Journal on Mathematics Education
Volume 16, No. 3, 2025, pp. 1093-1118

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

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Received: 17 June 2025 | Revised: 29 September 2025 | Accepted: 1 October 2025 | Published Online: 2 October 2025

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, adaptive quizzes supported metacognitive regulation, digital worksheets improved originality, and collaborative forums fostered responsibility. Overall, the DLS proved effective even in low-resource contexts and scalable through teacher training, offering evidence-based guidance for advancing digital literacy and supporting the *Merdeka Belajar* policy.

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

How to Cite: Yulianto, D., & Juniawan, E. A. (2025). Fostering mathematical creativity and autonomy through a STEM-based digital learning space. *Journal on Mathematics Education, 16*(3), 1093–1118. https://doi.org/10.22342/jme.v16i3.pp1093-1118

Recent findings from the Organisation for Economic Co-operation and Development (OECD, 2023) reveal that Indonesian students consistently underperform in mathematical literacy, particularly on non-routine problems that require adaptive and flexible reasoning. This pattern of low performance underscores the urgent need to cultivate creative mathematical thinking and learner autonomy within the national education system. In response, Indonesia's Ministry of Education introduced the *Merdeka Belajar* (Freedom to Learn) policy in 2019, which seeks to advance student-centered and competency-based education by expanding curricular autonomy, reducing the dominance of high-stakes examinations, and promoting project-based, contextualized instruction (Yulianto et al., 2024). Despite these reforms, classroom practices remain heavily reliant on rote procedures and teacher-centered instruction, limiting opportunities for problem-solving, creativity, and higher-order reasoning (OECD, 2023).

Empirical evidence indicates that the success of digital learning initiatives depends substantially on teachers' technological readiness and institutional capacity (Cezar et al., 2019). Observations from secondary mathematics classrooms in Banten Province confirm that instruction remains predominantly textbook-driven, with minimal integration of interdisciplinary STEM principles (Tambunan & Yang, 2022). To respond to these challenges, this study develops and evaluates a project-based STEM Digital Learning Space (DLS) integrated within a teacher-orchestrated Personal Teaching Environment (PTE) (Yuliardi et al., 2024). The DLS incorporates culturally grounded, inquiry-oriented activities, such as mathematical explorations of *Baduy* weaving patterns and weather-monitoring projects, to promote meaningful, context-sensitive learning.

Mathematical creativity in this study is conceptualized through four interrelated dimensions: fluency, flexibility, originality, and elaboration. Learner autonomy is operationalized through indicators of self-regulation, initiative, and metacognitive awareness (Hidajat, 2022; Yuliardi et al., 2024). The study's results demonstrate that the DLS substantially enhances both creativity and autonomy, suggesting that digital project-based learning can serve as an effective and scalable model for mathematics education in contexts with limited ICT infrastructure.

Indonesia's persistent deficiencies in mathematical literacy are well documented. In the 2022 PISA cycle, only 18% of Indonesian fifteen-year-olds attained at least Level 2 proficiency, significantly below the OECD average (OECD, 2023). Similarly, the 2018 assessment reported merely 28% of students reaching basic or intermediate competency levels (OECD, 2019). Although the need for improvement is widely recognized, few studies have systematically addressed both creative mathematical thinking—defined as the ability to generate, transform, and flexibly apply ideas in complex, non-routine situations—and learner autonomy within a validated task-based framework.

To address this gap, the present study maps Torrance-inspired creativity constructs onto analytic rubrics (Yoon, 2017): fluency (number of distinct solution pathways), flexibility (diversity of strategies), originality (novelty and non-redundancy of responses), and elaboration (depth of reasoning, representational richness, and justification). Learner autonomy is assessed through validated subscales measuring self-regulation, initiative, and metacognitive awareness. All instruments underwent expert validation (Aiken's V > 0.80) and inter-rater reliability testing (ICC ≥ 0.75) (López-Angulo et al., 2024), ensuring rigorous pre-post comparison through normalized gain, effect-size, and interaction analyses (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.

While the Torrance Tests of Creative Thinking (TTCT) remain a global standard for assessing general creativity, they insufficiently capture domain-specific features of mathematical thinking, including precision, logical consistency, and multi-strategy reasoning (Meier et al., 2021). To address this limitation, the present study adapts the TTCT framework for mathematical problem-solving, aligning the four creativity dimensions with the epistemic characteristics of mathematics (Meier et al., 2021; Suherman & Vidakovich, 2022). For instance, one culturally embedded task invites students to estimate rainfall probabilities in the Baduy region, requiring multiple valid procedures (fluency), diverse analytical, heuristic, and simulation-based strategies (flexibility), novel reasoning approaches (originality), and detailed justifications supported by symbolic, graphical, and statistical representations (elaboration) (Grajzel et al., 2023; Lu et al., 2025).

The scoring rubrics are aligned with international frameworks: the fluency and flexibility dimensions correspond to PISA 2018 problem-solving constructs (OECD, 2019), while originality and elaboration align with PISA 2022 creative-thinking indicators (OECD, 2023). This synthesis results in a domain-specific, internationally benchmarked assessment instrument capable of more accurately measuring mathematical creativity (López-Angulo et al., 2024; Yulianto et al., 2024). The model thereby strengthens the validity and comparability of creativity assessment within mathematics education research.

Creative mathematical thinking flourishes in learning environments that promote exploration, reflection, and conceptual reconstruction (Junaedi et al., 2021). However, Indonesia's STEM pedagogy continues to face substantial barriers, including procedural instruction, high textbook dependence, and uneven digital access—only 65% of secondary schools report reliable internet connectivity, and fewer than 40% of students have personal computers (Chai et al., 2020; Revina et al., 2023). This study's DLS seeks to overcome such constraints by providing a hybrid, project-based learning platform capable of operating in low-connectivity environments while fostering creative reasoning and autonomous learning (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.

These efforts are situated within Indonesia's broader educational reform landscape, notably the *Merdeka* Curriculum and the *Sekolah Penggerak* (Driving Schools) initiative, which emphasize competency-based and project-oriented learning supported by intensive mentoring (Jasiah et al., 2024). Nonetheless, classroom practices remain predominantly procedural and teacher-directed (Cheon et al., 2020). Limited teacher digital literacy, insufficient interdisciplinary collaboration, and a lack of adaptive digital platforms further constrain reform implementation (Li & Yu, 2022; Rawal, 2024). Effective STEM education thus requires not only policy alignment but also pedagogical transformation that nurtures learner autonomy, cognitive flexibility, and creativity through authentic problem-solving and reflective teaching (McGuire & Ó 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 has become a central construct in 21st-century education, positioning students as self-regulated agents who actively plan, monitor, and evaluate their learning processes (González-Pérez & Ramírez-Montoya, 2022; Yuliardi et al., 2024). Within mathematics education, learner autonomy is essential for fostering metacognitive awareness and sustained engagement in problem solving. Digital learning tools, therefore, should function not merely as administrative or content delivery mechanisms but as mediators of transformative, self-directed learning experiences (Athaya et al., 2021). In this context, a STEM-based Digital Learning Space (DLS) must be conceptualized to promote openness, contextual relevance, and learner agency—three interdependent principles that together cultivate autonomous and creative engagement with mathematical ideas.

Openness in digital learning environments enables learners to access diverse and dynamic resources flexibly, encouraging individualized learning trajectories and self-directed inquiry (Aini et al., 2023). Contextualized digital environments that embed tasks in authentic, culturally situated problem scenarios have been found to significantly enhance conceptual understanding and knowledge transfer in STEM learning (Conde et al., 2021). Equally important, the design of a DLS must integrate mechanisms that foster learner agency through interactive features allowing students to make instructional choices, set personal learning goals, and monitor progress. These processes promote the development of self-regulation and metacognitive competence, both of which are essential components of mathematical autonomy (Nguyen et al., 2020). Collectively, these features distinguish an effective STEM-DLS from traditional e-learning systems by emphasizing cognitive flexibility, reflection, and student-driven inquiry rather than passive content consumption.

Despite these pedagogical advantages, several systemic barriers hinder the realization of autonomous digital learning in developing contexts. In Indonesia, rigid curricular structures, limited access to digital infrastructure, and inadequate teacher competence continue to constrain innovation in STEM education (Yulianto et al., 2024). Without targeted professional development and institutional support, the ideals of STEM integration, learner autonomy, and digital learning risk remaining rhetorical rather than practical. Addressing these challenges requires a shift toward networked learning principles that emphasize collaboration, knowledge co-construction, and technological adaptability (Gourlay et al., 2021). DLS grounded in this framework facilitate both synchronous and asynchronous interactions that support flexible goal setting, peer exchange, and self-regulated learning (Dignath & Veenman, 2021; Sun & Chen, 2023).

Integrating Personal Learning Environments (PLEs) for students and Personal Teaching Environments (PTEs) for instructors enhances personalization and adaptive instruction within the DLS framework (Nan Cenka et al., 2023). Interactive components such as collaborative forums, formative feedback cycles, and adaptive assessments strengthen cognitive presence and reflective engagement (Maranna et al., 2022). Nonetheless, claims regarding the accessibility and cost-effectiveness of digital learning technologies must be critically examined in light of persistent disparities in connectivity, device ownership, and digital literacy in low-resource settings (Gumbi et al., 2023). Sustainable implementation, therefore, depends not only on innovative pedagogical design but also on equitable policy support and infrastructural investment (Al-Said et al., 2023).

Moving beyond access, STEM-based DLS research must focus on designing environments that stimulate exploration, experimentation, and authentic problem solving (Fitriasari et al., 2024; Mahardhika et al., 2024). The DLS developed in this study aligns with TIMSS–PISA frameworks and integrates ethnomathematical contexts—such as local cultural practices—into digital materials, assessments, and discussions. Key features include adaptive feedback, open-ended simulations, and collaborative learning spaces that foster divergent thinking and conceptual generalization (Johnston et al., 2022). Unlike conventional digital models, this platform aims to enhance both creative mathematical thinking—defined through fluency, flexibility, originality, and elaboration—and learner autonomy, operationalized via self-regulation, initiative, and metacognitive awareness. Accordingly, the study investigates two core inquiries: (a) the validity and practicality of a culturally responsive, STEM-oriented DLS in ICT-limited environments; and (b) its effectiveness in simultaneously advancing mathematical creativity and learner autonomy. The findings are expected to contribute empirically grounded insights into how context-sensitive digital ecosystems can bridge persistent gaps between curriculum aspirations and classroom realities, advancing equitable and innovation-driven mathematics education.

METHODS

Research Design

This study employed a Research and Development (R&D) methodology based on the 4D model—Define, Design, Develop, and Disseminate—to construct and evaluate a STEM-based Digital Learning

Space (DLS) for secondary mathematics instruction. Grounded in design-based research principles (Pehkonen, 1997), the development process followed iterative cycles of prototyping, expert validation, classroom implementation, and systematic refinement. Each stage sought to ensure theoretical alignment, pedagogical coherence, and technological functionality. To assess the instructional effectiveness of the developed DLS, a quasi-experimental non-equivalent control group design was implemented using a pretest–posttest structure (experimental group = 60; control group = 60). The research sequence included a pilot study (n = 7), an expanded classroom trial (n = 60), and a large-scale field test (n = 120) conducted across multiple school sites. The DLS integrated two complementary components: a Personal Teaching Environment (PTE) for teachers—featuring pedagogical dashboards, rubric-based assessments, and orchestration tools—and a Personal Learning Environment (PLE) for students—offering adaptive quizzes, collaborative workspaces, and reflective tools designed to foster self-regulated and creative mathematical learning.

School selection followed three predetermined inclusion criteria: (1) basic ICT readiness, including a minimum of ten operational devices, reliable internet access, or a local server network; (2) demonstrated teacher commitment to integrating digital pedagogy; and (3) representation across varying accreditation levels and geographic settings to ensure external validity. To maintain data integrity, role-based authentication, secure communication protocols, and anonymized activity logs were implemented. Ethical considerations were rigorously upheld, including the acquisition of informed consent from students and their parents or guardians, Institutional Review Board (IRB) approval from the University of Latansa Mashiro (No. 29/E-5/UNILAM/2025), and adherence to data minimization and confidentiality standards consistent with international research ethics in educational technology studies.

Participant demographics were documented across three phases of implementation. The pilot study involved seven Grade VIII students (57% male; M age = 13.4, SD = 0.5) at SMP Latansa 2, providing initial usability feedback. The expanded classroom trial engaged sixty Grade VII students (47% male; M age = 13.1, SD = 0.6) from SMP Latansa 2 and SMP Kun Karimma to examine learning feasibility and functionality. The final field test involved 120 Grade VII students (48% male; M age = 12.8, SD = 0.5) drawn from SMP Daar El Qolam 2, SMP Daar El Qolam 3, and SMP Latansa 1, representing four schools with accreditation level A located in rural, peri-urban, and urban regions. This sampling ensured ecological diversity and representativeness within Indonesia's secondary education landscape.

Overall, the methodological design ensured a rigorous and transparent development process, integrating iterative validation, empirical testing, and ethical compliance. The multi-phase implementation allowed for continuous refinement of both pedagogical and technological dimensions of the STEM-DLS. Through this approach, the study generated robust evidence concerning the platform's feasibility (practical deployment across diverse contexts), practicality (teacher and student usability), and learning effectiveness (enhancement of mathematical creativity and learner autonomy). The systematic R&D process thereby positions the STEM-DLS as a theoretically grounded and empirically validated model for advancing innovation in mathematics education within resource-variable environments.

Measurement Instruments

Students' creative mathematical thinking was evaluated using pretest and posttest instruments comprising five open-ended tasks derived from Torrance's (1974) framework of creative thinking, such as fluency, flexibility, originality, elaboration, and connection-making. Each item was designed to elicit students' ability to generate, diversify, and refine mathematical ideas within authentic problem contexts. The instrument demonstrated strong psychometric properties, including satisfactory content validity

(Aiken's V = 0.85), internal consistency (Cronbach's $\alpha = 0.81$), and inter-rater reliability (intraclass correlation coefficient [ICC] = 0.82–0.91). Students' autonomous learning was measured using a 30-item questionnaire adapted from Fisher et al.'s (2001) Self-Directed Learning Readiness Scale, encompassing the dimensions of initiative, self-regulation, and metacognitive awareness. Items were rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating greater learner autonomy. The scale demonstrated high internal reliability (Cronbach's $\alpha = 0.873$), confirming its consistency for use in the present study.

Construct validity of the autonomous learning instrument was examined through exploratory factor analysis (Principal Axis Factoring with Direct Oblimin rotation). Sampling adequacy and sphericity assumptions were met (Kaiser–Meyer–Olkin = 0.846; Bartlett's test of sphericity: $\chi^2(435) = 1824.37$, $p < .001$). The analysis yielded a three-factor solution corresponding to initiative, self-regulation, and metacognitive awareness, which collectively accounted for 57.8% of the total variance. One item exhibiting a low factor loading was removed to optimize construct coherence. Reliability coefficients for the resulting subscales were $\alpha = 0.82$, 0.86, and 0.78, respectively, indicating acceptable internal consistency across all dimensions.

The STEM-based Digital Learning Space (STEM-DLS) was further evaluated for content validity and practicality through expert and user assessments. Five experts—two mathematics education specialists, one STEM pedagogy expert, and two digital media experts—rated the platform using a 5-point Likert rubric (1 = very poor to 5 = excellent). The overall mean validity score was 4.42 (SD = 0.31), indicating a high level of validity. Sub-dimension ratings were 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 examined through student questionnaires administered during the expanded trial ($n = 60$) and field test ($n = 120$), covering usability, clarity, readability, and time adequacy. The mean practicality scores were 82.4% and 84.7%, respectively, surpassing the 70% threshold for acceptable practicality. Subscale means ranged from 80.1% (time adequacy) to 86.5% (usability), suggesting that students found the DLS accessible, intuitive, and effectively aligned with classroom time constraints.

Data Collection and Analysis

This study adopted a convergent mixed-methods design to comprehensively examine the impact of the STEM-based Digital Learning Space (DLS) on students' creative mathematical thinking and autonomous learning. Qualitative data, consisting of multimodal documentation such as classroom photographs, videos, and audio recordings, were analyzed thematically following Braun and Clarke's (2006) six-phase framework to identify emergent patterns of mathematical reasoning, interaction, and learner autonomy within authentic instructional contexts. Quantitative analyses encompassed three sequential components: instrument validation, practicality evaluation, and effectiveness testing. Instrument validity was established using Aiken's V (≥ 0.80), confirming content relevance, while practicality was determined through student questionnaires, with mean ratings above 70% indicating feasible classroom implementation. To assess effectiveness, normalized gain scores ($\langle g \rangle$) were calculated to measure relative improvement, supplemented by paired-samples t-tests for within-group comparisons and independent-samples t-tests for between-group differences.

Subsequently, a mixed-design multivariate analysis of variance (MANOVA) was conducted across 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). MANOVA was chosen over analysis of covariance (ANCOVA) because baseline equivalence between experimental and control groups was established ($p > .05$), eliminating the need for covariate adjustment. Significant multivariate effects were further examined through Bonferroni-adjusted univariate ANOVAs to determine the contribution of individual variables. All relevant statistical assumptions were verified using the Shapiro–Wilk test for normality, Levene's test for homogeneity of variance, and Box's M test for equality of covariance matrices, with Pillai's trace reported when assumptions were violated. This analytic framework ensured methodological rigor and interpretive validity, yielding a robust evaluation of the STEM-DLS's effectiveness in fostering creative mathematical thinking and learner autonomy within secondary mathematics education.

RESULTS AND DISCUSSION

Define Stage

A preliminary needs analysis conducted at SMP Latansa Mashiro and its affiliated schools identified several systemic challenges in STEM education. The learning process remains fragmented across disciplines, such as Science, Mathematics, and Information and Communication Technology (ICT), with minimal interdisciplinary integration. Technology use is largely limited to conventional presentation tools such as PowerPoint, without the inclusion of interactive or exploratory digital media.

Student data revealed that 72.2% possess only basic digital literacy, primarily using applications such as WhatsApp and YouTube. Moreover, substantial barriers impede equitable access to technology: 58.3% of students experience unstable internet connectivity, and 25% rely on low-specification mobile devices. Learning autonomy is also limited, with 61.1% of students demonstrating difficulty in self-directed learning and a heavy dependence on teacher guidance. Only 16.7% exhibit indicators of creative potential, such as formulating critical questions or proposing alternative solutions presented in Table 1.

Table 1. Summary of front-end and learner analysis findings

Aspect	Key Findings	Implications for Solution Design
STEM Integration	Learning remains siloed, with no explicit connections among Science, Mathematics, and Technology.	Develop project-based learning scenarios that integrate multidisciplinary concepts.
Technology Use	Teachers primarily use PowerPoint; interactive media and digital simulations are absent.	Design a Digital Learning Space (DLS) emphasizing exploration and interactive visualization.
Student Digital Literacy	72.2% of students are familiar only with basic applications and lack experience with LMSs, GeoGebra, or similar tools.	Provide adaptive, stepwise digital literacy training aligned with students' initial competencies.
Learning Autonomy	61.1% struggle with independent learning and rely on continuous teacher support.	Incorporate scaffolding within digital task designs to progressively build learner autonomy.
Technical Constraints	58.3% lack stable internet access; 25% use low-performance smartphones.	Develop lightweight, offline or semi-offline learning media (e.g., interactive HTML, locally stored videos).
Creative Potential	Only 16.7% demonstrate creative tendencies such as questioning or generating alternative solutions.	Employ strategies that cultivate creativity through authentic, real-world problem contexts and open-ended exploration.

These findings underscore the necessity of developing a STEM-DLS that addresses both pedagogical and infrastructural deficiencies. By integrating project-based learning, adaptive scaffolding, and lightweight offline-compatible digital resources, the proposed system aims to enhance students' digital literacy, promote learning autonomy, and foster creative mathematical thinking. In doing so, the STEM-DLS responds directly to the identified systemic challenges while aligning with broader educational goals of cultivating 21st-century competencies.

Design Stage

In the Design Stage, a prototype of the STEM-DLS was developed, guided by the theoretical frameworks of the Personal Teaching Environment (PTE) and Personal Learning Environment (PLE). The prototype comprises four principal components:

1. Assessment instruments for measuring creative mathematical thinking and learner autonomy;
2. Lightweight HTML-based digital media and locally produced videos designed to accommodate low-specification devices and limited internet access;
3. Integrated STEM instructional materials embedded within project-based learning scenarios; and
4. Platform features, including discussion forums, reflective spaces, interactive quizzes, and peer-assessment tools, to support autonomy and collaborative engagement.

Expert validation involving specialists in instructional design and STEM content affirmed the feasibility and relevance of the prototype for classroom implementation. The finalized STEM-DLS platform is publicly accessible at https://learningspace.my.id as shown in Figure 1.

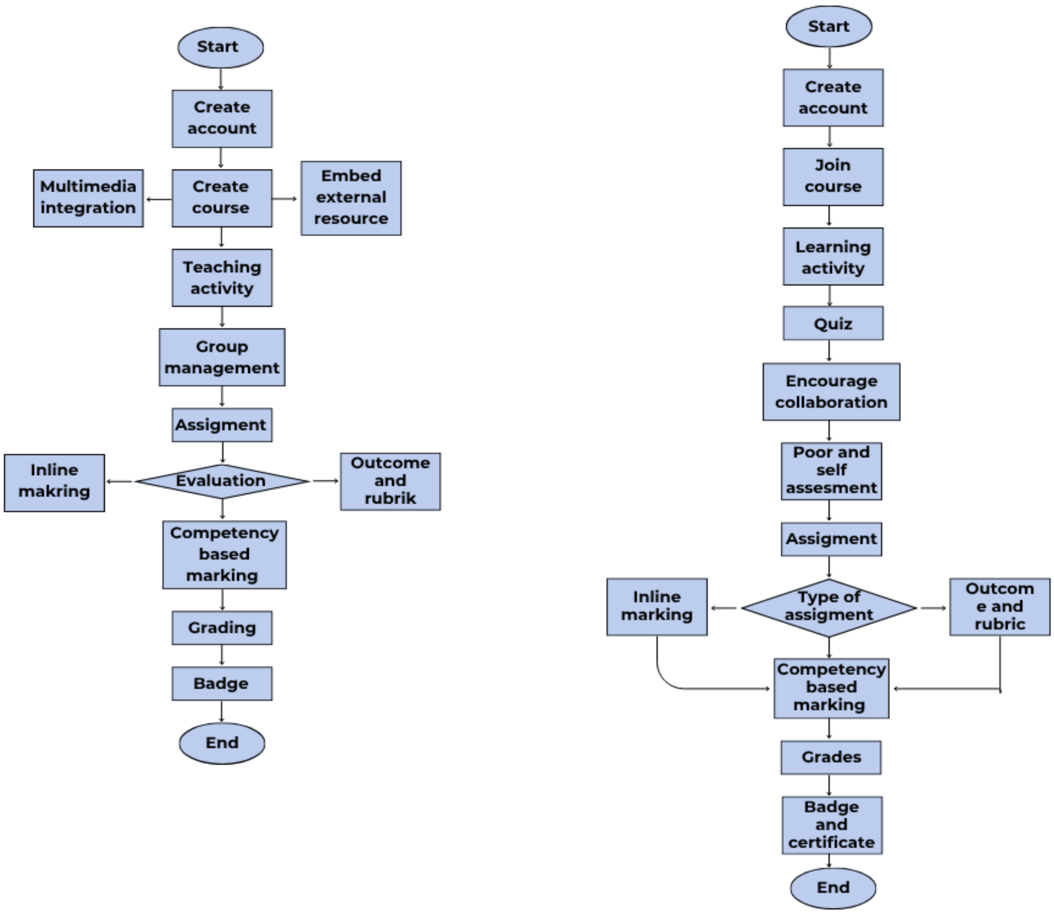

Figure 1. Flow diagram of PTE and PLE (Yuliardi et al., 2024)

Development Stage

Expert validation confirmed that the STEM-DLS prototype was both pedagogically robust and technically feasible. Content validation achieved a mean score of 4.35 (Valid), while media validation received 4.11 (Good) (see Appendix A). Panel discussions involving experts and practitioners further substantiated its classroom applicability, indicating that the system effectively responds to the contextual and infrastructural challenges identified during the Define stage. The platform was collaboratively developed by academics, developers, teachers, and students, integrating international frameworks—such as Project-Based Learning (PBL) and TIMSS/PISA orientations—with local educational constraints.

The resulting platform is modular, lightweight, and optimized for asynchronous learning. It incorporates a learning dashboard, interactive simulations, digital worksheets, automated assessments, and a collaborative hub—each designed to strengthen students' 21st-century competencies (4Cs) and learning autonomy. A summary of its core features is presented in Table 2.

Table 2. Summary of Key Features of the STEM-DLS

Feature	Main Function	Benefits for Teachers or Students
Learning Dashboard	Provides guidance, content navigation, and progress tracking.	Facilitates independent learning and enables efficient teacher monitoring.
Interactive Simulations & Videos	Visualizes STEM concepts through multimodal representation.	Enhances conceptual understanding and contextual application of abstract ideas.
Digital Worksheets & Project Upload	Serves as a medium for task completion and project documentation.	Promotes project-based learning and digital portfolio development.
Automated Formative Assessment	Offers interactive quizzes with immediate feedback and solution alternatives.	Provides instant diagnostic feedback and generates performance-based analytics.
Collaborative Learning Hub	Functions as a discussion forum and peer knowledge-sharing space.	Encourages collaboration, reflection, and peer-to-peer interaction.
Resource Center (STEM Gallery)	Houses repositories of student projects, videos, and context-based STEM tasks.	Supports knowledge transfer and inspiration from authentic learning experiences.

The STEM-DLS interface (Figures 2–3) was deliberately designed to be intuitive, accessible, and user-friendly. Formative evaluations affirmed 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) (see Appendix B). The thematic STEM tasks integrated Mathematics, Science, Technology, and Engineering with the local Baduy culture, encompassing activities such as weaving pattern analysis, traditional architecture modeling, probability in local games, and resource mapping. These tasks were structured to promote the dimensions of fluency, flexibility, originality, and elaboration, aligning with established indicators of mathematical creativity (Appendix C).

The culminating project, focused on designing a simple weather monitoring tool responsive to local agricultural needs, embodied the principles of problem-based and contextually grounded STEM learning. It was aligned with the *Merdeka Belajar* policy and the *Pancasila* Student Profile, fostering both cognitive and character competencies. The project was implemented through six interrelated phases, each strategically designed to scaffold creativity and learner autonomy:

1. Problem Formulation: Students generated essential questions to identify authentic, locally relevant problems, anchoring STEM inquiry in meaningful contexts.
2. Prototype Design: Learners translated conceptual understanding into tangible designs or models.
3. Trial and Refinement: Students tested prototype functionality, identified limitations, and improved their designs through iterative revision.
4. Data Analysis: Empirical results from the trials were analyzed, guiding evidence-based modifications and reinforcing analytical reasoning.
5. Reflection: Learners critically evaluated their processes and outcomes, fostering metacognitive awareness and self-regulation.
6. Dissemination: Students presented their projects to peers, teachers, and community members, transforming individual learning outcomes into collective knowledge while enhancing communication and collaboration skills.

Overall, the findings demonstrate that the STEM-DLS is pedagogically valid, technically practical, and contextually adaptive, effectively enhancing creative mathematical thinking and autonomous learning in lower secondary education. The subsequent section elaborates on the implementation process of the culminating project, detailing its progression from problem formulation to prototype development, scheduling, monitoring, data analysis, and dissemination.

Figure 2. STEM-DLS learning dashboard

Phase 1: Facilitating Meaningful Questions

In the initial phase, students explored the local climatic challenges experienced by Baduy farmers, particularly the unpredictability of planting seasons and the occurrence of extreme weather events. These explorations were facilitated through contextual videos and guided classroom discussions. The teacher assumed the role of a learning coach, bridging scientific concepts with indigenous knowledge systems to promote epistemic connections between formal science and local wisdom.

Students subsequently formulated exploratory questions intended to guide the design of simple weather-prediction tools utilizing locally available materials. Their questions were evaluated using analytic rubrics emphasizing relevance, originality, and feasibility. Illustrative examples of student-generated inquiries included "*How can we design a simple yet accurate tool to predict the weather?*" and "*Is it possible to construct a temperature and humidity gauge using local materials?*". As illustrated in Figure 3, the teacher's coaching emphasized metacognitive questioning strategies and guided inquiry, enabling students to pose meaningful, contextually grounded questions that linked STEM learning with real-world environmental issues.

Figure 3. Teacher functioning as a learning coach during the question formulation phase

Phase 2: Designing Prototypes

During this phase, students collaborated with teachers and local farmer associations to design an IoT-based climate monitoring prototype. The initial design employed an Arduino platform integrated with a DHT11 sensor to measure temperature, humidity, and rainfall. Subsequent iterations upgraded the system to a Raspberry Pi architecture, featuring real-time data visualization via a Python-based graphical user interface (GUI). To ensure contextual feasibility for rural areas with limited connectivity, the system was designed to store data locally in CSV format, allowing offline access and analysis. The connectivity and workflow architecture of this IoT-based weather monitoring prototype is presented in Figure 4.

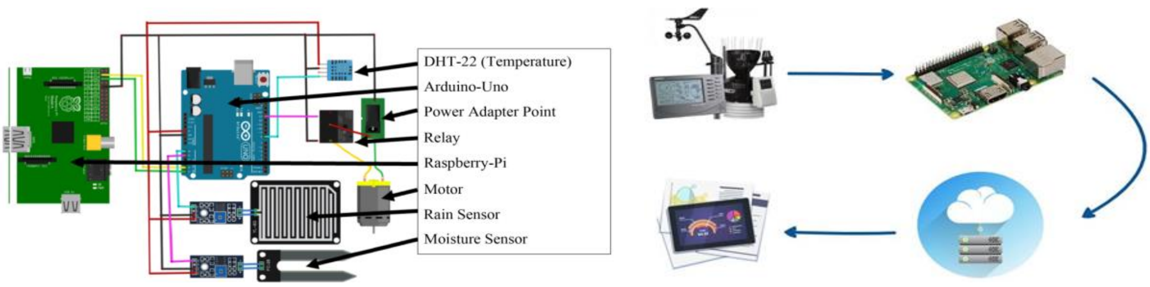

Figure 4. Connectivity and workflow of the IoT-based climate monitoring prototype

Phase 3: Project Scheduling

Within a 50-minute classroom session, students collaboratively developed a structured project work plan, distributed roles according to individual strengths, and utilized digital tools—including the Learning Management System (LMS), Google Calendar, and WhatsApp forums—for asynchronous coordination.

Progress was continuously monitored through the use of a Project Planning Rubric, Activity Log Tracker, and Team Reflection Sheets, ensuring alignment with the *Pancasila* Student Profile competencies. Following prototype development, local farmers operated the system to collect data automatically, receive LCD-based alerts, and participate in student-led training sessions. The user interface of the online STEM-DLS platform, which hosted these collaborative activities, is shown in Figure 5.

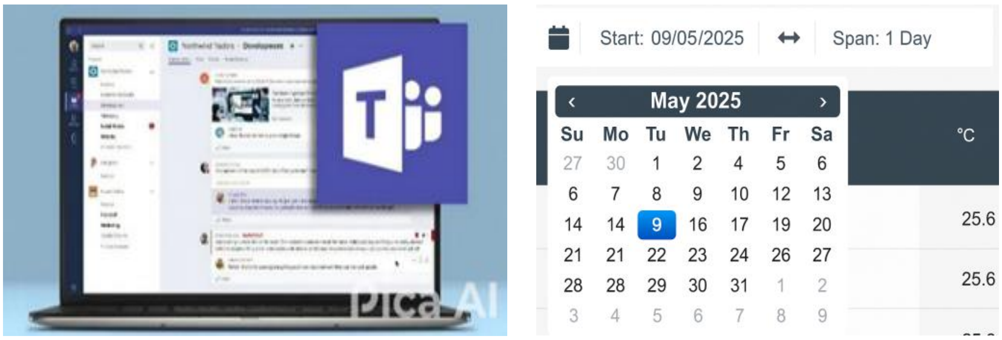

Figure 5. Online STEM-DLS platform, accessible at https://learningspace.my.id

Phase 4: Project Monitoring and Evaluation

In this phase, both teachers and students engaged in systematic evaluation of the prototype's performance using rubrics that assessed originality, accuracy, scientific validity, and local contextual relevance. A five-day field trial was conducted, during which data generated by the student-designed system were compared with official meteorological records from BMKG (Meteorological, Climatological, and Geophysical Agency).

This comparative testing provided empirical feedback for iterative refinements under teacher mentorship, reinforcing the principles of design iteration and evidence-based learning. A demonstration of the prototype during the classroom implementation is displayed in Figure 6.

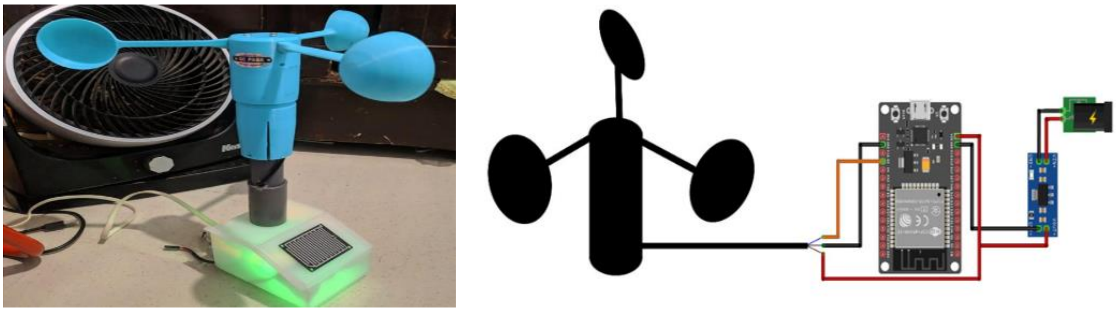

Figure 6. Demonstration of the student-developed climate monitoring prototype during classroom implementation

Phase 5: Data Analysis and Dissemination

In the final phase, students conducted a quantitative and qualitative analysis of five consecutive days of weather data. They visualized observed trends, formulated hypotheses regarding potential agricultural implications, and engaged in reflective group discussions to interpret their findings.

The results were disseminated through infographics and short video presentations shared via the LMS, with the aim of promoting community awareness and adaptive resilience toward climate change. This dissemination process also strengthened students' communication, collaboration, and digital literacy skills. The outcomes of this phase are illustrated in Figure 7.

Figure 7. Output results of the project

Dissemination Stage

The effectiveness of the STEM-DLS was examined through a quasi-experimental field study involving experimental and control groups. The findings demonstrated that students in the experimental group exhibited significantly greater improvement in creative mathematical thinking compared to their counterparts in the control condition presented in Table 3.

Table 3. Summary of pretest, posttest, and N-Gain scores in creative mathematical thinking

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	—

An N-Gain analysis indicated moderate effectiveness for the STEM-DLS intervention ($\langle g \rangle = 0.554$), whereas the control group achieved low effectiveness ($\langle g \rangle = 0.223$). These results suggest that the integration of STEM-DLS meaningfully enhanced students' ability to engage in creative mathematical reasoning.

A two-way ANOVA further revealed significant main effects of both learning autonomy and learning model, as well as a statistically significant interaction effect between these variables ($F = 4.62$, $p = 0.012$, $\eta^2 = 0.07$). Likewise, significant interaction effects were observed between creative thinking level and learning model ($F = 4.52$, $p = 0.013$, $\eta^2 = 0.07$).

Post hoc analyses indicated that students with higher levels of autonomy and creative thinking derived the greatest benefits from the STEM-DLS intervention (see Appendix D). As illustrated in Figure 8, the interaction between autonomy level and learning model demonstrates that the STEM-DLS condition amplifies learning gains for students exhibiting greater independence. Similarly, Figure 9 shows that the system's adaptive design enhances creative outcomes, particularly among students with higher baseline creativity. These findings underscore the learner-centered and adaptive qualities of the STEM-DLS in promoting differentiated learning outcomes.

Complementary qualitative evidence, derived from classroom observations, field notes, video recordings, and engagement rubrics, corroborated these quantitative findings. Notable improvements were documented in students' inquiry behaviors, collaborative problem-solving, and multimodal representations of mathematical ideas. Collectively, these data affirm the pedagogical adaptability and cognitive impact of the STEM-DLS in enhancing both creativity and autonomy.

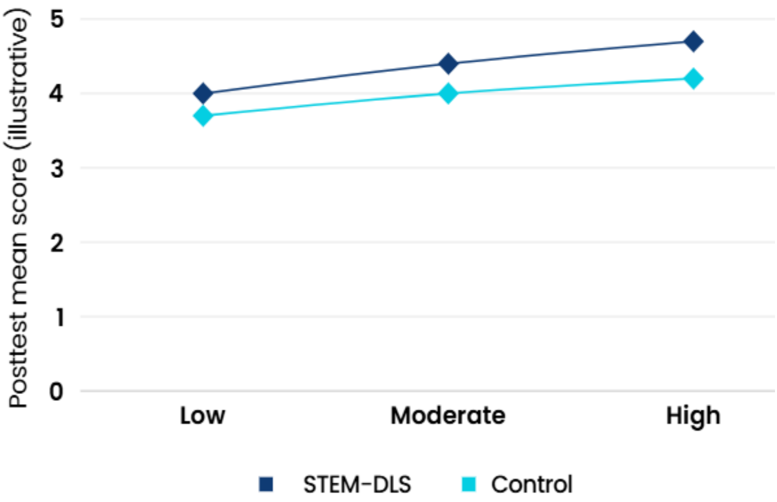

Figure 8. Interaction effect between autonomy level and learning model

Moreover, the dissemination phase demonstrated strong indicators of scalability and sustainability. A total of 42 teachers participated in professional development workshops, achieving a 78.6% readiness rate for classroom implementation. Additionally, six non-research partner schools independently adopted the STEM-DLS model, and a teacher learning community was established to facilitate monthly reflective practice.

These outcomes provide compelling evidence of the transferability and institutional viability of the STEM-DLS, particularly when implementation is supported through ongoing professional learning and systematic monitoring. The results collectively suggest that the STEM-DLS constitutes a scalable, adaptive, and pedagogically effective innovation for advancing creative and autonomous learning in secondary mathematics education.

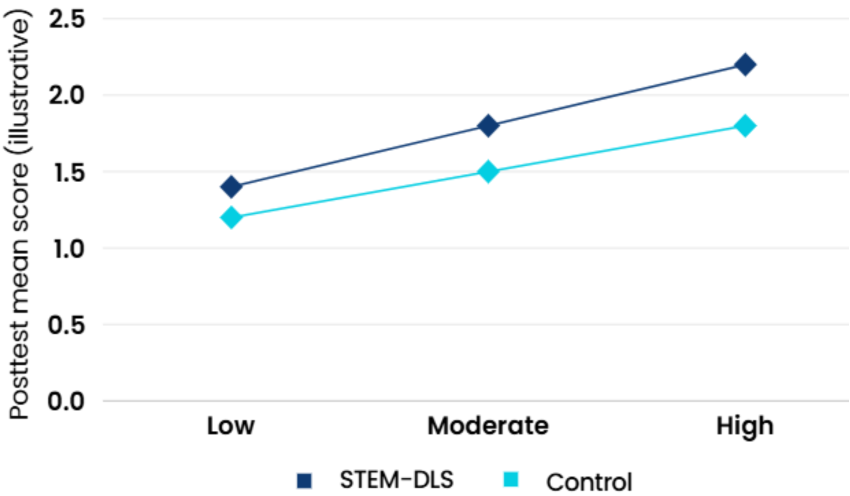

Figure 9. Interaction effect between creative thinking and learning model

Discussion

The present study provides empirical evidence that the STEM-DLS effectively enhances students' mathematical creativity and self-directed learning. Quantitative results indicated that students in the experimental group achieved a higher N-Gain (⟨g⟩ = 0.554, moderate) than those in the control group (⟨g⟩ = 0.223, low), confirming the pedagogical value of the intervention. However, this effectiveness was not uniform across contexts; it varied according to students' ICT access, with 58.3% lacking stable internet and 25% relying on low-specification devices, and teachers' implementation fidelity. Consistent with previous findings (Li et al., 2020; Rawal, 2024), meaningful learning gains were observed primarily in classrooms where sufficient ICT support was available and teachers implemented the learning modules with high fidelity (Cheon et al., 2020; Elmabaredy & Gencel, 2024). Thus, in resource-limited school contexts, the success of STEM-DLS is determined not only by technological infrastructure but also by instructional quality and equitable access.

The context-dependent effectiveness of the STEM-DLS was evident in the interaction between connectivity and teacher fidelity. Students with stable internet access achieved greater gains in creative mathematical thinking (N-Gain = 0.554) than those facing limited access (N-Gain = 0.223), where offline adaptations-maintained participation but constrained the depth of exploration (Li & Yu, 2022; Rawal, 2024). Teacher fidelity further moderated outcomes: high fidelity supported coherent scaffolding and integration across STEM domains, whereas low fidelity led to fragmented learning trajectories, consistent with the significant interaction effects observed between learning model × autonomy and learning model × creative thinking (Cheon et al., 2020). These findings substantiate that the success of digital learning environments hinges on the dual provision of technological readiness and pedagogical consistency, echoing Suherman and Vidákovich's (2022) argument that authentic mathematical creativity emerges only when both dimensions are adequately supported. Consequently, the effects observed in this study are context-specific rather than universally generalizable.

Stratified analyses further illuminated this context dependence. The strongest effects were found among student groups and schools characterized by both adequate ICT infrastructure and high instructional fidelity (d = 0.72, 95% CI [0.41, 1.03]), whereas institutions constrained by unstable connectivity and low-spec devices achieved smaller gains (d = 0.29, 95% CI [0.05, 0.52]). These results align with prior evidence reporting moderate effects in urban contexts (d = 0.55) and weaker outcomes in rural ICT-limited environments (d = 0.32) (Al-Said et al., 2023; Yuliardi et al., 2024). Within the present study, these disparities can be traced to challenges identified in the Define stage—namely, students limited digital literacy (72.2% proficient only in basic applications) and infrastructural barriers (58.3% without stable internet, 25% using low-performance devices). When combined with variations in teacher fidelity, these factors explain why higher outcomes emerged among subgroups with stronger access and consistent scaffolding, while others showed only incremental progress. This evidence reinforces that STEM-DLS effectiveness cannot be generalized uniformly; rather, it reflects the interactive influence of digital access and instructional quality in shaping learning outcomes in resource-constrained schools.

Three principal contributions emerge from this study. First, it identifies the moderating role of digital connectivity in determining the success of STEM-DLS, corroborating evidence that infrastructural readiness remains a decisive factor in digital learning outcomes (Li & Yu, 2022; Rawal, 2024). Second, it presents stratified evidence based on ICT access and teacher fidelity, offering a nuanced, equity-oriented understanding that extends beyond mean effects, an approach increasingly emphasized in contemporary STEM education research (Al-Said et al., 2023; Chai et al., 2020). Third, the study operationalizes implementation fidelity as a quantifiable construct across multiple dimensions, producing a practical framework for monitoring fidelity that is feasible in low-resource contexts (Cheon et al., 2020; Fontaine et al., 2020).

These contributions, however, should be interpreted within the study's contextual boundaries, namely, secondary schools characterized by limited infrastructure and heterogeneous teacher readiness, and not generalized to all educational settings. From a practical standpoint, the findings highlight the importance of contextualized implementation strategies, including fidelity monitoring, short-cycle coaching, and integration of STEM-DLS within teachers' professional portfolios to maintain instructional quality (Cezar et al., 2019; Revina et al., 2023).

Several limitations warrant consideration. The quasi-experimental design and the use of motivated partner schools may introduce selection bias and Hawthorne effects. Although inter-rater reliability was high, potential measurement bias and participant attrition cannot be fully ruled out. To strengthen causal inference, future studies should employ cluster-randomized controlled trials and longitudinal follow-ups spanning 6–12 months to examine sustainability. Furthermore, stratified analyses should be extended to include socio-economic variables and broader equity indicators to deepen understanding of how STEM-DLS can be adapted across diverse educational contexts.

The dissemination phase provided preliminary evidence of the model's scalability within the research setting. Forty-two teachers participated in professional training sessions, achieving a replication readiness rate of 78.6%, and six non-research schools voluntarily adopted the platform. While these results suggest positive reception, they remain descriptive and context-bound, as readiness levels may reflect the self-selection of digitally literate and motivated teachers (Rawal, 2024; Revina et al., 2023). Accordingly, claims regarding scalability should be interpreted with caution. The principal contribution of this phase lies in demonstrating that voluntary adoption beyond research sites is achievable when supported by targeted professional development and peer mentoring, consistent with previous findings that teacher readiness and continuous coaching are critical for the sustained success of digital innovations (Cezar et al., 2019; Cheon et al., 2020).

Within the scope of this study, STEM-DLS demonstrates promising adaptability and pedagogical efficacy at the micro level of participating schools. Nevertheless, longitudinal, multi-site investigations are necessary to validate its effectiveness under more varied conditions, particularly within schools characterized by low digital literacy, infrastructural limitations, and uneven teacher preparedness.

CONCLUSION

The STEM-DLS, developed through the 4D model, has demonstrated measurable effectiveness in enhancing students' creative mathematical thinking and self-directed learning, particularly among learners with sufficient ICT access and teachers maintaining high implementation fidelity. These outcomes directly address the study's research objectives, confirming that STEM-DLS is pedagogically valid, practically applicable, and capable of promoting both learner autonomy and mathematical creativity. In practical terms, STEM-DLS functions as a semi-offline interactive platform that integrates contextualized STEM content, project-based learning, and digital scaffolding to cultivate 4C competencies (critical thinking, creativity, collaboration, and communication) and learner independence. Methodologically, this study contributes by introducing a five-dimensional fidelity index and employing stratified multilevel analyses, offering a robust framework to monitor implementation consistency and to capture the heterogeneity of learning effects across varying contexts.

Despite these promising findings, several limitations warrant acknowledgment. The quasi-experimental design and purposive sampling of supportive partner schools constrain the generalizability of results to broader educational settings. Moreover, ICT constraints—with 58.3% of students lacking stable internet connections and 25% relying on low-specification devices—moderated the intervention's impact. Variations in teacher fidelity across classrooms introduced potential implementation bias, even though the fidelity index was employed to track consistency. The short intervention duration (one semester) also limited the ability to assess long-term sustainability of learning outcomes. Additionally, contextual factors such as socioeconomic disparities and cultural alignment were not fully examined, which may influence both implementation quality and student engagement.

The study's policy implications underscore the urgency of advancing digital equity initiatives, including subsidized data access, affordable device provision, and infrastructure enhancement to support large-scale implementation. Furthermore, differentiated teacher professional development and continuous instructional support systems are essential to sustain effective integration of STEM-DLS.

Future research should extend these findings by employing cluster-randomized or stepped-wedge designs, conducting longitudinal investigations (≥6–12 months), and incorporating cost-effectiveness analyses to examine the scalability and sustainability of the intervention. Particular attention should be given to how connectivity, teacher fidelity, and contextual factors moderate learning outcomes, as well as to exploring interdisciplinary integration and authentic problem-solving within digital environments. Utilizing standardized and validated instruments—such as creative thinking rubrics, self-directed learning scales, and learning management system (LMS) analytics—alongside open science practices, future studies can further substantiate the robustness and replicability of findings. Finally, STEM-DLS exhibits strong potential as an adaptive, inclusive, and scalable educational innovation that bridges persistent gaps in digital literacy, learner autonomy, and equitable access within STEM education. The findings fulfill the study's aims of establishing the validity, effectiveness, and distinctive design characteristics of the model, while contributing to ongoing efforts to design sustainable and equity-oriented digital learning systems in mathematics education.

Acknowledgments

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 through the Beginner Lecturer Research Grant (*Hibah Penelitian Dosen Pemula*), fiscal year 2025, under contract number 8031/LL4/PG/2025, 29/E-5/UNILAM/2025. The authors would also like to express their sincere gratitude to the Institute for Research and Community Service (LPPM) of Universitas La Tansa Mashiro for its support in facilitating and assisting the funding process of this research.

Declarations

Author Contribution	:	DYA: Conceptualization, Methodology, Writing – Original Draft, Editing, Visualization, and Supervision. EAJ: Formal Analysis, Writing – Review & Editing, Supervision.
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 through the Beginner Lecturer Research Grant (*Hibah Penelitian Dosen Pemula*), fiscal year 2025, under contract number 8031/LL4/PG/2025, 29/E-

5/UNILAM/2025.

Conflict of Interest : The authors declare no conflict of interest.

Additional Information : Additional information is available for this paper.

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Appendix A

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

Appendix B

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**

Appendix C

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

Appendix D

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

Autonomy Level	Indicators Autonomy	Boys			Girls		
		Before	After	$t_{emp.}$	Before	After	$t_{emp.}$
	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
	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

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	Sign. (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