Thinking Level × Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.750	5	0.550	26.190	0.000
Intercept	51.200	1	51.200	2438.10	0.000
Creative Thinking Level	2.100	2	1.050	50.000	0.000
Learning Model	0.460	1	0.460	21.905	0.000
Creative Thinking × Learning Model	0.190	2	0.095	4.524	0.013
Error	2.400	114	0.021		
Total	56.350	120			
Corrected Total	5.150	119			

Table D6. Tukey HSD Test on Creative Thinking

(I) Creative Thinking Level	(J) Creative Thinking Level	Mean Difference (I-J)	Standard Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.175	0.028	0.000	Significant: Low < Moderate
	High	-0.279	0.028	0.000	Significant: Low < High
Moderate	Low	0.175	0.028	0.000	Significant: Moderate > Low
	High	-0.104	0.028	0.001	Significant: Moderate < High
High	Low	0.279	0.028	0.000	Significant: High > Low
	Moderate	0.104	0.028	0.001	Significant: High > Moderate



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Designing a STEM-Based Digital Learning Space to Foster Creative Mathematical Thinking and Autonomous Learning in Secondary Education

Abstract

This study aims to develop and evaluate the effectiveness of a STEM-Based Digital Learning Space (DLS) designed to enhance junior high school students' creative mathematical thinking skills and autonomous learning. The DLS was developed in response to the limited interdisciplinary integration of science, technology, engineering, and mathematics in teaching, as well as the lack of access to contextualized and personalized digital learning environments. The development process followed the 4D model (Define, Design, Develop, Disseminate), accompanied by expert validation and multi-stage field testing. Expert validation results indicated that the DLS was highly feasible, while student practicality testing categorized the system as very practical. Effectiveness testing demonstrated a significant improvement in students' creative mathematical thinking abilities (N-Gain = 0.554, moderate category) and strengthened their autonomous learning. The DLS was designed as an ecosystem integrating both a Personal Learning Environment (PLE) and a Personal Teaching Environment (PTE), equipped with interactive features such as simulations, adaptive quizzes, digital worksheets, and collaborative forums. This innovation holds strong potential to support the transformation of digital mathematics learning at the secondary school level, aligning with the Deep Learning Curriculum and national digital literacy enhancement programs, particularly in regions with limited technological infrastructure.

Keywords: Autonomous Learning, Creative Mathematical Thinking, Digital Learning Space, Secondary Education, STEM-Based Learning.

In the era of the Industrial Revolution 4.0 and the post-COVID-19 period, educational challenges can no longer be addressed merely through partial technological adoption (González-Pérez & Ramírez-Montoya, 2022). A comprehensive pedagogical transformation is required to prepare a generation capable of adapting to the complexities of the digital age (Røe et al., 2022). In this context, creative mathematical thinking emerges as a critical 21st-century competency, particularly in response to automation and the explosion of data (Yulianto et al., 2024; Szabo et al., 2020). Unfortunately, digitalization in Indonesian education continues to face disparities in access and digital literacy (Samane-Cutipa et al., 2022; Li & Yu, 2022; Rawal, 2024). These gaps are exacerbated by procedural teaching systems that fail to sufficiently promote creativity and idea exploration (Yulianto et al., 2024), as reflected in the OECD (2023) report that ranks Indonesian students low in mathematical literacy, particularly on non-routine problems requiring flexible thinking.

Creative mathematical thinking, which involves the formulation, transformation, and flexible application of ideas in complex situations, serves as the foundation of 21st-century numeracy skills (Dilekçi & Karatay, 2023). This activity encompasses logical reasoning (Shuib et al., 2021) as well as the capacity to generate original and effective solutions (Rosengren et al., 2020). In mathematics education, creativity manifests through novel ideas, effective strategies, and interconnected solutions for solving non-routine problems (Joklitschke et al., 2022). However, Indonesian students' performance in this domain remains low (Tanujaya et al., 2021), largely due to an instructional culture that limits contextual exploration (Prahmana et al., 2020). Therefore, STEM-based curricula and learning media are urgently needed to foster students' autonomy and creative exploration in addressing real-world problems (Yuliardi et al., 2024; Nurintya & Agoestanto, 2022).

The core dimensions of creative thinking fluency, flexibility, originality, and elaboration are widely recognized through the Torrance Test of Creative Thinking (TTCT) framework, which has been adapted across various disciplines, including mathematics (Alabbasi et al., 2022; Suherman & Vidákovich, 2022). However, conventional approaches to assessing mathematical creativity remain generic and fail to reflect the discipline's specific demands for precision, logical structure, and multi-strategic exploration (Hjelte et al., 2020). Therefore, this study adapts the TTCT indicators within the context of probability learning: fluency as the ability to generate diverse experimental procedures and representations; flexibility as the formulation of alternative strategies based on probability data; originality in designing unconventional solutions; and elaboration through the development and justification of solutions using statistical arguments. These adjustments aim to capture the complexity of heuristic processes in solving mathematical probability problems (Yulianto et al., 2024).

Developing creative thinking skills requires a learning environment that fosters exploration, reflection, and the reconstruction of conceptual meaning (Zhou et al., 2024; Junaedi et al., 2021). In this context, the STEM approach offers an integrative framework that combines science, technology, engineering, and mathematics to address authentic problem-solving tasks (Purwaningsih et al., 2020; Setiawati & Agoestanto, 2023). STEM not only enhances cognitive flexibility through multimodal representations (Hallström & Ankiewicz, 2023) but also fosters originality via digital design and experimentation (Nugraha et al., 2023). Studies by Yuliardi et al. (2024) and Stoyanov et al. (2022) have demonstrated that integrating a Digital Learning Space (DLS) within STEM education significantly improves students' autonomy, collaboration, and creativity.

Based on these findings, the development of a STEM-Based Digital Learning Space in this study was designed as a pedagogical intervention to cultivate students' creative thinking, autonomous learning, and critical reflection in solving data-driven mathematical problems (Yuliardi et al., 2024). This strategy is intended to contribute to the transformation of Indonesia's education system towards a more adaptive, innovative, and globally competitive model (Cheng, 2022; Akhmetova et al., 2025). In the digital disruption and automation era, STEM serves not merely as an interdisciplinary field but as an epistemic framework integrating conceptual knowledge with practical application through project-based learning, collaboration, and authentic problem-solving (Nguyen et al., 2020; Conde et al., 2021). Countries such as Finland, the United States, Taiwan, and Malaysia have implemented national STEM policies that emphasize cross-disciplinary creativity, computational reasoning, and strategic reflection (Ha et al., 2020). At the global level, several universities have developed Self-Access Learning Centers (SALCs) such as those at Kanda University, ASLLC (EdUHK), and ELSAC (University of Auckland) to enhance academic autonomy. However, adoption in Indonesia remains limited (de Vink et al., 2023; Martín-Páez et al., 2019), hindered by low digital literacy, conventional instructional cultures, and inadequate STEM learning infrastructure. Yet, integrated STEM approaches inherently promote cross-disciplinary exploration and authentic problem-solving (Tramonti et al., 2024).

In Indonesia, although the "Merdeka Curriculum" and "Sekolah Penggerak" programs rhetorically advocate STEM-based education policies, their implementation in practice has not fully reflected this transformative approach (Jasiah et al., 2024). Learning models remain largely procedural and teacher-centered (Cheon et al., 2020), further constrained by low digital literacy among teachers, insufficient interdisciplinary training, and the scarcity of adaptive DLS platforms (Samane-Cutipa et al., 2022; Li & Yu, 2022; Rawal, 2024). Without systemic solutions, this gap risks widening the global competence divide faced by Indonesian students in meeting 21st-century demands. Therefore, STEM education in Indonesia must be reconceptualized as a pedagogical foundation that nurtures autonomy, cognitive flexibility, and



creativity in authentic problem-solving. This strategy should include cross-subject integration, the enhancement of reflective pedagogical capacities among teachers (McGuire & Lay, 2019; Romijn et al., 2021), and the development of STEM-based DLS platforms that empower students as solution designers (Hughes & Morrison, 2020). Through this approach, STEM education is expected to foster adaptive, self-directed learners capable of driving meaningful change (Yuliardi et al., 2024).

In the context of 21st-century education, autonomous learning has been recognized as a fundamental foundation for shaping resilient, reflective, and adaptive learners (González-Pérez & Ramírez-Montoya, 2022). Unlike traditional teacher-centered models, autonomous learning positions students as the primary agents in managing learning strategies, reflecting on achievements, and conducting self-assessment (Yuliardi et al., 2024). Technologies such as LMSs are expected to facilitate transformative self-directed learning, not merely serve as administrative tools (Athaya et al., 2021; Clark et al., 2021; OECD, 2023). Therefore, the design of digital pedagogy must shift towards STEM-based Digital Learning Spaces (DLS) that are open, contextual, and foster student agency (Aini et al., 2022; Nguyen et al., 2020; Conde et al., 2021). However, its realization is still hindered by systemic factors such as rigid curricula, limited teacher digital competence, and unequal access to technology (Yulianto et al., 2024). Without comprehensive intervention, the synergistic potential of STEM, autonomous learning, and DLS risks becoming mere jargon without meaningful transformational impact in educational practice.

Digital Learning Spaces (DLS) are developed based on the principles of Networked Learning, emphasizing connectivity, collaborative knowledge construction, and active collaboration (NLEC, 2021). DLS serves as infrastructure for both synchronous and asynchronous learning, aligned with the self-regulated learning framework that supports flexible access, goal setting, and learner autonomy (Dignath & Veenman, 2020; Sun et al., 2023). The DLS design also integrates the concepts of Personal Learning Environments (PLE) and Personal Teaching Environments (PTE), allowing for personalization and adaptive instructional design (Cenka et al., 2022; Tur et al., 2022). Collaborative forums and formative assessments within the DLS enhance students' cognitive presence (Maranna et al., 2022). However, the widely claimed accessibility and low-cost benefits of DLS require critical evaluation, especially in developing countries facing infrastructure, device, and digital literacy gaps (Gumbi et al., 2023). These disparities risk widening educational inequality, particularly among marginalized student groups. The effectiveness of DLS as a medium for flipped classrooms and inquiry-based learning also heavily depends on teacher professional development, supportive policies, and equitable digital infrastructure (Al-Said et al., 2023; Sosa Diaz et al., 2021; NLEC, 2021).

Research on DLS in the STEM context should transcend mere access issues by fostering digital learning environments that encourage exploration, experimentation, and authentic problem-solving (Purwaningsih et al., 2020; Setiawati & Agoestanto, 2023). The integration of STEM within DLS should not only deliver digital content but also create creative learning spaces that strengthen contextual mathematical reasoning and active participation (Wan et al., 2020; Johnston et al., 2022). Specifically, this study responds to the need for a digital learning environment that promotes creative mathematical thinking within local contexts. The STEM-Based Digital Learning Space (DLS) developed in this study is integrated with a problem-solving approach based on pedagogically and culturally adapted TIMSS-PISA content. This model addresses a gap in the literature concerning the integration of content design, local culture, and learner autonomy within digital platforms. The DLS is designed with a culturally responsive pedagogy that incorporates ethnomathematics and local wisdom into assessments, materials, and digital discussions. Interactive features such as adaptive feedback, open-ended simulations, and collaborative spaces support the activation of self-regulated learning (SRL), divergent thinking, and conceptual



generalization in authentic situations.

Unlike previous studies, this model offers a transformative approach that not only stimulates creative mathematical thinking but also builds contextual, independent, and inclusive digital literacy. Based on this background, the present study aims to answer two main research questions: (1) What are the characteristics of a valid and practical STEM-based DLS design that supports autonomous digital mathematics learning? (2) How does the DLS influence students' creative mathematical thinking skills in the context of self-directed learning?

METHODS

This study employed a Research and Development (R&D) approach using the 4D model (Define, Design, Develop, Disseminate) by Roman (2022) to develop a STEM-Based Digital Learning Space (DLS) integrated into both synchronous and asynchronous learning environments. This model was selected for its systematic, flexible, and iterative nature, allowing multi-stage validation and expert involvement from the early stages of development, crucial for producing a digital product that is valid, practical, and effective within the STEM education context. The final product consists of a web-based digital learning system equipped with interactive modules, probability simulations, discussion forums, and digital worksheets (LKPD) designed to enhance students' scientific literacy and creative mathematical thinking skills. The DLS design integrates two main functions: (1) Pedagogical and Technological Enhancement (PTE), emphasizing instructional management by teachers (account setup, multimedia integration, task management, and rubric-based evaluation), and (2) Personalized Learning Environment (PLE), promoting active student engagement through independent and collaborative activities, quizzes, reflection, and peer assessment based on task performance.

In the Define stage, a front-end analysis was conducted to map STEM learning needs in partner schools, along with a learner analysis to identify student characteristics, challenges, and learning requirements. The Design stage involved the development of evaluation instruments based on Torrance's (1974) indicators for creative mathematical thinking tests (fluency, flexibility, elaboration, originality, and connection-making) and Fisher et al.'s (2001) framework for the autonomous learning questionnaire (self-regulation, motivation control, initiative). Lightweight digital media were selected, and instructional materials were developed, integrating STEM content with technology. During the development stage, validation by content experts, media specialists, and initial user teachers was conducted using Aiken's V, with all items exceeding a value of 0.80. The trials followed a design-based research principle, encompassing a small-scale trial (7 students from Grade VIII at SMP Latansa 2), an expanded trial (60 students from SMP Latansa 2 and SMP Kun Karimma), and field testing (120 students from SMP Daar El Qolam 2 and 3, and SMP Latansa 1), purposively selected based on theoretical and contextual considerations.

Inclusion criteria included: (1) availability of adequate ICT infrastructure (computer labs and stable internet connections); (2) active involvement of mathematics teachers in technology-based learning; and (3) representation of school diversity based on accreditation status (A) and geographical location to evaluate practicality, engagement, and product effectiveness. Each stage was accompanied by teacher training and observations conducted by a trained evaluation team. At the Disseminate stage, the developed product was distributed through accredited scientific publications, national teacher training workshops, and intellectual property rights (IPR) applications to strengthen the product's legitimacy. These efforts aimed to build a sustainable digital learning ecosystem through teacher learning



communities and integration with the Merdeka Mengajar platform. Through this design, the STEM-DLS is expected to promote contextual, adaptive, and reflective learning while supporting the Merdeka Belajar policy and the national digital education transformation agenda.

Instruments and Validity

Students' creative mathematical thinking skills were assessed using pre-test and post-test instruments based on five core indicators: fluency, flexibility, elaboration, originality, and connection-making, as proposed by Torrance (1974). The test consisted of five open-ended essay questions, validated by three mathematics education experts, yielding an Aiken's V coefficient of 0.85, indicating high content validity. Internal reliability was confirmed with Cronbach's alpha ($\alpha = 0.81$), demonstrating good consistency. Students' autonomous learning was measured using a 30-item questionnaire based on the Self-Directed Learning Readiness model (Fisher et al., 2001), encompassing learning initiative, self-regulation, and metacognitive awareness. Responses were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), with an internal reliability coefficient of $\alpha = 0.873$. Construct validity was verified through exploratory factor analysis ($KMO > 0.8$), supporting the appropriateness of the three-factor model. In addition to these measurement instruments, the content validity and practicality of the STEM-Based Digital Learning Space (DLS) platform were evaluated by subject matter experts, digital media specialists, and STEM education experts using a standardized evaluation rubric and a student practicality questionnaire.

Data Collection and Analysis

Data were collected using a mixed-methods approach (Creswell & Plano Clark, 2018) to evaluate the effectiveness and user experience of the STEM-DLS. Qualitative data, in the form of multimodal documentation transcripts (photos, videos, audio recordings), were analyzed thematically (Braun & Clarke, 2006) to explore students' mathematical reasoning during the assembly, experimentation, and presentation phases. Quantitative analysis included content validity testing (Aiken's V), practicality evaluation (descriptive statistics), and effectiveness assessment (N-Gain, paired and independent t-tests, one-way ANOVA), as well as MANOVA to examine the effectiveness of the STEM-DLS across multiple variables. The STEM-DLS product was validated by three experts: an educational technology specialist, a mathematics expert, and a mathematics teacher as a pedagogical evaluator. Validation was conducted using a 5-point Likert scale covering content substance, alignment with core competencies, STEM integration, instructional design quality, assessment, and collaborative features. The mean validation scores determined the product's feasibility, categorized as invalid, less valid, fairly valid, valid, and highly valid. The product was deemed feasible if it achieved at least the "valid" or "highly valid" category; otherwise, revisions were made accordingly. In terms of practicality, students evaluated the DLS based on usability, clarity, readability, and time adequacy. A mean score of $\geq 70\%$ indicated practicality; scores below this threshold required improvements based on user feedback.

RESULTS AND DISCUSSION

Results

In the Define stage, participatory front-end and learner analyses were conducted at SMP Latansa Mashiro to map students' pedagogical needs and characteristics. The analysis revealed that learning in the school remained compartmentalized across disciplines (Science, Mathematics, ICT), technology use was limited



to passive presentation media, and students' digital literacy was low, with most unfamiliar with LMS platforms or exploratory applications (see Table 1).

Table 1. Summary of Front-End and Learner Analysis Findings

Aspect	Key Findings	Implications for Solution Design
STEM Integration	Learning remains sectoral; no explicit integration across disciplines (Science, Mathematics, Technology).	Design project-based learning scenarios that integrate concepts from multiple disciplines.
Technology Utilization	Teachers rarely use supporting applications other than PowerPoint; no interactive digital media or simulations are employed.	Develop a Digital Learning Space that emphasizes exploratory and interactive visualization.
Student Digital Literacy	72.2% of students are only proficient with basic applications (WhatsApp, YouTube); unfamiliar with LMS platforms, GeoGebra, or other exploratory tools.	Provide gradual, adaptive digital media training tailored to students' initial skill levels.
Learning Autonomy	61.1% of students struggle with independent learning; they require intensive teacher guidance.	Integrate scaffolding into the digital task design to enable progressive student autonomy.
Technical Constraints	58.3% of students lack stable internet access at home; 25% own only low-spec smartphones.	Design lightweight learning media accessible offline or semi-offline (e.g., interactive HTML, locally stored videos).
Student Creative Potential	Only 16.7% of students exhibit tendencies towards creative thinking (e.g., asking critical questions, offering alternative solutions).	Apply strategies to stimulate creative thinking through real-world problem contexts and provide open exploration spaces.

At the Design stage, an initial prototype of the STEM-Based Digital Learning Space (STEM-DLS) was developed based on the framework of the Personal Teaching Environment (PTE) and Personal Learning Environment (PLE) (Figure 1). Four main components were designed: (1) Assessment instruments, consisting of a mathematical creative thinking test based on the indicators of fluency, flexibility, elaboration, originality, and connection-making (Torrance, 1974), along with an autonomous learning questionnaire referring to the dimensions of self-regulation, initiative, and metacognitive awareness (Fisher et al., 2001; Gu et al., 2023); (2) Digital media, using lightweight HTML and locally produced videos to support exploratory STEM principles and accommodate students' limited device access; (3) Integrated teaching materials, connecting science, mathematics, and ICT in a project-based learning scenario; and (4) The DLS design, which distinguishes between teachers' roles (PTE) and students' independent and collaborative activities (PLE). Key platform features include discussion forums, assignment reflection spaces, interactive quizzes, and peer assessment, all of which promote learner autonomy. The entire design was validated by two instructional design experts and one STEM content expert, who confirmed its feasibility for further implementation. The STEM-DLS platform prototype is accessible at <https://kalana.my.id>, as illustrated in Figure 1.



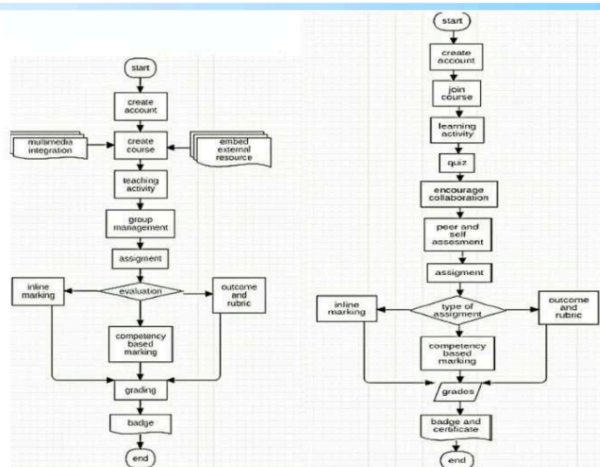


Figure 1. Flow diagram of PTE and PLE (Yuliardi et al., 2024)

The development phase of the STEM-DLS aimed to ensure content validity, pedagogical suitability, and practical applicability within a digital learning context. Validation was conducted by two experts in educational technology and mathematics, as well as a mathematics teacher serving as a pedagogical evaluator. The validation instrument consisted of 20 items covering content substance, relevance to core competencies, and the integration of STEM components. The entire validation process was supported by a panel discussion using a triangulated consensus approach to align perspectives between academic experts and field practitioners. Therefore, the developed DLS product meets both substantive and technical feasibility criteria for implementation in digital STEM learning (see Tables 2 and 3).

Table 2. Expert Validation Results – Content

Assessed Aspect	Description	AV	Validity Category
Content Quality and Objectives	Alignment with learning objectives and student competencies	3.90	Valid
Instructional Design	Structure, delivery strategy, and material sequencing	4.00	Valid
Learning Design	Activity planning, student engagement, and scenario development	4.05	Valid
Evaluation and Feedback	Clarity of assessment instruments and effectiveness of feedback	3.86	Valid
Discussion and Collaboration Features	Ease of information sharing and online discussion facilities	3.95	Valid
Average Validity	Overall mean score from content experts	4.35	Practical

Table 3. Expert Validation Results – Media

Assessed Aspect	Description	AV	Validity Category
DLS Web Appearance	Layout clarity, visual aesthetics, readability, and user interface navigation	4.20	Good



Assessed Aspect	Description	AV	Validity Category
DLS Menu Design	Menu structure, icons, ease of access, and completeness of digital navigation	3.80	Good
Audio-Visual Clarity and Interactivity	Media sound/image quality, system response to user interaction, and user engagement	4.25	Good
Programming	Technical performance, cross-device compatibility, and system reliability in practice	4.20	Good
Appropriateness and Functionality			
Average Validity	Aggregate score from all media validation aspects	4.11	Practical

Development Results of STEM-DLS Features

The development of the STEM-DLS was carried out through collaboration among the academic team, web developers, teachers, and students to ensure both pedagogical relevance and contextual suitability for partner schools. The design of the DLS integrates international best practices, such as Project-Based Learning and TIMSS/PISA frameworks, while being adapted to local constraints, including low-specification devices, visual preferences, and limited digital literacy. Therefore, the platform was designed to be modular, lightweight, and supportive of asynchronous access to enhance inclusivity. The STEM-DLS features include interactive simulations, a progress dashboard, digital student worksheets, and a Collaborative Learning Hub, all aimed at fostering 4C skills (Creativity, Critical Thinking, Communication, Collaboration) as well as self-directed learning through a self-regulated learning approach. In addition to STEM-based content, the DLS is equipped with automated formative assessments, adaptive feedback, and performance tracking via learning analytics, enabling teachers to conduct real-time, data-driven assessments.

Table 4. Summary of Key Features of the STEM-DLS

Feature	Main Function	Benefits for Teachers/Students
Learning Dashboard	Provides learning guidance, content navigation, and student progress tracking.	Supports independent learning management; helps teachers monitor students' progress efficiently.
Interactive Simulations & Videos	Presents STEM concepts visually and multimodally.	Enhances contextual and applied understanding of abstract concepts.
Digital Student Worksheets & Project Upload	Serves as a medium for task completion and student project documentation.	Encourages project-based learning and the development of digital portfolios.
Automated Formative Assessment	Offers interactive quizzes with feedback and alternative solutions.	Delivers instant feedback; provides teachers with performance-based assessment data.
Collaborative Learning Hub	Acts as a discussion forum and a space for sharing learning outcomes.	Facilitates collaboration, reflection, and idea exchange among users.
Resource Center (STEM Gallery)	Hosts a gallery of projects, videos, and context-based assignments.	Enhances knowledge transfer and inspiration from real learning environments.

These features were developed following the principles of connected learning to support contextual education in the digital era. Formative validation and limited student trials were conducted iteratively to refine the design and functionality. As part of the STEM-DLS, seven units of digital Student Worksheets were designed and validated by content experts. The content validation was carried out by two university



lecturers specializing in educational technology and mathematics, as well as a mathematics teacher who served as a pedagogical evaluator, assessing the format, language, content, and illustrations. The results indicated that all assessed aspects achieved the "Very Valid" category, with an average score of 95.07% (see Table 5). In terms of practicality, the DLS was evaluated by students using a practicality questionnaire covering ease of access, clarity of presentation, readability of information, and appropriateness of time allocation. All aspects scored above 70%, with an average of 89.38%, classified as "Very Practical" (Table 6).

Table 5. Results of Student Worksheet Validation Analysis

Validator Rating Average	Face Validity	Content Validity	Construct Validity	Validation Average
Student Worksheet – 1	96.35%	93.06%	96.21%	95.21%
Student Worksheet – 2	95.83%	92.36%	96.21%	94.80%
Student Worksheet – 3	95.83%	92.36%	95.45%	94.55%
Student Worksheet – 4	95.83%	93.75%	96.21%	95.26%
Student Worksheet – 5	96.88%	93.06%	94.70%	94.88%
Student Worksheet – 6	96.35%	93.75%	97.73%	95.94%
Student Worksheet – 7	95.31%	93.06%	96.21%	94.86%
Average	96.05%	93.06%	96.10%	95.07%
Category	Very Valid	Very Valid	Very Valid	Very Valid

Table 6. Practicality of STEM-Based DLS Based on Student Assessment

Practicality Aspects	1	2	3	4	5	6	7	Average	Category
Ease of Access and Navigation	92.78	95.00	90.83	92.78	90.83	90.83	89.17	91.75	Very Practical
Clarity of Information and STEM Content	91.67	90.67	88.67	87.67	87.67	85.00	87.00	88.34	Very Practical
Presentation Readability of Text and Digital Visualization	88.33	89.00	89.33	90.00	90.67	91.33	88.33	89.57	Very Practical
Appropriateness of Feature Usage Time Allocation	88.33	89.17	87.50	87.50	86.67	87.50	88.33	87.86	Very Practical
Overall Practicality Average	90.28	90.96	89.08	89.49	88.96	88.67	88.21	89.38	Very Practical

STEM Task Description

This program aims to enhance secondary school students' creative mathematical thinking through STEM learning rooted in the local culture of the Baduy community. Preliminary observations revealed that many students struggle with data interpretation, constructing numerical arguments, and applying concepts of probability and ratio in real-life contexts. To address these challenges, a series of thematic activities was developed, integrating mathematical concepts (data, scale, probability), science (weather observation, energy), technology (basic LMS, simulations), and engineering (designing simple tools). These activities are organized into seven main topics, each reflecting elements of Baduy daily life, such as traditional



games, weaving patterns, house structures, and local natural resources. Every task incorporates Torrance's dimensions of creativity fluency, flexibility, originality, and elaboration through open-ended problem-solving exercises.

Table 7. STEM Learning Plan Based on Baduy Local Culture

Mathematics Topic	Creative Thinking Indicators	STEM Components	Digital Learning Media
Patterns and Sequences in Baduy Weaving Motifs	Fluency, Elaboration	M, A, T	Weaving motif images, pattern exploration videos, and interactive pattern simulations in LMS
Ratios and Scale: Baduy Traditional Village Map	Flexibility, Originality	M, T, E	Digital village maps, drone videos, digital measurement apps, and building scale simulations
Data and Statistics: Traditional Energy Survey of Baduy Houses	Fluency, Flexibility, Elaboration	M, S, T	Digital questionnaires, interactive graphs, LMS for survey data input and visualization
Probability: Traditional Baduy Games Experiment	Fluency, Originality, Elaboration	M, S, T	Experiment videos, simple spin wheel simulations, data-based experiment dashboards
Plane and Solid Figures: Baduy Traditional House Architecture	Originality, Elaboration	M, A, T	3D house models, area and volume simulations, local architectural animations
Cartesian Coordinates: Locating Baduy Natural Resources	Flexibility, Elaboration	M, S, T	Interactive coordinate maps, position and distance exercises, and digital mapping tools
Final Project: Designing a Simple Traditional Weather Monitoring Tool	Elaboration, Originality, Flexibility	S, T, E, M	Digital weather tool simulations, local rainfall observation videos, and an LMS for experiment documentation

Note: M = Mathematics (concepts and calculations); T = Technology (digital tools, calculators, LMS, simulations); S = Science (observation and real experiments); E = Engineering (design of simple technological solutions).

To strengthen the integration of mathematical concepts and STEM principles in real-world contexts, the final project was designed to address the needs of the local community, specifically farmers in the Baduy region who face difficulties in predicting weather patterns for subsistence farming. This project challenges students to design and implement a simple weather data collection tool using an engineering-for-social-context approach, fully incorporating Science, Technology, Engineering, and Mathematics (STEM) components. Unlike conventional experiment-based methods, this project emphasizes problem-based learning, focusing on designing practical solutions for local environmental issues. The project follows six structured stages (see Table 7) aimed at fostering creative thinking skills, elaboration, originality, flexibility, fluency, as well as developing students' social responsibility by designing solutions aligned with community needs. Learning activities are conducted both synchronously and asynchronously using an open-source LMS, supported by videos, simulations, and digital collaboration. Students are encouraged to design, build, and test prototypes of mini weather monitoring tools, present data through graphs, and provide interpretations relevant to local agricultural practices. This project not only integrates subjects such as Science, Mathematics, and ICT but also embodies the values of *Merdeka Belajar* and the *Pancasila Student Profile* by promoting exploration, independence, and social contribution. The detailed project stages are presented in Table 7.



Table 7. Final STEM Project Design: Simple Weather Data Collection Tool

STEM Phase	Task Description	Explanation	Guidelines	Duration
Asking Essential Questions	Identifying community problems and formulating research questions	Students explore farmers' needs (e.g., difficulties in predicting weather changes) and formulate a research question: "How can we measure and predict weather simply?"	Use local farmer interview videos, LMS discussion forums, and inquiry guides based on community needs.	2 lessons @ 50 minutes (synchronous)
Designing a Prototype Tool	Designing a simple weather monitoring tool	Students discuss and design a tool by selecting the type of weather data to collect (temperature, humidity, rainfall) and determining methods for data visualization and documentation.	Provide sensor tutorial videos, weather instrument simulations, and digital design templates via LMS. Emphasize measurement principles and interdisciplinary STEM connections.	3 lessons @ 50 minutes (synchronous & asynchronous)
Scheduling and Task Division	Project management within teams	Students create a project work plan, assign roles (designer, data recorder, analyst), and establish activity flow and data collection schedules.	Utilize LMS planner templates, teamwork rubrics, and collaborative forum discussions. Encourage accountability among team members.	1 lesson @ 50 minutes (synchronous)
Building and Testing the Tool	Construction and testing of a mini weather monitoring tool	Students build a simple tool (e.g., a manual ombrometer), record daily data for five days, and compare their results with simulation or digital weather forecasts.	Use data recording sheets, simple data loggers, and LMS platforms to compare actual data with simulations (e.g., online BMKG forecasts).	4 lessons @ 50 minutes (asynchronous)
Analyzing and Presenting Data	Data interpretation and visualization	Collected data is analyzed using graphs and narratives. Students connect findings to local agricultural phenomena and practical implications.	Provide digital table templates, Google Sheets spreadsheets, and trend analysis rubrics. Encourage discussions linking data insights to real-life farming challenges.	2 lessons @ 50 minutes (synchronous)
Reflection and Presentation	Delivering project outcomes and self-evaluation	Students prepare reports, create digital presentations, and reflect on their learning experience and encountered technical challenges.	Use LMS video recorders for documentation, presentation rubrics, and Zoom/Google Meet for project exposure sessions with classmates and mentors.	2 lessons @ 50 minutes (synchronous)



Phase 1: Facilitating Meaningful Questions in a Local STEM Context

This phase aims to foster students' scientific curiosity and divergent thinking through a community-based problem-based learning approach centered on real issues faced by Baduy farmers, such as planting season uncertainty and extreme weather conditions. Students are encouraged to explore these problems through contextual videos and guided discussions, with the teacher acting as a learning coach who connects scientific concepts with local wisdom. Through this process, students formulate exploratory questions to design simple, locally sourced weather prediction tools. The success of this phase is evaluated using an exploratory question rubric that assesses relevance to applied science, originality, and the feasibility of tool development, in order to build cross-disciplinary understanding rooted in the local context. Examples of the exploratory questions formulated by students include: "How can we create a simple yet accurate tool for predicting weather for farmers?" and "Is it possible to build a temperature and humidity measuring device using local materials?"



Figure 2. Learning Coach



Figure 3. Students Conducting Literature Review

Phase 2: Designing the Prototype

In this phase, students, teachers, and local farmer groups collaboratively designed a simple climate monitoring prototype based on the Internet of Things (IoT) to assist Baduy farmers in adapting to shifting planting patterns caused by climate change. The students developed a data logger using temperature (DHT11), humidity, and rainfall (rain gauge) sensors integrated with Arduino, which was tested for seven days to record environmental data. The prototype was then upgraded into a Raspberry Pi-based system, enabling real-time weather data monitoring and visualization through a Python GUI interface, with data stored in CSV format on a local server without requiring an internet connection (see Figure 4).

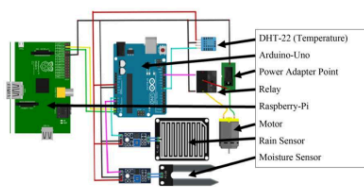


Figure 4. Connectivity view.



Figure 5. Demo photo of the project

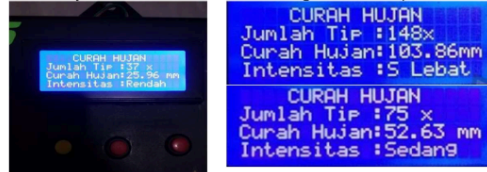


Figure 6. Output results of the project



Stage 3: Project Scheduling

In a 50-minute synchronous learning session, students are guided to develop a structured project work plan and distribute roles based on each team member's competencies and interests. They utilize digital tools such as the local LMS, Google Calendar (for structured physical scheduling), and online discussion platforms like WhatsApp or LMS forums. The success of this stage is evaluated using three main instruments: (1) a Project Planning Rubric developed based on indicators of time management effectiveness and role distribution; (2) an Activity Log Tracker that automatically monitors individual digital contributions via the LMS; and (3) a Team Reflection Sheet, designed following the Pancasila Student Profile reflection guidelines issued by the Indonesian Ministry of Education and Culture. System Usage Procedure by Indigenous Farmers: 1) The system automatically activates at 5:00 AM and 4:00 PM to collect data; 2) Sensors detect temperature, humidity, and rainfall levels; 3) Raspberry Pi stores and processes data into daily graphical visualizations (simple icons: hot, humid, heavy rain); 4) Farmers read a small LCD screen displaying weather status and simple warnings ("Planting delayed," "Heavy rain alert"); and 5) Training is provided by students and teachers to explain how to interpret weather patterns and their impact on the local rice cultivation cycle.

Stage 4: Project Monitoring and Evaluation

This stage ensures the technical quality and learning impact of the student-constructed weather monitoring device. Teachers and students serve as evaluators using rubrics based on design originality, measurement accuracy, scientific validity, and local contextual relevance. A five-day field test compares the device's readings with official data from the Meteorology, Climatology, and Geophysics Agency (BMKG) to assess validity and reliability. Evaluation results are then used as the basis for design improvement, facilitated by mentors.

Stage 5: Data Analysis and Dissemination

After five days of weather data collection, students process the observations using spreadsheets to visualize trends in temperature, humidity, and rainfall. This activity enhances data literacy and contextual understanding through a STEM-based scientific inquiry approach. Students formulate simple hypotheses on the impact of weather conditions on agriculture and engage in reflective discussions under teacher guidance. This phase contributes to strengthening community scientific literacy and adaptive resilience to local climate change. A key activity is stimulating students to develop and test hypotheses regarding the effects of weather patterns on planting cycles, soil fertility, and crop yields. Teachers facilitate reflective discussions using analytical questions such as: "How can this data help farmers make planting decisions?" or "What are the limitations of this data for short-term predictions?" The processed data is presented in simple infographics designed to be easily understood by community members with limited educational backgrounds. These infographics are then presented by students in small video forums uploaded to the LMS.

Effectiveness of STEM-DLS

After completing all stages of development and implementation, the next step was to evaluate the effectiveness of the STEM-DLS using a quasi-experimental design at the field level. Based on the results of the independent sample t-test presented in Table 8, a significant difference was found in creative thinking abilities between students in the experimental and control groups, indicating a moderate to large practical effect. These findings confirm that the STEM-DLS learning model is demonstrably more effective



than conventional approaches in stimulating creative thinking, particularly through the integration of visual exploration, contextual projects, and digital scaffolding.

Table 8. Autonomy Levels and Creative Thinking Before and After in the Control Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t_{emp}	Before	After	t_{emp}
High	Self-initiation	4.111	4.455	2.533	4.022	4.388	2.402
	Goal orientation	4.233	4.600	2.642	4.100	4.478	2.318
	Persistence	3.988	4.300	2.200	3.877	4.188	2.011
	Responsibility	4.211	4.622	2.881	4.078	4.500	2.540
	Decision-making	4.089	4.500	2.700	3.955	4.388	2.380
Moderate	Self-initiation	3.788	4.100	2.200	3.689	4.022	2.089
	Goal orientation	3.955	4.344	2.478	3.822	4.256	2.204
	Persistence	3.700	4.044	2.100	3.566	3.900	1.922
	Responsibility	3.800	4.222	2.820	3.755	4.211	2.322
	Decision-making	3.789	4.178	2.511	3.688	4.089	2.144
Low	Self-initiation	3.411	3.800	2.000	3.388	3.700	1.901
	Goal orientation	3.544	3.900	2.211	3.422	3.833	2.100
	Persistence	3.422	3.700	1.889	3.311	3.600	1.800
	Responsibility	3.655	3.978	2.000	3.588	3.911	2.045
	Decision-making	3.611	3.944	2.022	3.489	3.822	2.033
Creative Thinking Level	Indicators Thinking Level	Boys			Girls		
		Before	After	t_{emp}	Before	After	t_{emp}
High	Fluency	1.322	1.544	2.111	1.200	1.422	2.015
	Flexibility	0.722	0.933	2.066	0.855	1.066	2.100
	Originality	2.100	2.400	2.220	2.566	2.822	1.966
	Elaboration	1.366	1.622	2.144	2.200	2.466	2.111
	Connection-making	1.533	1.789	2.089	1.644	1.922	2.022
Moderate	Fluency	1.078	1.300	2.010	0.988	1.200	1.885
	Flexibility	0.633	0.844	2.033	0.744	0.955	2.044
	Originality	1.855	2.122	2.150	2.422	2.655	1.933
	Elaboration	1.200	1.456	2.244	2.100	2.356	2.088
	Connection-making	1.444	1.678	2.033	1.522	1.744	2.011
Low	Fluency	0.889	1.066	2.089	0.855	1.044	2.012
	Flexibility	0.422	0.633	2.066	0.622	0.811	2.000
	Originality	1.433	1.678	2.033	2.211	2.433	1.889
	Elaboration	1.000	1.211	2.011	1.944	2.177	2.022
	Connection-making	1.233	1.455	2.077	1.311	1.522	1.955

Table 9. Autonomy Levels and Creative Thinking Before and After in the Experimental Class.

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	t_{emp}	Before	After	t_{emp}
High	Self-initiation	4.133	4.722	3.122	4.089	4.678	3.055
	Goal orientation	4.200	4.789	3.300	4.122	4.733	3.188
	Persistence	4.011	4.611	3.122	3.911	4.500	3.044
	Responsibility	4.255	4.855	3.233	4.144	4.755	3.211
	Decision-making	4.144	4.800	3.344	4.022	4.688	3.278
Moderate	Self-initiation	3.822	4.444	3.144	3.722	4.366	3.100
	Goal orientation	3.977	4.600	3.266	3.855	4.544	3.189
	Persistence	3.755	4.333	3.000	3.622	4.255	2.944
	Responsibility	3.866	4.522	3.144	3.811	4.466	3.111
	Decision-making	3.833	4.478	3.188	3.755	4.400	3.077
Low	Self-initiation	3.433	4.011	2.933	3.400	3.977	2.855
	Goal orientation	3.577	4.144	2.988	3.444	4.111	2.911
	Persistence	3.433	4.000	2.800	3.322	3.911	2.733



Autonomy Level	Indicators	Boys			Girls		
		Before	After	t_{emp-}	Before	After	t_{emp-}
	Responsibility	3.688	4.244	2.944	3.622	4.200	2.866
	Decision-making	3.633	4.222	3.022	3.511	4.122	2.900
Creative Thinking Level	Indicators	Boys			Girls		
		Before	After	t_{emp-}	Before	After	t_{emp-}
High	Fluency	1.344	1.700	2.455	1.244	1.644	2.333
	Flexibility	0.755	1.144	2.566	0.900	1.300	2.488
	Originality	2.188	2.722	2.611	2.633	3.044	2.444
	Elaboration	1.411	1.877	2.488	2.255	2.733	2.600
	Connection-making	1.577	2.033	2.533	1.677	2.100	2.511
Moderate	Fluency	1.100	1.544	2.366	1.000	1.466	2.233
	Flexibility	0.655	1.044	2.500	0.766	1.144	2.411
	Originality	1.900	2.433	2.577	2.466	2.977	2.388
	Elaboration	1.222	1.700	2.611	2.144	2.677	2.544
	Connection-making	1.488	1.933	2.544	1.555	2.000	2.466
Low	Fluency	0.911	1.366	2.433	0.877	1.322	2.355
	Flexibility	0.444	0.877	2.488	0.655	1.044	2.344
	Originality	1.477	2.011	2.611	2.233	2.744	2.477
	Elaboration	1.033	1.511	2.555	2.000	2.511	2.500
	Connection-making	1.266	1.755	2.500	1.344	1.833	2.455

The results indicate that the STEM-DLS intervention contributed positively to enhancing students' learning autonomy and creative thinking skills compared to the control class. To assess the extent of this learning model's impact on students' cognitive achievements, a comparative analysis of pretest, posttest, and N-Gain scores in mathematical creative thinking was conducted, as presented in Table 10.

Table 10. Mean Scores of Pretest, Posttest, and N-Gain in Mathematical Creative Thinking Ability

Group	N	Pretest Mean	Posttest Mean	N-Gain ((g))	Effectiveness Interpretation
Experimental (STEM-DLS)	60	53.12	75.46	0.554	Moderate (Effective)
Control (Conventional)	60	52.78	63.29	0.223	Low (Less Effective)
Difference	—	—	+12.17	+0.331	—

The difference in N-Gain scores between the experimental and control groups indicates that the implementation of STEM-DLS was more effective in improving students' mathematical creative thinking abilities. To further examine the interaction effect between the learning model and students' autonomy levels, a Two-Way ANOVA was conducted, with the results shown in Table 11.

Table 11. Two-Way ANOVA (Autonomy Level × Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.450	5	0.490	37.690	0.000
Intercept	40.320	1	40.320	3102.31	0.000
Autonomy Level	1.750	2	0.875	67.310	0.000
Learning Model	0.580	1	0.580	44.620	0.000
Autonomy Level * Learning Model	0.120	2	0.060	4.620	0.012
Error	1.500	114	0.013		
Total	44.270	120			
Corrected Total	3.950	119			

The Two-Way ANOVA results reveal a significant interaction between students' autonomy levels and the learning model on their autonomy scores. To identify which groups differed significantly, a post hoc Tukey HSD test was performed, as presented in Table 12.



Table 12. Tukey HSD Test – Learning Autonomy Level

(I) Autonomy Level	(J) Autonomy Level	Mean Difference (I-J)	Std. Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.348*	0.033	0.000	Significant: Low < Moderate
Low	High	-0.601*	0.033	0.000	Significant: Low < High
Moderate	High	-0.253*	0.033	0.000	Significant: Moderate < High

The Tukey HSD test confirms that higher levels of learning autonomy correspond to higher learning achievements, particularly when applying the STEM-DLS model. These findings highlight the critical role of students' autonomy readiness in maximizing the effectiveness of STEM-based instruction. To complement these findings, the next analysis focuses on the interaction between creative thinking ability levels and the learning model (see Table 13).

Table 13. Two-Way ANOVA (Creative Thinking Level × Learning Model)

Source	Sum of Squares	df	Mean Square	F	Significance
Corrected Model	2.750	5	0.550	26.190	0.000
Intercept	51.200	1	51.200	2438.10	0.000
Creative Thinking Level	2.100	2	1.050	50.000	0.000
Learning Model	0.460	1	0.460	21.905	0.000
Creative Thinking × Learning Model	0.190	2	0.095	4.524	0.013
Error	2.400	114	0.021		
Total	56.350	120			
Corrected Total	5.150	119			

The results of the Two-Way ANOVA test revealed a significant interaction between students' levels of creative thinking ability and the learning model employed. These findings indicate that the impact of the STEM-DLS model varies across different categories of students' creative thinking skills. To determine the specific differences between groups, a post-hoc Tukey HSD test was conducted, as presented in Table 14.

Table 14. Tukey HSD Test on Creative Thinking

(I) Creative Thinking Level	(J) Creative Thinking Level	Mean Difference (I-J)	Standard Error	Sig. (p)	Academic Interpretation
Low	Moderate	-0.175	0.028	0.000	Significant: Low < Moderate
	High	-0.279	0.028	0.000	Significant: Low < High
Moderate	Low	0.175	0.028	0.000	Significant: Moderate > Low
	High	-0.104	0.028	0.001	Significant: Moderate < High
High	Low	0.279	0.028	0.000	Significant: High > Low
	Moderate	0.104	0.028	0.001	Significant: High > Moderate

The results of the Tukey HSD test confirmed significant differences in creative thinking abilities among the three levels of creativity. Students in the high creativity group demonstrated substantially higher performance compared to those in the moderate and low creativity groups. These findings provide a critical basis for supporting the dissemination and broader replication of the STEM-DLS model as outlined in the subsequent phase. The fourth phase of this study focused on a structured dissemination strategy to expand the impact of the STEM-DLS innovation adaptively and sustainably. This strategy encompassed four main pillars: academic legitimacy, independent replication, intellectual property rights legalization, and the activation of learning communities. First, scientific articles related to the conceptual framework and design of STEM-DLS were submitted as a means of academic validation and outreach.



Second, a national training program involving 42 teachers from various regions of Lebak and Pandeglang resulted in a replication readiness rate of 78.6%, with two non-research schools beginning to implement portions of the modules. The effectiveness of dissemination was evaluated through three key indicators: (1) adoption by six non-research subject teachers, supported by lesson plans and video documentation; (2) the establishment of an independent Teacher Learning Community with a monthly reflection agenda; and (3) transformation of instructional practices as evidenced by project portfolios and increased use of interdisciplinary interactive digital media. These findings suggest that an adaptive, data-driven dissemination strategy can lay the groundwork for a participatory, contextual, and potentially nationwide replicable digital learning ecosystem.

Discussion

The development of the STEM-Based Digital Learning Space (DLS) successfully addressed the limitations of conventional LMS platforms in partner schools, particularly in terms of flexibility, visualization, and student empowerment. Figure 7 illustrates one of the STEM-DLS products, which was designed based on local needs through a participatory front-end analysis involving teachers and students, in line with the concept of a collaborative digital ecosystem.

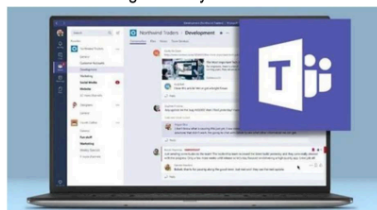


Figure 7 presents the online STEM-DLS platform, which can be accessed at <https://kalana.my.id>.

The project-based STEM learning stages were applied to foster students' creative mathematical thinking skills, starting from the *Essential Question* phase, which enhances fluency and flexibility, to the *Design a Plan* phase, which develops originality and elaboration, and the *Schedule & Monitor* phase, which promotes autonomous learning and independent project management. In the *Assess the Outcome* phase, students sharpen their data literacy skills through experimental result analysis and theoretical reflection. Initial implementation demonstrated a significant increase in student participation and improvement in creative mathematical thinking skills, as measured by various TTCT indicators. These findings align with the main objective of this study, which was to develop an effective STEM-DLS model for enhancing students' mathematical creativity and autonomous learning.

The STEM-DLS innovation developed in this study successfully addressed the shortcomings of conventional LMS platforms in supporting contextual and collaborative learning (Nurintya & Agoestanto, 2022). The DLS features innovative elements such as STEM project videos, a shared practice space, and interactive discussions, enabling teachers and students from various regions to access and replicate this learning model. Validation results in terms of practicality, validity, and effectiveness indicate that the DLS significantly enhances learning quality, student engagement, and teacher creativity. Its key strengths include easy web access, a user-friendly interface, contextual STEM content integration, and interactive quizzes with automated feedback. These findings are consistent with those of Lin et al. (2017) and Yuliardi et al. (2024), who emphasized the effectiveness of DLS in promoting interaction and learning outcomes. However, as noted by Saputro & Tri. (2019), the success of DLS also depends on teacher



readiness, the enhancement of digital literacy, and the reinforcement of interactive pedagogy. Therefore, the DLS implementation was accompanied by intensive training and the development of teacher communities of practice to ensure sustainable, transformative impact.

This study reinforces the theoretical framework of STEM integration through digital technology by developing an adaptive and contextual Digital Learning Space (DLS) model. This DLS innovation broadens the STEM learning framework by emphasizing the integration of science, technology, creativity development, digital literacy, and autonomous learning. The DLS prototype is flexible and can be replicated by teachers through a co-design approach to support project-based learning models. Practically, the DLS provides tangible benefits for teachers by offering an open, modular, and collaborative digital learning platform, supported by teacher training and learning communities for broader regional replication. For policymakers, these findings serve as a valuable reference for accelerating digital transformation in education, aligned with the Merdeka Belajar policy and SDG Goal 4 on quality education. The study's limitations lie in the relatively small sample size ($N = 120$) and limited geographical representation, restricting the generalizability of the findings. Future research is recommended to involve more diverse samples across educational levels and regions and to test the effectiveness of the DLS model in various STEM project contexts. Infrastructure limitations and unequal internet access also present challenges that require policy support in the form of minimum technology provision in schools and teacher training to optimize the use of DLS as a sustainable digital learning ecosystem.

CONCLUSION

The development of the STEM-Based Digital Learning Space (STEM-DLS) using the 4D model has successfully addressed the need for adaptive digital learning media to overcome the limitations of conventional LMS platforms in fostering student autonomy and creative learning. The DLS has been proven valid, practical, and effective in enhancing students' self-directed learning and creative mathematical thinking through the integration of contextual learning principles, STEM syntax, and interactive digital features. Effectiveness testing revealed that the DLS promotes active student engagement, strengthens digital literacy, and facilitates collaboration among educational stakeholders. With its accessibility and flexibility, the DLS holds strong potential for widespread adoption to support the development of an inclusive and sustainable digital learning ecosystem, aligned with the 'Merdeka Belajar' educational policy.

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Declarations

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