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DEVELOPING A STEM-BASED PYTHAGOREAN CUP MODEL TO FOSTER MATHEMATICAL AND CREATIVE THINKING DISPOSITIONS

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Abstract

This study aims to develop a STEM-based learning model utilizing the Pythagorean Cup to effectively enhance elementary students' creative thinking skills and mathematical dispositions. The central issue addressed is the weak integration of cognitive and affective aspects in mathematics learning, which remains predominantly procedural and lacking in contextual relevance. A Research and Development (R&D) approach employing a 4D design model (Define–Design–Develop–Disseminate) was used to design and test the learning model. Data were collected through observations, questionnaires, tests, and interviews involving 80 fifth-grade students from three elementary schools in Banten Province, Indonesia. Validation results confirmed strong content and construct validity. Practicality testing indicated the model was highly feasible for both teachers and students. Effectiveness analysis using a quasi-experimental design revealed statistically significant improvements across all indicators of creative thinking (fluency, flexibility, elaboration, originality) and mathematical disposition (curiosity, perseverance, confidence, risk-taking), with p-values < 0.05. The integration of the historically scientific artifact, the Pythagorean Cup, into instruction proved to foster meaningful inquiry, experimentation, and reflection-based learning experiences. These findings highlight the potential of a contextually designed, manipulative-based STEM learning model to simultaneously cultivate students' cognitive competencies and dispositional character, both essential for 21st-century education success.

Keywords: Creative Thinking; Mathematical Disposition; STEM; Pythagorean Cup; Elementary School.

Abstrak

Penelitian ini bertujuan untuk mengembangkan model pembelajaran STEM berbasis Pythagorean Cup yang efektif dalam meningkatkan kemampuan berpikir kreatif dan disposisi matematis siswa sekolah dasar. Permasalahan utama yang diangkat adalah lemahnya integrasi aspek kognitif dan afektif dalam pembelajaran matematika, yang selama ini cenderung prosedural dan kurang kontekstual. Pendekatan Research and Development (R&D) dengan desain 4D (Define–Design–Develop–Disseminate) digunakan untuk merancang dan menguji model pembelajaran, dengan data dikumpulkan melalui observasi, angket, tes, dan wawancara pada 80 siswa kelas V di tiga sekolah dasar di Provinsi Banten. Hasil validasi menunjukkan bahwa model ini sangat valid secara isi dan konstruk. Uji kepraktisan mengindikasikan bahwa model dinilai sangat layak diterapkan oleh guru dan siswa. Analisis efektivitas menggunakan desain kuasi-eksperimen menunjukkan peningkatan signifikan pada semua indikator kemampuan berpikir kreatif (fluency, flexibility, elaboration, originality) dan disposisi matematis (curiosity, perseverance, confidence, risk-taking), dengan nilai signifikansi p < 0,05. Integrasi artefak ilmiah-historis Pythagorean Cup dalam pembelajaran terbukti mampu memfasilitasi pengalaman belajar berbasis inkuiri, eksperimen, dan refleksi yang bermakna. Temuan ini menegaskan bahwa model pembelajaran STEM yang dirancang secara kontekstual dan berbasis alat manipulatif dapat secara simultan membangun kompetensi kognitif dan karakter disposisional yang krusial bagi keberhasilan pendidikan abad ke-21.

***Kata kunci**: Berpikir Kreatif; Disposisi Matematis; STEM; Pythagorean Cup; Sekolah Dasar.*

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INTRODUCTION

Creativity is widely recognized as a critical 21st-century skill essential for addressing complex global challenges in education (Ramírez-Montoya et al., 2022; Thornhill-Miller et al., 2023). Research indicates that the implementation of curricula emphasizing 21st-century skills can significantly enhance students' creative thinking abilities (Dilekçi & Karatay, 2023). These competencies, commonly referred to as the "4Cs": creativity, critical thinking, communication, and collaboration, are considered vital for future careers and educational success (Thornhill-Miller et al., 2023). In the context of mathematics education, creativity plays a pivotal role in enabling students to identify core problems, connect various elements of a problem, and explore diverse and innovative solution strategies (Schindler & Lilienthal, 2022; Utemov et al., 2020; Vink, 2022; Yulianto et al., 2024).

Recent empirical studies have demonstrated that mathematical creativity significantly contributes to the development of higher-order thinking skills, particularly in solving non-routine and open-ended mathematical problems, where students are required to generate multiple and original solution strategies (Vu et al., 2022). In classroom-based interventions, the use of open-ended and exploratory tasks has been shown to improve students' cognitive flexibility, fluency, and originality, which are key indicators of mathematical creative thinking (Bevan & Capraro, 2021; Shaw, 2022).

In addition, several recent studies have reported that STEM-based instructional approaches can enhance students' problem-solving abilities and conceptual understanding through interdisciplinary and inquiry-driven learning experiences (Aizikovitsh-Udi & Cheng, 2015; Elgrably, 2021). However, these studies predominantly focus on cognitive outcomes, with limited attention to how such approaches influence students' mathematical creativity and, more importantly, their creative dispositions and metacognitive engagement.

Furthermore, existing research tends to utilize general STEM activities without integrating contextual or artifact-based learning media that can bridge abstract mathematical concepts with real-world phenomena. As a result, the potential of concrete and inquiry-based tools in fostering both cognitive and affective dimensions of learning remains underexplored. Despite these advancements, classroom practices at the elementary level still largely emphasize procedural instruction and rote memorization, with limited opportunities for students to engage in creative and reflective mathematical thinking processes (Andrade et al., 2020; Yulianto et al., 2024). This indicates a critical gap between research-based instructional innovations and actual classroom implementation, which may hinder the optimal development of students' mathematical creativity and dispositions. To address this issue, this study proposes developing a STEM-based instructional model that integrates the Pythagorean Cup as a contextual, inquiry-based learning medium. This approach is expected to provide a meaningful learning experience that bridges abstract mathematical concepts with real-world phenomena, while simultaneously fostering students' creative thinking and metacognitive awareness.

Creativity in mathematics encompasses not only the ability to generate diverse and valuable solutions but is also characterized by risk-taking,

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curiosity, a passion for challenges, and a reflective capacity regarding the thinking process (Fiori et al., 2022; Rabi & Masran, 2016). These attributes constitute what is known as creative disposition, a behavioral tendency that supports the development of mathematical creative thinking (Setiyani et al., 2022). Accordingly, strengthening this dispositional dimension is essential in fostering students' cognitive creativity.

Several studies concur that mathematical creativity emerges through the interaction between creative thinking abilities and a positive disposition toward learning mathematics (Aizikovitsh-Udi & Cheng, 2015; Elgrably, 2021). Four core indicators of mathematical creative thinking fluency, flexibility, elaboration, and originality are widely recognized in the literature and have been used as foundational elements in the development of assessment instruments and instructional design (Bulut et al., 2022; Grégoire, 2016; Tan et al., 2021).

Unfortunately, most research on creativity-based mathematics learning at the elementary school level remains predominantly focused on cognitive aspects, with limited attention to the integration of affective components such as students' dispositions and metacognitive regulation (Yulianto et al., 2025). Yet, the success of mathematics education does not solely rely on conceptual mastery but also on students' readiness to think critically and reflectively when faced with complex and unstructured mathematical problems.

Despite the increasing emphasis on 21st-century skills, global evidence indicates that students' mathematical creative thinking and dispositions remain underdeveloped, as mathematics instruction continues to be dominated by procedural approaches that limit opportunities for exploration, originality, and reflective thinking (Thornhill-Miller et al., 2023; Vu et al., 2022). This issue is also evident in elementary education contexts, where learning practices tend to prioritize routine problem solving and single-answer tasks, thereby restricting the development of students' creativity and positive dispositions toward mathematics (Andrade et al., 2020; Yulianto et al., 2024).

The limited integration of cognitive and affective dimensions in mathematics learning highlights a critical problem, as students are not only expected to master concepts but also to demonstrate creative engagement, curiosity, and persistence in solving complex problems (Fiori et al., 2022; Setiyani et al., 2022; Vu et al., 2022). Consequently, there is a pressing need to design instructional approaches that can simultaneously foster mathematical creative thinking and students' creative dispositions as key outcomes of mathematics education.

To address this challenge, the STEM (Science, Technology, Engineering, and Mathematics) approach has emerged as a strategic alternative increasingly adopted in many countries to enhance scientific and mathematical literacy from the early years of formal education (Aguilera & Ortiz-Revilla, 2021; Ilyas et al., 2022). STEM-based instructional models are designed to integrate interdisciplinary concepts and promote active student engagement through contextual learning, experimentation, engineering design, and real-world problem solving, which are essential for developing both cognitive and dispositional aspects of creativity (Li, 2020).

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Recent studies have demonstrated that STEM-based learning significantly enhances students' conceptual understanding and problem-solving skills, particularly through interdisciplinary and inquiry-based approaches (Sahito & Wassan, 2024; Terzieva et al., 2024). However, these studies predominantly focus on cognitive outcomes, with limited attention to the development of mathematical creativity and students' metacognitive and dispositional dimensions, especially at the elementary education level. Furthermore, existing research tends to employ conventional STEM implementations without integrating culturally or historically meaningful scientific artifacts as contextual learning tools.

This indicates a critical research gap in the integration of cognitive and affective domains within STEM-based mathematics learning. In particular, there is a lack of empirically validated instructional models that simultaneously foster mathematical creative thinking and creative dispositions through concrete, inquiry-driven experiences. Moreover, the potential of scientific-historical artifacts, such as the Pythagorean Cup, remains underexplored in mathematics education, despite its strong relevance for illustrating interdisciplinary concepts involving mathematics, physics, and engineering principles.

The Pythagorean Cup is a scientific-historical artifact that operates on the principles of fluid pressure and the communicating vessels law, making it useful for illustrating physics and mathematics concepts such as ratio, volume, and fluid dynamics. When applied in a STEM education context, this medium offers students meaningful opportunities to explore mathematical ideas in concrete, reflective, and inquiry-based ways (Rehman et al., 2025). However, to date, no empirical studies have been conducted to develop and evaluate the effectiveness of a STEM-based instructional model that incorporates the Pythagorean Cup in elementary school settings.

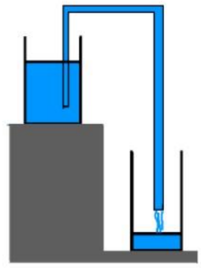

Figure 1. Pythagorean Cup

Therefore, this study aims to: (1) develop a theoretically and empirically validated STEM-based Pythagorean Cup learning model; (2) examine its practicality and effectiveness in fostering elementary students' mathematical creative thinking; and (3) analyze its impact on students' creative dispositions and metacognitive engagement. The novelty of this study lies in the integration of a scientific-historical artifact within a STEM framework to simultaneously develop cognitive and affective competencies through a design-based research approach.

METHODS

This study employed a Research and Development (R&D) approach using a mixed-methods design that integrated both qualitative and quantitative procedures (Smajic et al., 2022; Tovin & Wormley, 2023). This methodological approach offers flexibility, rapid data insights, and reflective potential for both researchers and participants (Manni & Löfgren, 2024). A STEM-based instructional model incorporating the *Pythagorean*

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Cup was developed through actual R&D stages, while its effectiveness was tested using a quasi-experimental design of the Non-Equivalent Control Group type. The combination of methodologies aligns with the principle that triangulated methods can enhance validity and minimize methodological artifacts (Tovin & Wormley, 2023).

Research Design

This study adopted the 4D development model, comprising the stages of Define, Design, Develop, and Disseminate (see Figure 2):

1. Define: Curriculum analysis, a literature review on STEM and thinking dispositions, and a needs analysis were conducted through classroom observations and teacher interviews at partner elementary schools.
2. Design: An initial prototype of a STEM learning device was designed, integrating the working principle of the *Pythagorean Cup* to represent fluid pressure within a simple engineering context. Dispositional indicators were translated into rubrics and theoretically validated.
3. Develop: Content validation was conducted by three experts (in STEM and educational psychology), followed by a limited trial at SDN 1 Citorek Tengah, Rangkasbitung City, Banten Province, involving fifth-grade students to assess practicality, student responses, and preliminary impacts on creative and mathematical thinking skills.
4. Disseminate: A large-scale trial was conducted at SDN 1 Rangkasbitung and SDN 1 Pandeglang to evaluate the model's practicality and effectiveness across varied learning contexts.

Subjects and Location

This study was conducted during the even semester of the 2023/2024 academic year, specifically between February and April 2024, at SDN 1 Citorek Tengah, located in Rangkasbitung City, Banten Province. The research involved 80 fifth-grade students selected purposively based on three main criteria: (1) the teacher's readiness to implement STEM-based instruction, (2) administrative support from the school, and (3) the availability of adequate classroom infrastructure. The study was conducted with formal approval from the school principal and written consent from the students' parents, following ethical standards for educational research.

The participants were distributed across different phases of the study as follows: 16 students (8 boys and 8 girls) from SDN 1 Citorek Tengah served as the experimental group in the small-scale pilot test for initial validation and practicality; 32 students from SDN 1 Rangkasbitung (14 boys and 18 girls) constituted the experimental group in the model effectiveness test; and 32 students from SDN 1 Pandeglang (13 boys and 19 girls) served as the control group receiving conventional instruction.

Effectiveness Test Design

The effectiveness of the model was evaluated using a quasi-experimental design involving pre-test and post-test procedures in both the experimental and control groups over ten weeks. The pre-tests were administered in the first week to both groups, as illustrated in Figure 3. Before the intervention, both groups received a briefing outlining the general and specific learning objectives. During the subsequent eight weeks, two

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different instructional models were implemented: the experimental group received instruction using the STEM–Pythagorean Cup model, while the control group followed a conventional teacher-centered approach. In the final week (week ten), post-tests were conducted to assess students' learning outcomes, metacognitive abilities, and critical thinking skills.

Research Instruments and Data Collection

Four types of instruments were developed based on theoretical reviews and expert consultation:

1. Student Activity Observation Sheet: Designed to assess student engagement in STEM-based inquiry activities using the Pythagorean Cup as a learning medium. The indicators include active participation, scientific observation, collaborative discussion, and the application of concepts such as volume and fluid pressure.
2. Mathematical Disposition Question-naire: Developed based on indicators from the National Research Council (Yulianto et al., 2025), encompassing six dimensions: curiosity, perseve-rance, flexibility, reflection, beliefs about the value of mathematics, and mathematical self-confidence. It consists of 24 Likert-scale items (4-point scale).
3. Mathematical Creative Thinking Test: Adapted from the Guilford and Torrance framework, this test mea-sures four dimensions: fluency, flexi-bility, elaboration, and originality through five contextual open-ended questions based on the Pythagorean Cup phenomenon.
4. Semi-Structured Interview Guide: Used for triangulation purposes to explore students' learning experien-ces, perceptions of STEM-based instruction, and reflections on their cognitive development and mathematical dispositions.

All instruments were validated by two mathematics education experts and one educational assessment specialist using Aiken's V method, yielding an average V coefficient of 0.89, indicating high validity. Revisions were made based on expert feedback, and preliminary trials produced Cronbach's Alpha reliability coefficients of 0.86 for the mathematical disposition question-naire and 0.82 for the mathematical creative thinking test.

Data Analysis Techniques

Quantitative data were analyzed using descriptive statistics (mean and standard deviation) and the Wilcoxon Signed-Rank Test, as the Shapiro-Wilk test indicated that the data were not normally distributed ($p < 0.05$). The Wilcoxon test was employed to compare the differences between pretest and posttest scores on indicators of mathematical disposition and creative mathematical thinking skills. Qualita-tive data were analyzed thematically through a process of open coding, categorization, and theme identification applied to interview transcripts and observational field notes.

This analysis was conducted inductively to explore students' res-ponses to the implementation of the STEM-Pythagorean Cup-based learning model. The process involved two independent researchers and included inter-coder reliability checks. To enhance the validity of the findings, methodological triangulation was con-ducted by comparing questionnaire results, observation data, and interview responses. Any discrepancies between data sources were critically examined to arrive at a more comprehensive and contextually grounded interpretation.

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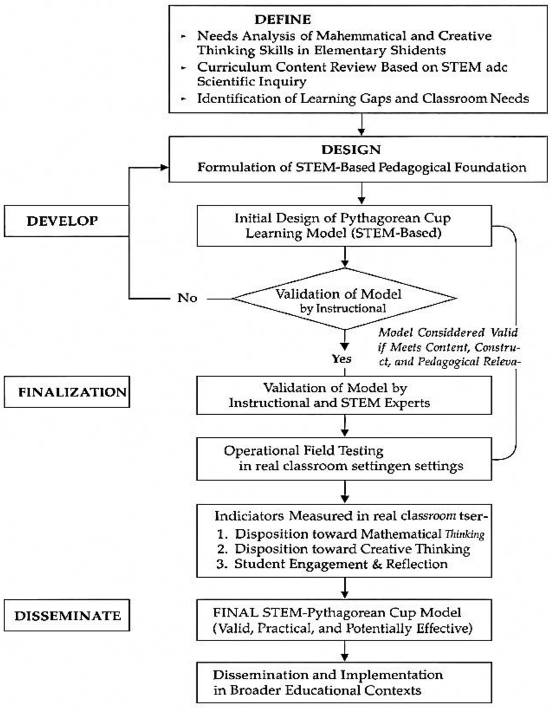

Figure 2. Development Model

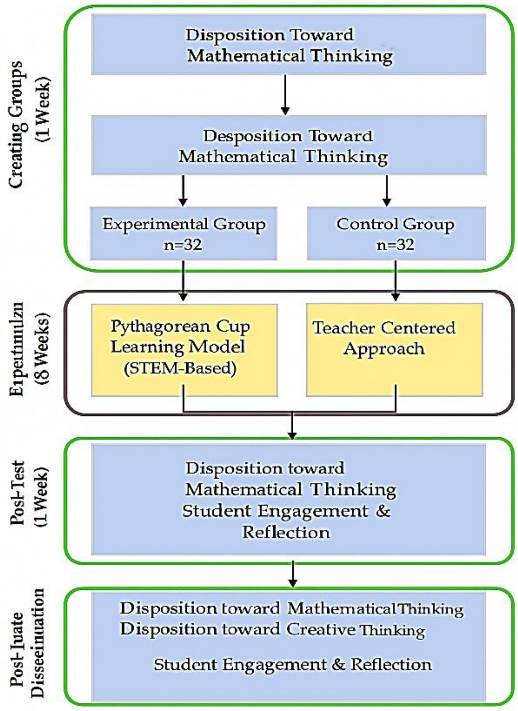

Figure 3. Experimental Design

RESULTS AND DISCUSSION

This section presents the results of the development and implementation of a STEM-based learning model utilizing the Pythagorean Cup to enhance elementary students' mathematical thinking dispositions and critical thinking skills. The evaluation focused on both cognitive and dispositional indicators. Mathematical disposition included perseverance, curiosity, risk-taking, and reflection (Rabi & Masran, 2016), while critical thinking was assessed using the CCTST framework (Facione, 2020), encompassing five dimensions: analysis, evaluation, inference, deductive reasoning, and inductive reasoning.

The findings revealed a significant increase in students' enthusiasm, willingness to explore ideas, and analytical abilities throughout the intervention. These outcomes indicate the model's effectiveness in concretely integrating science and mathematics. Beyond improving cognitive domains, the model also fostered positive attitudes and long-term learning motivation through active, contextual, and interdisciplinary instruction.

A preliminary study was conducted to identify the key challenges in elementary mathematics education, particularly regarding the limited student engagement in creative exploration, critical reasoning, and metacognitive reflection. Initial findings highlighted a persistent gap in students' dispositions toward mathematical and critical thinking, especially within learning environments dominated by procedural instruction and single-answer tasks. These insights formed the foundation for designing a learning model that integrates STEM principles with the Pythagorean Cup as a contextual and meaningful manipulative tool.

The development of the STEM-Based Pythagorean Cup model followed the 4D framework. The initial needs analysis and problem identification

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revealed that students lacked meaningful learning experiences that could foster sustained curiosity, critical inquiry, and interdisciplinary conceptual integration. The Design phase focused on integrating STEM elements into a coherent instructional sequence through physical exploration, mathematical modeling, and reflective engagement with the working mechanism of the Pythagorean Cup, grounded in principles of fluid dynamics, geometry, and causal relationships.

In the Develop phase, the model syntax was structured into eight sequential steps: 1) Observing the Pythagorean Cup phenomenon; 2) Identifying and formulating mathematical-physical problems; 3) Proposing hypotheses and alternative solutions; 4) Designing investigative strategies (e.g., measurement, estimation, comparison); 5) Constructing mathematical models from real-world representations; 6) Executing STEM-based tasks (experiments, simulations); 7) Engaging in critical reflection through guided questions and metacognitive prompts; and 8) Presenting and evaluating findings collaboratively.

The model is supported by a set of instructional components, including a teacher's guide, student STEM modules, manipulative tools, and disposition-based assessment instruments. The learning's social system encourages active student collaboration, the development of mathematical discourse, and peer-driven inquiry. The observed impacts extend beyond cognitive outcomes to include affective domains such as engagement, perseverance, and curiosity and dispositional traits such as risk-taking, reflective thinking, and critical questioning.

Quantitative and qualitative validations confirmed that the model is valid, practical, and effective. Statistical tests demonstrated significant improvements in students' mathematical and critical thinking dispositions, particularly in dimensions of flexibility, originality, reflective thinking, and evaluative judgment. Effectiveness testing using a pretest–posttest design further confirmed that the STEM-Based Pythagorean Cup model produced statistically significant gains ($p < 0.05$) in fostering higher-order thinking tendencies and learning engagement among elementary school students.

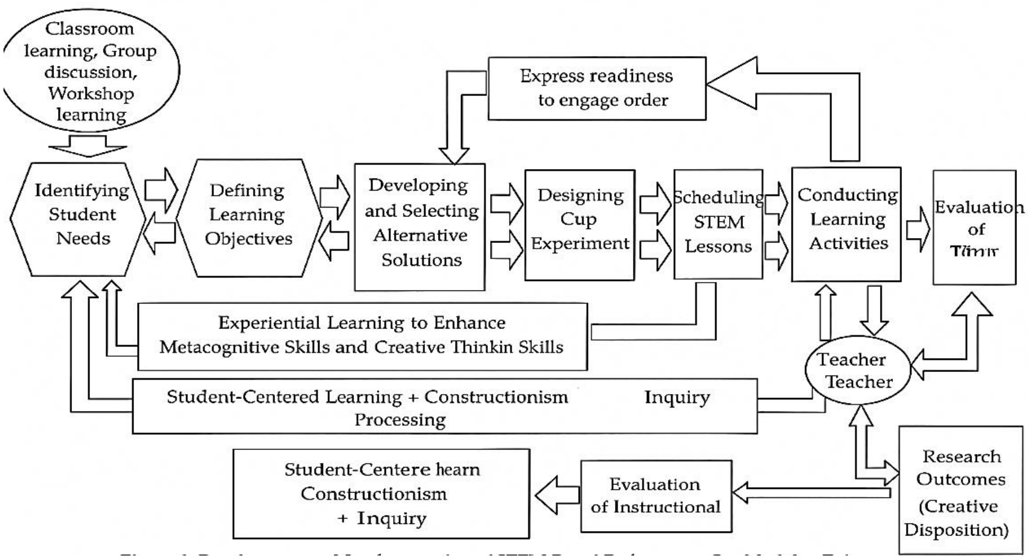

Figure 4. Development and Implementation of the STEM-Based Pythagorean Cup Model

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Validity of the Learning Model

The construct validity assessment of the STEM-based learning model utilizing the *Pythagorean Cup* is presented in Table 1. This model was developed to foster mathematical thinking dispositions and creativity among elementary school students through contextual learning grounded in simple experimental activities. The validation instruments comprised four types of measurement tools, all designed based on theoretical foundations and reviewed by two mathematics education experts and one educational evaluation specialist. The validation process aimed to evaluate the alignment of the model's syntax, the integration of STEM components, the coherence between learning objectives and the characteristics of elementary students, as well as the targeted dispositional relevance.

Table 1. Validation Results for STEM-Based Pythagorean Cup Model Syntax

Syntax Construct	**χ^2**	**p**	**RMSEA**	**χ^2/df**	**Fit Criteria**
Identifying Mathematical Challenges	16.33	0.127	0.048	0.892	Valid / Fit
Understanding STEM Concepts	3.27	0.342	0.000	0.429	Valid / Fit
Designing Solution Strategies	10.21	0.725	0.093	1.332	Valid / Fit
Planning Experiments	20.12	0.169	0.049	1.511	Valid / Fit
Structuring Tasks and Roles	14.65	0.309	0.045	1.176	Valid / Fit
Organizing Experiment Schedule	12.91	0.238	0.000	0.782	Valid / Fit
Conducting the STEM Activity	10.27	0.365	0.042	0.871	Valid / Fit
Reflecting and Quality Monitoring	21.53	0.075	0.041	1.024	Valid / Fit
Assessing Disposition (Curiosity, Risk-taking, etc.)	17.21	0.098	0.025	1.074	Valid / Fit
Overall Model Fit	**13.87**	**0.813**	**0.000**	**1.145**	**Valid / Fit**

Construct validity of the STEM-based Pythagorean Cup instructional model was tested using Confirmatory Factor Analysis (CFA) with LISREL to verify whether the proposed nine-phase syntax matched the theoretical frame-work of STEM integration, inquiry learning, and the development of mathematical creativity and disposition. The results showed a Chi-Square (χ^2) value of 13.87 with $p = 0.813$, indicating no significant difference between the theoretical and empirical models, thus confirming good model fit.

This result was strengthened by other fit indices. The RMSEA value of 0.000 indicates negligible residual error, while the χ^2/df ratio of 1.145 (below the threshold of 2.00) confirms a parsimonious and stable structure. These findings suggest that the nine learning phases operate as an integrated instructional system rather than separate procedural steps.

Each syntax component also showed acceptable loading values, meaning that every phase contributed meaningfully to the construct. Early phases, such as *Identifying Mathematical Challenges* and *Understanding STEM Concepts,* activate prior knowledge and contextual reasoning. Middle phases, such as *Designing Solution Strategies* and *Planning Experiments*, promote engineering thinking and problem-solving. Final phases, such as *Reflecting and Quality Monitoring*, and *Assessing Disposition*, strengthen metacognitive awareness and affective development. This coherent sequence likely supports stronger learning transfer and engagement.

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The strong construct validity also helps explain the significant improvement in students' mathematical creative thinking and disposition. A well-structured model provides clearer learning flow, better cognitive scaffolding, and stronger alignment between activities, objectives, and assessment. Therefore, the positive outcomes found in this study are logically linked to the sound internal structure of the validated model.

All syntax elements demonstrated factor loadings above 0.50 and inter-indicator correlations exceeding 0.30, suggesting substantial contributions to the underlying construct. Overall, these findings affirm that the developed instructional model possesses strong construct validity.

Model Practicality

The practicality of the model was assessed using an evaluation instrument comprising ten key indicators, including clarity of instructions, relevance of syntax, content-method alignment, time efficiency, physical design, as well as perceived usefulness and language clarity. The instrument was administered to both teachers and students during the implementation phase.

The results indicated that the model was considered highly practical. Teachers reported that the learning flow was systematic and supported inquiry-based and problem-solving approaches. The Pythagorean Cup effectively contextualized abstract concepts such as pressure and volume into concrete learning activities. Meanwhile, students perceived the language as easy to understand, the activities as enjoyable, and the learning environment as conducive to active exploration. Overall, the model was deemed operationally feasible and well-received by both teachers and students. The integration of STEM into Pythagorean Cup-based activities successfully stimulated students' curiosity, reflective thinking, and creativity in primary mathematics learning.

Table 2. Summary of Practicality Test Results

Indicator	Teacher	Student	Avg.	Achievement	Category
Clarity of Instructions	4.52	4.59	4.56	91.10%	Very Practical
Learning Syntax Relevance	4.49	4.61	4.55	91.00%	Very Practical
Content–Method Compatibility	4.53	4.64	4.59	91.70%	Very Practical
Time Efficiency	4.47	4.60	4.54	90.90%	Very Practical
Visual Design & Layout	4.67	4.39	4.53	91.00%	Very Practical
Language Clarity	4.60	4.58	4.59	91.80%	Very Practical
Implementation Feasibility	4.55	4.57	4.56	91.20%	Very Practical
Engagement & Enjoyment	4.51	4.66	4.59	91.60%	Very Practical
Usefulness & Benefits	4.62	4.65	4.64	92.70%	Very Practical
STEM Integration & Model Coherence	4.50	4.63	4.57	91.30%	Very Practical

Note: Scores are based on a 1–5 Likert scale; 4.20–5.00 = Very Practical.

The practicality test results indicate that the STEM-based Pythagorean Cup learning model was perceived as highly practical by both teachers and students across all indicators. Mean scores ranged from 4.53 to 4.64, with achievement levels between 90.90% and 92.70%, placing all aspects within the "Very Practical" category. This consistent pattern

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suggests that the model was positively received not only in terms of user satisfaction but also in terms of classroom feasibility and instructional usability.

From the teachers' perspective, the highest score was obtained by Visual Design and Layout (M = 4.67). This finding suggests that teachers particularly valued the structured and visually accessible format of the learning materials. In elementary STEM settings, clear layouts and organized visual guidance are important because they reduce preparation time, support classroom management, and help teachers coordinate multi-step inquiry activities more efficiently.

From the students' perspective, the highest score was reported for Engagement and Enjoyment (M = 4.66). This indicates that the learning activities were experienced as enjoyable and motivating. The use of the Pythagorean Cup as a contextual manipulative likely contributed to this outcome by transforming abstract mathematical concepts into observable and interactive experiences. Such novelty and hands-on exploration can stimulate curiosity, sustain attention, and increase willingness to participate actively.

At the aggregate level, Usefulness and Benefits received the highest combined average score (M = 4.64; 92.70%), indicating that both teachers and students perceived clear instructional value in the model. This suggests that the intervention was not merely interesting but was also considered meaningful for supporting conceptual understanding, collaboration, and problem-solving processes.

Other indicators, including clarity of instructions, time efficiency, implementation feasibility, and STEM integration, also received consistently high ratings. These findings imply that the model was manageable within normal classroom constraints and that its interdisciplinary components were experienced as coherent rather than fragmented. This is particularly relevant because implementation complexity is often reported as a major barrier in STEM education.

Taken together, these results provide strong evidence that the STEM-based Pythagorean Cup model possesses high practical validity. Its usability, relevance, and positive reception indicate substantial potential for broader classroom adoption, especially in elementary contexts that require engaging, structured, and exploratory learning experiences.

To evaluate the effectiveness of the STEM-based Pythagorean Cup learning model on students' mathematical creative thinking skills (MCTS) and mathematical disposition (MD), pretest and posttest assessments were conducted for both the control and experimental groups. This measurement aimed to determine changes in student achievement before and after the implementation of the instructional intervention (see Table 3).

Table 3. Pretest and Posttest Results of MCTS and MD

Descriptive Statistics	**MCTS - Control**		**MCTS - Experimental**		**DM - Control**		**DM - Experimental**	
	Pre-test	**Post-test**	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**
Number of Students	32	32	32	32	32	32	32	32
Mean	53.75	75.87	51.30	87.73	52.00	71.25	50.20	85.40

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Descriptive Statistics	MCTS - Control		MCTS - Experimental		DM - Control		DM - Experimental	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Median	54.00	65.00	53.00	81.00	53.00	68.00	51.00	83.00
5% Trimmed Mean	52.77	62.63	52.40	81.86	51.75	66.40	50.60	84.20
Standard Deviation	9.18	9.44	7.10	7.23	8.95	8.33	6.85	6.71
Variance	84.28	89.20	50.37	52.32	80.10	69.42	46.92	45.02
Range	35.00	30.00	25.50	26.00	32.00	28.00	23.00	25.00
Interquartile Range	8.88	16.00	10.62	10.88	9.10	14.00	8.20	9.50
Minimum	35.50	59.00	37.50	72.00	34.00	55.00	36.00	70.00
Maximum	69.80	89.00	63.00	98.00	66.00	83.00	59.00	95.00
Skewness	-0.42	-0.04	-0.13	0.22	-0.31	-0.08	-0.10	0.18

The pre- and post-test results indicate that both mathematical creative thinking skills and mathematical dispositions of students significantly improved following the implementation of the STEM-based Pythagorean Cup model. The average score for mathe-matical creative thinking in the experi-mental group increased from 51.30 to 87.73, substantially higher than the control group, which rose from 53.75 to 75.87. Similarly, the mathematical disposition scores in the experimental group increased from 50.20 to 85.40, while the control group only showed a modest gain from 52.00 to 71.25. Improvements in the median, trimmed mean, and reduced variance within the experimental group further reinforce the stability of the outcomes. In addition, the higher minimum scores and the positive skewness in the experimental group's post-test results indicate enhanced consistency and a shift toward stronger performance across students. These findings affirm that the developed model is effective in fostering higher-order thinking skills and cultivating positive mathematical dispositions more evenly and signifi-cantly than conventional instruction. For a more detailed analysis of the intervention's impact on each indicator of mathematical creative thinking and disposition, refer to Table 4.

Table 4. Pretest–Posttest Results of MCTS and MD

Variables	Indicator	Group	Pretest	Posttest	Improvement
MCTS	Fluency	Control	52.45	68.33	+15.88
		Experimental	51.25	82.76	+31.51
	Flexibility	Control	50.30	66.12	+15.82
		Experimental	48.90	80.45	+31.55
	Elaboration	Control	53.10	69.85	+16.75
		Experimental	50.80	84.10	+33.30
	Originality	Control	51.70	67.40	+15.70
		Experimental	49.50	83.25	+33.75
MD	Curiosity	Control	54.20	69.15	+14.95
		Experimental	52.10	81.60	+29.50
	Perseverance	Control	53.75	68.00	+14.25
		Experimental	51.80	83.45	+31.65

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Variables	Indicator	Group	Pretest	Posttest	Improvement
	Confidence	Control	55.10	70.35	+15.25
		Experimental	53.00	85.10	+32.10
	Risk-taking	Control	52.40	67.25	+14.85
		Experimental	50.70	82.85	+32.15

Table 4 demonstrates that all indicators of mathematical creative thinking skills (fluency, flexibility, elaboration, and originality) and mathematical dispositions (curiosity, perseverance, confidence, and risk-taking) improved substantially after the intervention, with gains in the experimental group consistently exceeding those of the control group. This pattern suggests that the observed improvements were not merely the result of routine instructional exposure, but were strongly associated with the specific pedagogical features of the STEM-based Pythagorean Cup model. In particular, the model required students to engage in iterative cycles of observing phenomena, generating conjectures, testing ideas, revising assumptions, and communicating findings. Such learning processes likely stimulated fluency by encouraging students to produce multiple responses, while flexibility was fostered through exposure to diverse solution pathways during collaborative inquiry and discussion.

The largest gain was found in originality (+33.75 in the experimental group versus +15.70 in the control group), indicating that the intervention was especially effective in promoting novel and non-routine thinking. A plausible explanation is that the Pythagorean Cup presents a counter-intuitive phenomenon liquid suddenly draining when a threshold is exceeded which naturally creates cognitive disequilibrium and curiosity. When students encounter unexpected outcomes, they are more likely to question prior assumptions, seek alternative explanations, and construct uncommon strategies, all of which are central characteristics of originality. By contrast, conventional instruction tends to prioritize fixed procedures and predetermined answers, thereby offering fewer opportunities for divergent reasoning.

Similar trends were identified in the dispositional domain. Confidence and risk-taking increased by more than 32 points in the experimental group, suggesting that the learning environment successfully reduced students’ fear of making mistakes and strengthened their willingness to test uncertain ideas. This can be attributed to the model’s emphasis on experimentation and formative feedback, where errors were treated as part of the investigative process rather than as failure. As a result, students developed stronger self-efficacy and became more willing to defend or revise their reasoning. In addition, the collaborative nature of STEM tasks may have contributed to perseverance, as peer interaction and shared problem-solving often sustain engagement when students encounter difficulty.

From a theoretical perspective, these findings align with constructivist and socio-cultural views of learning, which posit that higher-order thinking develops when learners actively construct meaning through authentic tasks, social negotiation, and reflective practice. The simultaneous growth of cognitive outcomes and dispositions also indicates that creative mathematical performance cannot be separated from affective readiness. Students are more

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likely to generate original and elaborated solutions when they are curious, confident, and willing to take intellectual risks.

Therefore, the evidence from Table 4 supports a stronger interpretation: the STEM-based Pythagorean Cup model did not simply raise test scores, but functioned as a mechanism that integrated conceptual exploration, emotional engagement, and reflective inquiry. This combination appears to explain why the experimental group achieved gains nearly twice those of the control group across most indicators. To confirm the statistical significance of the differences between pretest and posttest scores, a non-parametric Wilcoxon Signed-Rank Test was conducted on the data from the experimental group (see Table 5).

Table 5. Results of the Wilcoxon Signed-Rank Test

Measured Aspect	N	Z-Score	Asymp. Sig. (2-tailed)	Description
MCTS	32	-4.892	0.000	Sign. (p < .05)
MD	32	-4.765	0.000	Sign. (p < .05)

The Wilcoxon Signed-Rank Test results (Table 5) demonstrated statistically significant improvements in both mathematical creative thinking skills (MCTS) ($Z = -4.892$, $p < .001$) and mathematical disposition (MD) ($Z = -4.765$, $p < .001$) following the intervention. These results indicate that the post-intervention gains were not random fluctuations, but consistent score increases experienced by the majority of students. In non-parametric paired comparisons, the negative Z values signify that posttest ranks systematically exceeded pretest ranks, confirming a stable learning effect across participants rather than gains concentrated among a small subset of high achievers.

More importantly, the statistical significance is supported by substantial practical gains shown in Table 4. In the experimental group, originality increased by +33.75 compared with only +15.70 in the control group, while flexibility improved by +31.55 compared with +15.82. Similar patterns were observed for mathematical disposition, where confidence rose by +32.10 and risk-taking by +32.15, nearly double the gains recorded in the control group. These differences suggest that the intervention generated not only measurable progress but also stronger developmental acceleration than conventional instruction.

A plausible causal explanation lies in the instructional architecture of the STEM-Pythagorean Cup model. Students were repeatedly engaged in observing anomalous phenomena, generating predictions, testing hypotheses, quantifying outcomes, and defending conclusions. Such sequences likely activated divergent thinking processes by requiring multiple interpretations and solution strategies, thereby strengthening fluency, flexibility, elaboration, and originality. In contrast, conventional mathematics lessons often emphasize algorithmic completion and single-answer procedures, which provide fewer opportunities for creative production.

The significant growth in mathematical disposition can also be theoretically explained through mastery experience and collaborative inquiry mechanisms. When students successfully solved authentic problems, communi-

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cated ideas, and revised misconceptions through peer discussion, they accumulated experiences that strengthen self-efficacy, perseverance, curiosity, and intellectual risk-taking. The surprising overflow mechanism of the Pythagorean Cup likely sustained emotional engagement and situational interest, which are known predictors of long-term positive attitudes toward mathematics.

Another important finding is the concurrent improvement of cognition and disposition, suggesting a reciprocal relationship. Students with higher confidence and curiosity became more willing to attempt non-routine mathematical challenges, while successful creative performance further reinforced persistence and self-belief. This confirms that higher-order thinking develops more effectively when cognitive demand is accompanied by affective support and meaningful participation.

Taken together, the findings provide stronger evidence that the STEM-Pythagorean Cup model is not merely statistically effective but pedagogically transformative. It improves the quality of mathematical thinking, broadens participation, and nurtures productive learning dispositions simultaneously. Therefore, the model offers a scalable alternative to procedural elementary mathematics instruction by integrating contextual STEM inquiry with affective development.

The significant effects of the STEM–Pythagorean Cup model can be explained by its integration of concrete manipulatives and structured inquiry processes. The use of the Pythagorean Cup reduces abstraction and supports experiential learning, while the model's syntax engages students in higher-order thinking activities such as hypothesis generation, experimentation, and reflection. These processes stimulate divergent thinking and conceptual understanding, leading to improvements in creative thinking indicators. Simultaneously, the exploratory and low-risk learning environment fosters positive dispositions such as curiosity, perseverance, and risk-taking. Thus, the observed outcomes result from the interaction between cognitive engagement and supportive affective conditions embedded within the model.

These results were obtained through a quasi-experimental approach using a Non-Equivalent Control Group Design (Smajic et al., 2022), and are supported by quantitative data showing substantial pretest–posttest gains in the experimental group, far exceeding those of the control group. This outcome is consistent with the initial hypothesis that integrating the STEM-Pythagorean Cup model would produce a significant impact on improving both creative mathematical thinking and student dispositions (Aizikovitsh-Udi & Cheng, 2015; Tan et al., 2021).

The most notable improvements were observed in key indicators of creative thinking, fluency, flexibility, originality, and elaboration, as conceptualized in the Guilford and Torrance frameworks (Bulut et al., 2022). In parallel, dispositional dimensions such as curiosity, perseverance, risk-taking, and self-reflection showed marked enhancement. These findings indicate that the integration of a historically scientific artifact like the Pythagorean Cup not only enriches the cognitive domain but also cultivates essential affective traits necessary for meaningful mathematical learning (Fiori et al., 2022; Setiyani et al., 2022; Vu et al., 2022).

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Field observations revealed that students demonstrated active engagement throughout all phases of the learning process, particularly when exploring fluid phenomena using the *Pythagorean Cup* as a manipulative medium. Activities such as formulating hypotheses, testing predictions, and participating in small-group discussions encouraged the emergence of reflective, inquisitive, and collaborative behaviors, skills that Thornhill-Miller et al. (2023) and Li et al. (2022) identify as foundational to 21st-century competencies. Observing teachers noted that students who were previously passive began to show increased interest in solving open-ended mathematical problems and exhibited a willingness to explore diverse solution strategies without fear of failure (Yulianto et al., 2024).

In-depth student interviews further revealed that the majority perceived this learning experience as “unlike the usual,” “more real and logical,” and “mentally challenging but enjoyable.” Several students specifically mentioned that the *Pythagorean Cup* experiments helped them to better understand concepts such as volume, pressure, and ratio more visually and contextually. Teachers also observed that students appeared more patient and persistent when solving problems and were able to articulate their thinking processes more systematically (Terzieva et al., 2024).

These observational and interview findings align with the results of the disposition questionnaire and mathematical creative thinking tests, which indicated significant improvements in indicators such as curiosity, perseverance, fluency, and originality. These findings were further substantiated through methodological triangulation, demonstrating consistency across multiple data sources: quantitative scores, observational notes, and interview narratives, all of which converged to reinforce the study's conclusions (Tovin & Wormley, 2023). Minor inconsistencies in student interview responses, such as hesitation in explaining experiments or reliance on teacher prompts, were interpreted as indicative of a transitional phase from conventional instruction to a more exploratory learning approach.

This effectiveness is influenced by the structured learning syntax, which encourages open-ended exploration, prediction, experimentation, and reflection pedagogical processes that foster students’ metacognitive awareness and justification of thought (Elgrably, 2021; Peter A. Facione, 2020). These findings are consistent with the research of Bensley & Spero (2020) and Diwangkoro & Soenarto (2020), who highlight the importance of contextual and active learning environments in cultivating reasoning and problem-solving abilities. The TEFA model developed by Mavrikios et al. (2018), which links student engagement with institutional support and cross-sector collaboration, aligns well with the principles embodied in the STEM–Pythagorean Cup model.

The model's main strength lies in its ability to simultaneously integrate cognitive and dispositional domains. Through a contextual STEM approach grounded in manipulative artifacts, students not only gain a deep understanding of mathematical concepts but also develop reflective, critical, and creative thinking skills (Dilekçi & Karatay, 2023). However, this study is limited in scope, being implemented within a single subject area and educational level. Broader trials across

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interdisciplinary curricula and diverse educational stages are necessary to assess the model's sustainability and generalizability. Additional limitations include the variability in student characteristics across schools and the restricted implementation timeline, which may affect the depth of long-term impact measurement. Teacher readiness and institutional support also remain crucial factors to consider in future model development and implementation (Sahito & Wassan, 2024).

The qualitative findings not only reinforce the quantitative results but also provide rich contextual insights into how students experience, interpret, and respond to inquiry- and exploration-based learning processes. From a theoretical perspective, this study contributes to the literature by empirically validating artifact-based STEM learning as an effective trans-disciplinary approach that integrates cognitive (mathematical creative thinking) and affective (mathematical disposition) domains, thereby extending existing constructivist and creativity frameworks in mathematics education (Ramírez-Montoya et al., 2022; Thornhill-Miller et al., 2023; Fiori et al., 2022).

Methodologically, this study demonstrates the value of a mixed-methods approach with triangulated data (tests, observations, and interviews) in capturing both measurable learning outcomes and nuanced student experiences, offering a robust model for future educational design research (Fiori et al., 2022).

Practically, the findings provide actionable guidance for teachers by illustrating how the integration of STEM principles with contextual manipulatives such as the Pythagorean Cup can enhance student engagement, foster reflective thinking, and support the development of higher-order thinking skills in elementary classrooms. At the curriculum level, this study contributes by proposing an innovative and scalable instructional model that aligns with the Merdeka Curriculum and the Profil Pelajar Pancasila, particularly in fostering critical thinking, creativity, collaboration, and learner autonomy (Yulianto et al., 2025). In terms of broader impact, the study highlights the potential of culturally and historically grounded scientific artifacts as pedagogical tools to bridge abstract mathematical concepts with real-world understanding, thereby supporting more meaningful, inclusive, and future-ready mathematics education.

CONCLUSIONS

This study demonstrates that the STEM–Pythagorean Cup learning model is significantly effective in enhancing elementary students' mathematical creative thinking skills and mathematical dispositions. The model was validated both in terms of content and construct, proven to be practical in its implementation, and capable of fostering key dimensions such as fluency, flexibility, elaboration, and originality, along with reflective thinking, curiosity, and intellectual risk-taking. These findings underscore the importance of integrating contextual manipulatives into STEM-based instructional design as a strategic approach to developing 21st-century competencies from the early stages of education.

Based on these results, it is recommended that similar models be developed and tested across various subjects and educational levels. Furthermore, longitudinal studies are needed to explore the long-term impact on students' dispositional development in thinking and learning.

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