

Impact of a STEAM-SDGs-Based Virtual Reality Mathematics Learning Model on Students' Critical Thinking and Creativity

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Abstract

The integration of STEAM (Science, Technology, Engineering, Arts, and Mathematics) and Sustainable Development Goals (SDGs) in higher education has gained increasing attention as a strategy to foster essential 21st-century competencies. In mathematics learning, the use of Virtual Reality (VR) offers immersive and interactive experiences that may enhance higher-order thinking skills. However, empirical evidence examining the impact of a STEAM-SDGs-based VR learning model on students' critical thinking and creativity remains limited. This study aims to investigate the effect of a STEAM-SDGs-based VR mathematics learning model on students' critical thinking and creativity. A quantitative research design was employed. The study collected data through structured questionnaires administered to 100 students at Universitas Muhammadiyah Tangerang. The proposed research model was analyzed using Structural Equation Modeling-Partial Least Squares (SEM-PLS) with SmartPLS version 3 to evaluate both measurement and structural models. The findings indicate that the STEAM-SDGs-based VR learning model has a significant positive effect on students' critical thinking and creativity. The immersive VR environment, combined with interdisciplinary STEAM integration and SDGs-oriented problem contexts, contributes to improved analytical reasoning, idea generation, and innovative problem-solving skills. This research provides empirical support for integrating STEAM, the SDGs, and Virtual Reality into mathematics education at the higher education level. The study contributes to the development of innovative, technology-enhanced learning models that promote critical thinking and creativity, offering practical implications for educators and policymakers seeking to strengthen 21st-century competencies in university settings.

INTRODUCTION

Geometry is a foundational domain in mathematics because it develops learners' spatial reasoning, visualization skills, and the ability to interpret and manipulate two- and three-dimensional representations (Gilligan et al., 2022; Ramful et al., 2023). Despite its importance, many university students continue to perceive geometry as abstract and challenging, particularly when dealing with three-dimensional objects such as solids, volume relationships, and geometric transformations (Gurmuu et al., 2024; Sudirman et al., 2023). These difficulties often stem from limited opportunities to visualize and interact dynamically with geometric forms (Hlongwana et al., 2025; Yang et al., 2025). To address these challenges, educators have increasingly adopted immersive VR in mathematics education. VR enables students to engage with geometric objects in an embodied, manipulable three-dimensional environment, making abstract concepts more concrete and experientially meaningful (Chonchaiya & Srithammee, 2025; Lavicza et al., 2023; Lehrman, 2025; Wang et al., 2025). Empirical studies indicate that VR-based geometry learning can improve students' motivation and academic performance (Rodríguez et al., 2021; Su et al., 2022). Furthermore, meta-analytic evidence suggests that immersive VR provides a small but positive overall effect on learning outcomes compared with conventional instructional approaches (Coban et al., 2022).

At the same time, contemporary educational discourse emphasizes the development of critical thinking and creativity as essential 21st-century competencies (Almulla, 2023; Cariaga, 2024; Herlinawati et al., 2024; Joynes et al., 2023). Integrating STEAM, particularly the "Arts" component as a driver of design thinking and creative representation, has been shown to strengthen creativity-related outcomes in higher education (Khairullina et al., 2022; Fang, 2026; Smith, 2022; Liu et al., 2024; Zhao et al., 2023). In parallel, embedding learning within contexts aligned with the SDGs offers opportunities for contextualized problem-solving and values-oriented mathematics learning (Bulut & Borromeo Ferri, 2025; He et al., 2025).

From a theoretical perspective, the integration of STEAM, SDGs, and mathematics can be understood as a complementary pedagogical framework. Mathematics provides the conceptual and analytical foundation for reasoning, modelling, and problem-solving; STEAM offers an interdisciplinary learning approach that connects mathematical ideas with scientific inquiry, technological tools, engineering design, and artistic creativity; while the SDGs provide authentic real-world contexts that make learning socially relevant and sustainability-oriented. In this relationship, mathematics functions as the core disciplinary knowledge, STEAM acts as the integrative pedagogy, and SDGs serve as the contextual orientation for meaningful application. Thus, a STEAM-SDGs-mathematics

framework does not merely teach mathematical content, but positions mathematics as a tool for solving contextual problems creatively, critically, and responsibly.

Although prior research has examined VR in mathematics learning and explored creativity within STEAM or technology-enhanced contexts separately (Coban et al., 2022; Hidajat, 2024; Zhao et al., 2023), limited empirical evidence exists on an integrated instructional model that simultaneously combines STEAM, SDGs, and VR. In particular, the extent to which a STEAM-SDGs-based VR mathematics learning model influences students' critical thinking and creativity in geometry-oriented learning remains underexplored (Bertrand et al., 2024; Yang et al., 2025). More importantly, previous studies have generally focused on either learning achievement, motivation, or the isolated contribution of a single approach, rather than examining the combined effect of an integrated STEAM-SDGs-VR model on higher-order thinking skills in geometry learning. Therefore, the novelty of this study lies in the development and empirical testing of a holistic instructional model that links immersive VR environments, interdisciplinary STEAM principles, and SDGs-based contextual problems to foster students' critical thinking and creativity in university geometry learning.

Therefore, this study aims to examine the impact of a STEAM-SDGs-based virtual reality mathematics learning model on students' critical thinking and creativity using a quantitative approach with SEM-PLS. This study is significant in several respects. First, it contributes to geometry education by investigating VR not only as a tool for conceptual understanding but also as a medium for fostering higher-order thinking skills. Second, it advances STEAM research by positioning the Arts component as a catalyst for creative problem-solving within mathematics tasks. Third, by integrating SDGs-oriented contexts, the study aligns mathematics learning with real-world sustainability challenges and the broader agenda of Education for Sustainable Development. Taken together, the theoretical gap, the limited empirical evidence, and the need for an integrated learning model indicate the importance of investigating whether STEAM-SDGs-based VR mathematics learning can significantly enhance students' critical thinking and creativity in geometry-oriented learning. This argument leads directly to the formulation of the following research questions.

Based on these considerations, the research questions are as follows: RQ1: Does a STEAM-SDGs-based VR mathematics learning model significantly affect students' critical thinking in geometry-oriented learning? RQ2: Does a STEAM-SDGs-based VR mathematics learning model significantly affect students' creativity in geometry-oriented learning? Accordingly, this study proposes the following hypotheses: H1: The STEAM-SDGs-based VR mathematics learning model has a positive and significant effect on students' critical thinking. H2: The STEAM-SDGs-based VR mathematics learning model has a positive and significant effect on students' creativity.

METHODS

This study employed a quantitative research design to examine the impact of a STEAM-SDGs-based virtual reality mathematics learning model on students' critical thinking and creativity. A cross-sectional survey approach was adopted, as it is appropriate for testing theoretical relationships among latent constructs and observable indicators within educational settings, particularly when applying SEM-PLS. Quantitative approaches of this type are widely used in educational technology research to validate conceptual models that explain the relationships between instructional strategies and student learning outcomes (Demir & Usxak, 2025).

The study collected data in September 2025 from 100 undergraduate students at Universitas Muhammadiyah Tangerang. The participants were selected using purposive sampling, in which students were chosen based on specific criteria relevant to the study objectives. The inclusion criteria were: (1) undergraduate students enrolled in mathematics-related courses, (2) students who had participated in geometry learning activities using the STEAM-SDGs-based VR mathematics learning model, and (3) students who were willing to complete the questionnaire voluntarily. Purposive sampling was considered appropriate because the study required respondents who had direct learning experience with the instructional model being evaluated.

The instrument employed a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. The study designed the questionnaire to measure students' perceptions of the STEAM-SDGs-based VR mathematics learning model and their levels of critical thinking and creativity. The use of Likert-scale questionnaires enables systematic measurement of attitudes and competencies in educational research (Nguyen, 2022). The study adapted the items from established instruments in mathematics education, STEAM integration, and educational technology studies. Prior to full-scale implementation, the instrument was pilot-tested to ensure clarity, reliability, and construct validity. The questionnaire consisted of three main constructs: the STEAM-SDGs-based VR mathematics learning model, critical thinking, and creativity. The STEAM-SDGs-based VR construct included items related to students' experiences in using virtual reality for geometry visualization, the integration of interdisciplinary STEAM elements in learning activities, and the use of SDGs-based real-world contexts in mathematical problem-solving. Example items included: "The VR environment helped me visualize three-dimensional geometric objects more clearly," "The learning activities connected mathematics with science, technology, engineering, arts, and real-life applications," and "The problems presented in learning were linked to sustainability issues relevant to daily life."

The critical thinking construct included items that measured students' ability to analyze problems, evaluate information, and make logical decisions during

geometry learning. Example items included: “I was able to analyze geometric problems from different perspectives,” “I could evaluate the correctness of mathematical solutions critically,” and “I was able to justify my answers using logical reasoning.” Meanwhile, the creativity construct included items related to idea generation, flexibility in solving problems, and originality in mathematical representation. Example items included: “I was able to generate more than one strategy to solve a geometry problem,” “I found new ways to represent mathematical ideas,” and “The learning activities encouraged me to think creatively when solving problems.”

The data were analyzed using SEM-PLS with SmartPLS version 3. SEM-PLS is a variance-based multivariate technique suitable for predictive and exploratory research, particularly when working with relatively small samples and complex models involving multiple latent variables (Demir & Usxak, 2025; Haji-Othman et al., 2024). The study analyzed two stages: first, evaluation of the measurement model to assess reliability and validity through indicators such as composite reliability and average variance extracted; and second, evaluation of the structural model to test the hypothesized relationships using path coefficients and R^2 values. By simultaneously assessing measurement and structural models, SEM-PLS provided robust empirical evidence on the extent to which the STEAM-SDGs-based VR mathematics learning model influences students' critical thinking and creativity.

RESULTS AND DISCUSSION

1. Convergent Validity

The convergent validity results presented in Table 1 and Figure 1 indicate that all indicators measuring the STEAM-SDGs-Based VR Mathematics Learning Model (MLM), Critical Thinking (CT), and Creativity (CR) exhibit outer loadings exceeding the recommended threshold of 0.50, thereby confirming adequate convergent validity. In fact, all loadings are substantially above 0.70, indicating strong indicator reliability and suggesting that each item contributes meaningfully to its respective latent construct (Hair et al., 2022).

Table 1. Results of cross-loading value results

Variables		Item	Outer loadings
STEAM-SDGs-Based Mathematics Learning Model (STEAM-SDGs-VR)	VR Interactivity & Immersion	VR1	0.882
		VR2	0.877
		VR3	0.852
		VR4	0.889
	STEAM Integration	ST1	0.874
		ST2	0.921
		ST3	0.854
	SDGs Contextualization	SDG1	0.875
		SDG2	0.867
		SDG3	0.819
Critical Thinking (CT)	CT1	0.854	

	CT2	0.863
	CT3	0.847
	CT4	0.849
	CT5	0.887
	CT6	0.855
Creativity (CR)	CR1	0.828
	CR2	0.790
	CR3	0.844
	CR4	0.787
	CR5	0.882
	CR6	0.895

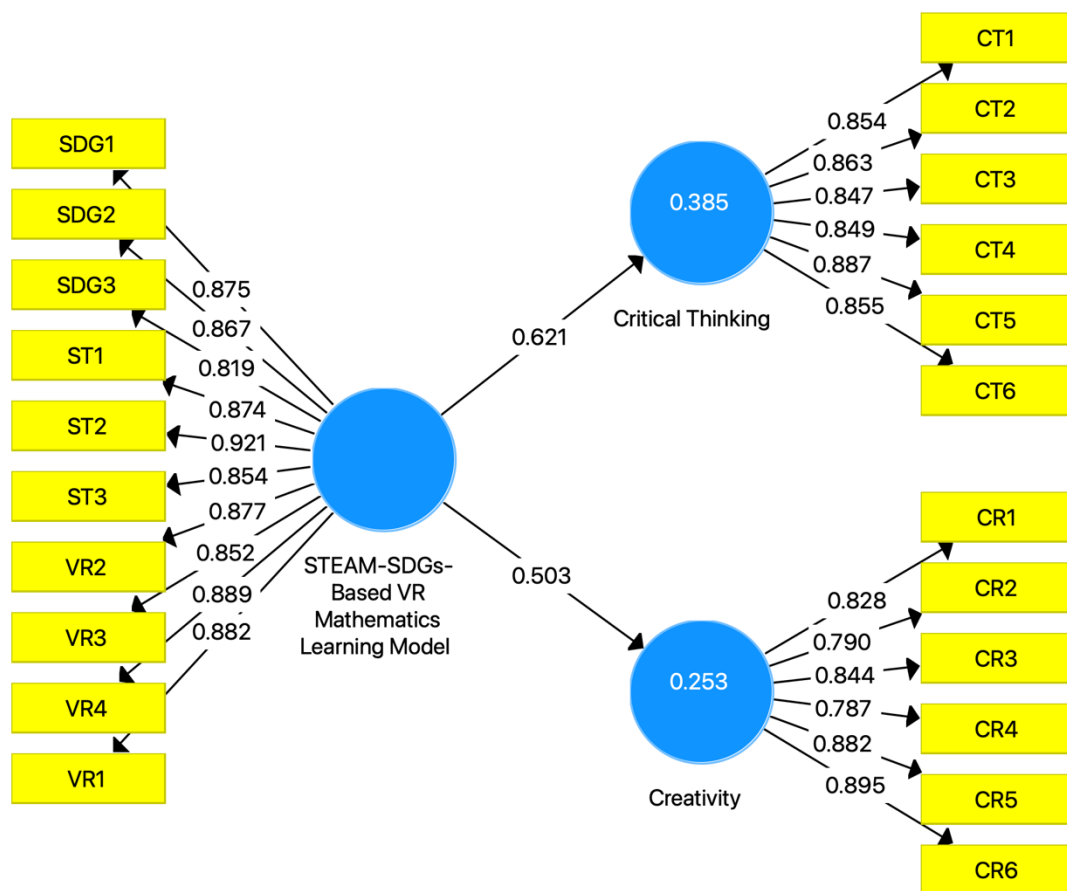


Figure 1. Structural drawing

Within the STEAM-SDGs-Based VR MLM construct, the VR Interactivity and Immersion indicators show high loadings ranging from 0.852 to 0.889, with VR4 (0.889) emerging as the strongest contributor. In the STEAM Integration dimension, ST2 exhibits a particularly strong loading of 0.921, indicating that interdisciplinary integration plays a central role in defining the construct. For the SDGs Contextualization dimension, all indicators surpass 0.80, with SDG1 (0.875) demonstrating robust alignment with the latent variable.

Similarly, the CT construct demonstrates consistently strong loadings (0.847–0.887), with CT5 (0.887) contributing most prominently. The CR construct also shows satisfactory loadings (0.787–0.895), with CR6 (0.895) and CR5 (0.882) indicating particularly strong measurement contributions. According to contemporary SEM-PLS guidelines, outer loadings above 0.70 confirm indicator reliability and strong convergence between observed variables and their intended constructs (Hair et al., 2022; Sarstedt et al., 2022).

Overall, the consistently high outer loading values across all constructs confirm that the measurement model demonstrates strong convergent validity. These findings indicate that the indicators reliably measure their theoretical constructs, thereby providing a solid foundation for further structural model evaluation in the context of STEAM-SDGs and VR-based mathematics learning.

2. Discriminant Validity

Table 2 presents the cross-loadings, indicating the extent to which each indicator loads more strongly on its intended construct than on other constructs in the model. The results demonstrate that all indicators associated with the STEAM-SDGs-Based VR MLM, CT, and CR exhibit the highest loadings on their respective latent constructs, thereby supporting discriminant validity.

Table 2. Results of cross-loading value results

Item	STEAM-SDGs-VR	Critical Thinking	Creativity
VR1	0.882	0.611	0.477
VR2	0.877	0.554	0.391
VR3	0.852	0.460	0.415
VR4	0.889	0.499	0.422
ST1	0.874	0.561	0.486
ST2	0.921	0.566	0.464
ST3	0.854	0.550	0.462
SDG1	0.875	0.541	0.461
SDG2	0.867	0.515	0.426
SDG3	0.819	0.513	0.354
CT1	0.581	0.854	0.325
CT2	0.515	0.863	0.244
CT3	0.494	0.847	0.319
CT4	0.461	0.849	0.320
CT5	0.596	0.887	0.345
CT6	0.532	0.855	0.262
CR1	0.299	0.237	0.828
CR2	0.390	0.298	0.790
CR3	0.436	0.256	0.844
CR4	0.359	0.202	0.787
CR5	0.520	0.389	0.882
CR6	0.462	0.345	0.895

For instance, indicator ST2 shows a loading of 0.921 on the STEAM-SDGs-VR construct, which is substantially higher than its loadings on CT (0.566) and CR (0.464). Similarly, VR4 loads more strongly on STEAM-SDGs-VR (0.889) than on CT (0.499) and CR (0.422), indicating a clear distinction among the constructs. CT5 demonstrates a dominant loading of 0.887, exceeding its cross-loadings on STEAM-SDGs-VR (0.596) and CR (0.345). Likewise, for the CR construct, CR6 exhibits the highest loading of 0.895 on its intended construct, compared to 0.462 on STEAM-SDGs-VR and 0.345 on CT.

Although theoretically related constructs—particularly STEAM-SDGs-VR and CT—show moderate cross-loadings, these values remain lower than the primary loadings of each indicator. This pattern reflects the conceptual interconnectedness among instructional models and higher-order cognitive skills while still maintaining empirical distinctiveness. According to recent PLS-SEM guidelines, the model demonstrates discriminant validity when each indicator loads higher on its assigned construct than on other constructs (Hair et al., 2022; Henseler et al., 2021).

Overall, the dominance of primary loadings over cross-loadings confirms the measurement model's adequate discriminant validity. These findings validate that each construct—STEAM-SDGs-based VR mathematics learning, CT, and CR—is empirically distinct, thereby ensuring reliable interpretation of the structural relationships in the subsequent SEM-PLS analysis. The results are consistent with contemporary methodological recommendations for assessing discriminant validity in variance-based SEM models (Sarstedt et al., 2022; Ringle et al., 2023).

3. Reliability Test

Table 3 presents the reliability and convergent validity assessment results for all constructs in the proposed model, indicating consistently high levels of internal consistency. The composite reliability values for STEAM-SDGs-Based VR Mathematics Learning (0.969), CT (0.944), and CR (0.934) all exceed the recommended threshold of 0.70, demonstrating strong internal consistency reliability (Hair et al., 2022; Ringle et al., 2023).

Table 3. Results of composite reliability values

Variable	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
STEAM-SDGs-VR	0.965	0.966	0.969	0.759
Critical Thinking	0.929	0.933	0.944	0.738
Creativity	0.916	0.931	0.934	0.703

Furthermore, Cronbach's Alpha (CA) and rho_A values are uniformly high across all constructs. The STEAM-SDGs-VR construct reports Cronbach's Alpha of 0.965 and rho_A of 0.966, while CT shows values of 0.929 and 0.933, and CR records 0.916 and 0.931, respectively. These values surpass the minimum acceptable level of 0.70, confirming the reliability and stability of the measurement model. Recent

SEM-PLS methodological literature emphasizes that reporting multiple reliability indices—Cronbach's Alpha, rho_A, and Composite Reliability—provides a more rigorous evaluation of construct consistency (Hair et al., 2022; Sarstedt et al., 2022).

In addition, the AVE values for all constructs are above the recommended threshold of 0.50, with STEAM-SDGs-VR at 0.759, CT at 0.738, and CR at 0.703. These results indicate that each latent variable explains more than 50% of the variance in its indicators, thereby satisfying the criterion for convergent validity (Hair et al., 2022; Henseler et al., 2021).

Overall, the strong reliability and validity indicators demonstrate that the constructs are measured consistently and accurately, providing a robust foundation for subsequent structural model analysis. The results reinforce the rigor of the measurement model and align with contemporary educational research, highlighting the importance of reliable and valid instruments when examining the effects of innovative instructional approaches—such as STEAM-SDGs integration and VR-based learning—on higher-order cognitive outcomes (Ringle et al., 2023; Sarstedt et al., 2022).

4. R Square (R^2) Analysis

Table 4 presents the R^2 values for the endogenous constructs, indicating the extent to which the proposed model explains variance in CT and CR. The results show that CT yields an R^2 value of 0.385, indicating that the STEAM-SDGs-Based VR MLM explains approximately 38.5% of the variance in students' critical thinking. Meanwhile, CR demonstrates an R^2 value of 0.253, indicating that the model accounts for 25.3% of the variance in students' creativity.

Table 4. Result of R-squared

Variable	R Square	R Square Adjusted
Critical Thinking	0.385	0.379
Creativity	0.253	0.245

The corresponding adjusted R^2 values (0.379 for CT and 0.245 for CR) are closely aligned with the R^2 coefficients, confirming the stability and consistency of the structural model estimates. According to contemporary PLS-SEM benchmarks, R^2 values of 0.25, 0.50, and 0.75 are considered weak, moderate, and substantial, respectively, depending on the research context (Hair et al., 2022; Sarstedt et al., 2022). Based on these guidelines, the R^2 value for CT can be interpreted as moderate, while the R^2 value for CR reflects a weak-to-moderate level of explanatory power.

These findings indicate that the STEAM-SDGs-based VR MLM demonstrates meaningful predictive capability, particularly in explaining students' critical thinking. Although the explanatory power for creativity is comparatively lower, it remains statistically relevant and theoretically meaningful, given the multifaceted

nature of creative competence. Recent research in technology-enhanced learning environments emphasizes that innovative instructional designs—especially those integrating immersive technologies and interdisciplinary approaches—can significantly contribute to higher-order cognitive outcomes, even when effect sizes vary across constructs (Hair et al., 2022; Ringle et al., 2023).

Overall, the R^2 results confirm that the proposed model has adequate predictive power in explaining variation in students' critical thinking and creativity. These findings support the relevance of STEAM-SDGs integration and virtual reality-based instructional strategies in fostering higher-order thinking skills in mathematics education.

2. Hypothesis Testing Results

Based on the bootstrapping results presented in Table 5, all hypothesized structural paths in the PLS-SEM model are statistically significant, thereby supporting the proposed hypotheses. The results indicate that the STEAM-SDGs-Based VR Mathematics Learning Model has a significant positive effect on Critical Thinking ($T = 11.267$, $p < .001$) and Creativity ($T = 7.320$, $p < .001$). The high T-statistics and p-values below the 0.001 threshold confirm strong statistical significance according to established PLS-SEM bootstrapping criteria (Hair et al., 2022; Sarstedt et al., 2022).

Table 5. Hypothesis test based on the path coefficient

Variable	T Statistics	P Value
STEM-SDGs-Based VR Mathematics Learning Model -> Critical Thinking	11.267	0.000
STEM-SDGs-Based VR Mathematics Learning Model -> Creativity	7.320	0.000

The substantial T-value for the relationship between the STEAM-SDGs-based VR model and Critical Thinking suggests that immersive, interdisciplinary, and sustainability-oriented instructional design plays a particularly strong role in enhancing students' analytical reasoning and evaluative skills. Similarly, the significant positive effect on Creativity indicates that integrating Arts within STEAM, combined with contextualized SDG problem scenarios and immersive VR environments, contributes meaningfully to students' idea generation and innovative problem-solving abilities.

All structural relationships operate in the hypothesized positive direction, confirming the robustness and feasibility of the proposed structural model. In line with contemporary SEM-PLS methodological standards, statistically significant path coefficients obtained through bootstrapping provide empirical evidence supporting causal inferences within predictive models (Ringle et al., 2023; Hair et al., 2022).

STEAM–SDGs–VR → Critical Thinking

The significant positive effect of the STEAM–SDGs–VR learning model on students' critical thinking suggests that immersive, interactive learning environments can strengthen analytical reasoning and evaluation processes in mathematics learning. This finding is consistent with prior evidence that immersive VR in mathematics/geometry learning environments can enhance learning motivation and performance—conditions that often support deeper Engagement in higher-order thinking activities (Liao et al., 2024; Shen et al., 2023; Su et al., 2022; Vázquez & Díaz-Palencia, 2024). It also aligns with broader evidence from meta-analytic research indicating that immersive VR provides an overall positive advantage for learning outcomes compared to conventional methods (Coban et al., 2022). In this study's context, the STEAM approach (interdisciplinary problem framing) combined with SDGs-oriented contexts (real-world, values-based challenges) plausibly encourages learners to justify solutions, evaluate alternatives, and connect mathematical reasoning to authentic problems—key elements of critical thinking (Boice et al., 2024; Choirunnisa et al., 2025; Ilham et al., 2025; Segarra-Morales & Juca-Aulestia, 2024; Sánchez-Milara & Cortés-Orduña, 2024; Zhou et al., 2023).

STEAM–SDGs–VR → Creativity

The significant positive effect on creativity indicates that the STEAM–SDGs–VR model also supports idea generation, flexibility, and originality in mathematical problem-solving. This finding aligns with research showing that VR's immersive and interactive experiences can foster mathematical creativity, including dimensions such as flexibility and originality (Balalle, 2025; Bertrand et al., 2024; Hidajat, 2024; Lyu et al., 2023; Zhang et al., 2024). Additionally, it aligns with higher education research that suggests incorporating STEAM activities into creativity training can strengthen students' creative thinking skills (Zhao et al., 2023). In the present model, the "Arts" component of STEAM likely plays an enabling role by supporting creative representation and design-oriented thinking, while SDGs problem contexts can stimulate divergent thinking through open-ended, socially relevant challenges—conditions conducive to creativity development (Ansari, 2025; García-González et al., 2024; Liao et al., 2025; Tyas, 2025; Zhou et al., 2023).

CONCLUSION

This study concludes that the STEAM-SDGs-based virtual reality mathematics learning model has a positive and significant effect on students' critical thinking and creativity in geometry-oriented learning. The main findings show that the integration of immersive VR environments, interdisciplinary STEAM elements, and SDG-oriented problem contexts can enhance students' analytical reasoning, flexible thinking, and innovative problem-solving abilities. These results confirm that

technology-enhanced and context-based instructional models can make an important contribution to the development of higher-order thinking skills in mathematics learning.

Building upon these findings, the study highlights the growing importance of integrating emerging technologies and interdisciplinary learning frameworks in higher education to address the demands of 21st-century competencies. By combining STEAM education, SDGs, and immersive virtual reality, the proposed learning model offers a more engaging and meaningful learning experience that supports both cognitive and creative development. This integrated approach responds to contemporary educational challenges that require students not only to master academic knowledge but also to develop critical thinking, creativity, and the ability to solve complex real-world problems. Consequently, the results underline the potential of VR-supported STEAM learning environments as an effective pedagogical strategy for modern mathematics education and for strengthening students' readiness to address sustainability-related challenges.

Based on these findings, several recommendations can be proposed. First, mathematics lecturers are encouraged to integrate VR-assisted learning activities with STEAM and SDGs contexts to promote students' critical and creative thinking more effectively. Second, higher education institutions should support the provision of technological facilities, training, and instructional design development to ensure the effective implementation of VR-based learning. Third, curriculum developers may consider incorporating interdisciplinary and sustainability-oriented mathematical tasks into geometry learning so that students can connect abstract concepts with real-world issues more meaningfully.

Despite these contributions, several directions for future research remain. Although the present study provides empirical evidence supporting the effectiveness of the STEAM-SDGs-based VR mathematics learning model, further studies are needed to expand and deepen the understanding of its educational impact. Future research could involve larger and more diverse samples across multiple universities to improve the generalizability of the findings. In addition, researchers may adopt experimental or longitudinal research designs to examine the long-term effects of VR-supported STEAM learning on students' higher-order thinking skills. Further investigations could also explore additional learning outcomes, such as student engagement, collaboration skills, digital literacy, or sustainability awareness, in order to provide a more comprehensive understanding of the broader educational benefits of VR-based learning environments. Finally, future studies may focus on the pedagogical design and usability of VR learning systems to optimize their effectiveness in mathematics and STEM education.

DISCLOSURE STATEMENT

The authors declare no potential conflict of interest.

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