Validating a Technology-Enhanced Learning Model: Correlation between STEAM, Gamification, and Critical Thinking Skills Using SEM

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Manuscript received August 15, 2025; revised September 10, 2025; accepted November 3, 2025; published March 19, 2026

***Abstract*—One of the issues currently faced by the Indonesian education system is the suboptimal quality of learning and student achievement in essential competencies, such as critical thinking skills. Therefore, there is a need for an innovative approach that integrates modern pedagogy and digital technology, including Science, Technology, Engineering, Art, and Mathematics (STEAM) and gamification. Before implementing it, designing a correlation model for critical thinking skills is essential. Therefore, this validation and reliability study investigates the correlation between gamification learning, STEAM, and the integration of both in developing critical thinking skills. The type of research conducted was a quantitative correlational study, with data collection involving the provision of response questionnaires and project observation sheets to 187 students, who served as the research sample. Structural Equation Modeling (SEM) analysis indicates that the gamification, STEAM, and integration models are feasible, as evidenced by the Goodness of Fit model value exceeding the criteria. In addition, the model is also stated to be valid. The reliability is indicated by the CR value > 0.7 and AVE > 0.5, namely gamification (CR = 0.88, AVE = 0.64), STEAM (CR = 0.85, AVE = 0.55), and Critical Thinking Skills (CR = 0.90, AVE = 0.66). The research findings also indicate that gamification (β = 0.83 > 0.5) and STEAM (β = 0.16 < 0.3) exhibit a positive correlation with critical thinking skills. Still, integrating both (β = 1.01> 0.5) can have a greater impact on critical thinking skills. The practical implications of this study are crucial for teachers to enhance their ability in designing effective gamification and STEAM learning innovations. This study has limitations, namely, the technology and samples used are still within a limited scope.**

***Keywords*—critical thinking skills, gamification, reliability, validity, Structural Equation Modeling (SEM), Science, Technology, Engineering, Art, and Mathematics (STEAM)**

I. Introduction

One of the issues facing education in Indonesia today is the suboptimal quality of learning and student achievement in essential competencies, such as critical thinking skills. Therefore, a viable strategy is to enhance the quality of teaching and learning by developing student-centered, contextual learning innovations that utilize digital technology and apply modern pedagogy, in line with the policy direction of the Indonesian Education Roadmap 2025–2045.

The use of digital technology in education is essential and urgent to prepare the next generation to face the challenges of digitalization in the future [1]. This suggests that digitalization is an key focus for enhancing the quality of learning and the student experience [2]. The digitalization in question encompasses not only the use of technology in education but also the preparation of a generation with critical thinking, creativity, collaboration, and communication skills to face the challenges of the technological era [3–5]. In addition, another essential thing that needs to be considered in applying digital technology to learning is the needs and characteristics of students [6]. One of the characteristics of today's students is the Digital Native generation, a group that is very familiar with technology and prefers digital learning [7]. Jayanti [8] in her research stated that as a digital native generation, students need various forms of learning innovation to develop their competencies.

Learning innovations that utilize technology include the implementation of digital teaching materials. [9] Digital teaching materials are educational resources designed for independent learning, easily accessible, representative, and that utilize media devices in real-time. The research findings by Jayanti and Muntahanah [10] show that 95.8% of students needed interactive digital teaching materials integrated with an approach. Furthermore, Jayanti and Muntahanah [11] in their research confirmed that students' need for digital technology is not only about integrating technology and approaches but also needs to pay attention to the accuracy of its selection by considering essential competencies, needs, and characteristics of students, so that it can truly facilitate the development of critical thinking skills. Based on this description, the problem addressed in this research is how to develop valid, practical, and effective teaching materials that improve students' critical thinking skills by utilizing digital technology in an appropriately integrated manner with a modern approach.

Empirical data show that critical thinking skills and the quality of student learning are not optimal [12], in line with Indonesia's low education ranking, which is ranked 6th out of 7 countries [13]. This fact confirms that contextual learning innovations integrating digital technology and appropriate approaches are an educational urgency. One approach believed to be effective in addressing these problems is Science, Technology, Engineering, Art, and Mathematics (STEAM). The STEAM approach is a crucial modern learning strategy because it is student-centered and oriented towards developing 21st-century skills [14]. STEAM holistically integrates science, technology, engineering, art, and mathematics as an interdisciplinary approach, emphasizing the solution of real-life, contextual

problems [15]. In the context of the industrial era 4.0, STEAM is an effective means to develop critical thinking skills through problem-based projects that require the ability to analyze, synthesize, and create innovative solutions [16, 17]. In addition to creating a dynamic and engaging learning environment, this approach has also been proven to improve critical thinking skills and other 21st-century competencies [18–22]. Furthermore, STEAM can be integrated into various media and learning models to provide students with contextual and meaningful learning experiences [23]. Its relevance is further strengthened because STEAM is one of the main focuses in the Indonesian Education Roadmap [12] and is recommended for implementation in science learning [24]. However, its implementation is still limited, with more than 50% of institutions not yet implementing it optimally [25].

Another popular approach in the digital era is gamification, which is an approach that incorporates game elements into the learning context [26]. Gamification is also known as a modern pedagogy suitable for digital natives, because it meets the needs of their learning styles [27]. The characteristics of gamification not only encourage student motivation and engagement [28, 29], but also improve critical thinking, creativity, and problem-solving skills [30–32]. Furthermore, the gamification approach has recently been recommended for integration into mobile learning. Combining gamification with mobile learning is an effective approach [33] to encourage meaningful and enjoyable learning, thereby improving critical thinking skills [34, 35]. It is stated that 87.5% of students need m-learning-based gamification as a learning medium, which is considered relevant to the characteristics of today's students [36, 37].

Gamification is also relevant when integrated with the STEAM approach. This aligns with the statement [38] that STEAM learning can be done through direct learning and game-based projects, encouraging students to develop critical thinking skills. [39] The STEAM approach, combined with gamification, can potentially promote student motivation, enthusiasm, and engagement in problem-solving. In addition, integrating STEAM with technology can make it easier for students to learn comprehensively [40].

A literature review shows that research related to gamification and STEAM learning on critical thinking skills has been conducted separately [41–51]. Most studies focus on improving motivation and cognitive achievement, while studies integrating both approaches, particularly in science education, are still very limited. The effectiveness of STEAM is strongly influenced by learning designs oriented towards problem-solving and inquiry [52]. At the same time, the impact of gamification on critical thinking skills still shows inconsistent results due to the dominance of reward-based elements [53, 54]. Therefore, this study offers novelty by presenting an integrative model that explicitly links STEAM activities to the critical thinking skill level, while incorporating gamification elements that encourage analysis, evaluation, and creation through narratives, tiered challenges, and reflective feedback. In addition, this study contributes to the body of knowledge by revealing the correlation between STEAM, gamification, and critical thinking skills using validated instruments, thereby providing conceptual and methodological contributions that are scarce in the literature related to STEAM and gamification.

The relationship between STEAM, gamification, and critical thinking skills was examined using the Structural Equation Modeling (SEM) method through Confirmatory Factor Analysis (CFA). This method was chosen considering the conceptual model developed is complex, integrative, and based on latent constructions. SEM tests the relationship between variables simultaneously and confirms construct validity, measuring the fit of the theoretical model with empirical data [55, 56]. Thus, SEM provides a stronger statistical and conceptual basis for explaining the relationship between STEAM learning, gamification, and critical thinking skills compared to conventional regression analysis methods [57].

The conceptual model determination in this study began by confirming the relationship between gamification and STEAM separately in terms of critical thinking skills. This step aims to obtain recommendations based on the results of Confirmatory Factor Analysis (CFA) in formulating the integration of both into a single learning model. The initial model developed in this study is presented in Fig. 1, which outlines two hypotheses: H1, there is a correlation between gamification learning and improving students' critical thinking skills in biology learning, and H2, there is a correlation between STEAM learning and improving students' critical thinking skills in biology learning. Although several previous studies have examined the effects of gamification and the STEAM approach on critical thinking separately, studies integrating the two within a single conceptual framework are still very limited. This innovation represents a significant novelty in the study, as it offers an integrated approach that can strengthen both the motivational and cognitive dimensions of biology learning. Therefore, a Structural Equation Modeling (SEM) model was constructed to answer the research hypothesis, as shown in Fig. 1. Specifically, this study aims to validate and investigate the correlation between STEAM learning, gamification, and critical thinking skills in the context of biology learning.

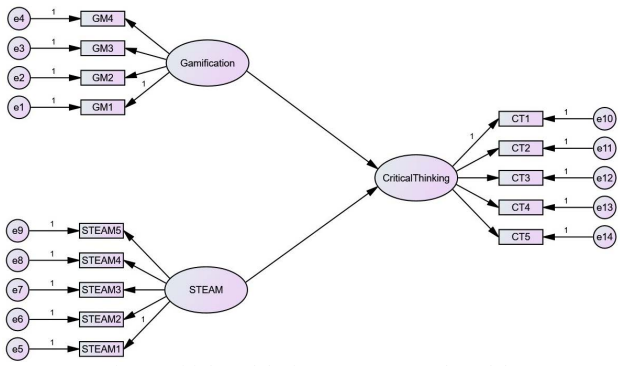

Fig. 1. Initial model of SEM (conceptual model).

II. METHODOLOGY

This quantitative correlational study uses Structural Equation Modeling (SEM) to investigate the causal relationship between predetermined research variables. Using statistical methods, this study focuses on the correlation between variable X (Gamification and STEAM) and variable Y (critical thinking skills). This study begins by confirming the feasibility of the model structure to examine the correlation between each research variable.

This study involved 187 students selected through purposive sampling, with the criterion that respondents were accustomed to using technology in learning. The respondents were 11th-grade students from several high schools in Bengkulu City, Indonesia, comprising 49% males and 51% females. School selection was conducted purposively, considering the availability of digital infrastructure, including internet access and learning devices. However, this purposive sampling technique limits the generalizability of the findings, because the study results better reflect the conditions of schools with adequate technological support. The research instruments used were a student response questionnaire on gamification learning [58–60], a student response questionnaire on STEAM learning [61, 62], and a project observation sheet to assess students' critical thinking skills developed using Ennis indicators [63], which include clarification, decision, inference, advanced clarification, supposition, and integration. The instruments were adopted and adapted from previous research, then adapted to the context of STEAM and gamification learning, and piloted on the main research sample to ensure construct validity and reliability through Confirmatory Factor Analysis (CFA). Before the construct trial, the developed instrument was validated by five subject matter experts. The Scale-Content Validity Index (S-CVI) results confirmed that the instrument had excellent validity, with a score of 0.88.

The questionnaire responses were assessed using a Likert scale, with a score of 1 for strongly disagree, a score of 2 for disagree, a score of 3 for agree, and a score of 4 for strongly agree. Critical thinking skills were assessed using a project observation sheet rubric, with scores ranging from 1 (low) to 4 (very high).

The data analysis technique was carried out through Structural Equation Modeling (SEM) with a quantitative approach and applying the Analysis of Moment Structures (AMOS) software version 22. The model structure validation measurement was analyzed by applying Confirmatory Factor Analysis (CFA). This step confirms whether the data support the hypothesised measurement model obtained [64].

Before the SEM analysis, the normality and sample adequacy assumptions were first tested. The results of the Assessment of Normality showed multivariate abnormality, with a critical kurtosis ratio value of 52.89 (> ±5) [65]. To address this, the analysis was conducted using the Bollen–Stine bootstrap method (2000 resampling), so that the model fit test and parameter estimate remained reliable even though the data were not normally distributed. The Bollen–Stine bootstrap results showed a p-value = 0.207 (> 0.05) [66], indicating that the model fits the empirical data even though the normality assumption was not met. The number of 187 respondents was considered adequate for SEM analysis, as it met the minimum criteria of 150 respondents [55] and a ratio of at least 5–10 times the number of estimated parameters.

Data analysis was carried out through 3 main stages, namely: 1) analysis of model feasibility by looking at the value of the goodness of fit model indicator [67], namely CMIN/df = ≤ 3, RMSE = < 0.08, RMR = < 0.50, GFI = ≥ 0.90, TLI = ≥ 0.90, and CFI = ≥ 0.90 (for the Chisquare index, RMSE and RMR are said to be getting better if they approach 0, while for the GFI index, TLI and CFI are said to be getting better if they approach a value of 1), 2) analysis of construct validity and reliability through factor loading and convergent validity, 3) and analysis of research hypothesis testing by looking at the β value in the research variables. (See Table 1).

Table 1. Convergent validity formula ([68–70])

Convergent Validity	Formula	Objectives	Criteria
AVE	$\frac{\sum \lambda_i^2}{\sum \lambda_i^2 + \sum \theta i}$	Measuring convergent validity	≥ 0.5
CR	$\frac{(\sum \lambda_i)^2}{(\sum \lambda_i)^2 + \sum \theta i}$	Measuring construct reliability	≥ 0.7

III. Results and Discussion

A. Reliability and Validity of Construct

The first step in Structural Equation Models is to check the suitability of the initial model through AMOS, with the finding that the model does not fit as indicated by the values of CMIN/df = 9.472, RMSE = 0.213, GFI = 0.700, RMR = 0.088, TLI = 0.714, and CFI = 0.764. The Goodness of Fit Model indicator falls below the predetermined standard criteria, necessitating modifications to the indices (MI). The MI results indicate a statistically significant relationship that could improve model fitness. This step will make the final model more representative of the empirical data without compromising conceptual validity. [71, 72] Modification Indices are used as a measuring tool to identify parameters that need to be improved to improve model fitness.

The modification indices shown in Table 2 were a reference for constructing a relationship line according to the recommended variables to obtain a fit model (Fig. 2). Table 2 also illustrates that one relationship was overlooked in the initial model development: the addition of covariance, or a path, between the gamification and STEAM variables. This indicates that the interaction between these variables also influences students' critical thinking skills, so the model was modified accordingly.

Based on the Modification Indices (MI) results, several relationships showed relatively high MI values, indicating potential relationships between constructs and error terms that could improve the model's fit to empirical data. The highest MI value was found for the relationship between the Gamification construct and STEAM (MI = 149.051), indicating that adding a correlation or direct path between the two could significantly improve the model. Theoretically, this relationship is justified because the gamification approach has been shown to increase student motivation, engagement, and creativity in STEAM (Science, Technology, Engineering, Arts, and Mathematics)-based learning. This is in line with the findings of Boytchev and Boytcheva [73], Wu *et al.* [74], Sailer and Homner [75], who emphasized that gamification supports the effectiveness of STEAM learning by enhancing interactive and meaningful learning experiences. Apart from that, several high MI values also appeared in the correlation between error terms, such as between e11 ↔ e12 (MI = 69.253), e10 ↔ e14 (MI = 29.051), e11 ↔ e14 (MI = 25.131), e7 ↔ e12 (MI = 51.137), e12 ↔ e14 (MI = 29.051), e6 ↔ e10 (MI = 6.407), e9 ↔ e11 (MI = 31.984), e9 ↔ e11 (MI = 15.673), e7↔ e9 (MI = 4.967), e6 ↔ e9 (MI = 4.757), and e5↔ e14 (MI = 8.462). The addition of correlation between the error terms is acceptable because the related indicators share a common measurement aspect or method effect. This

condition can occur because the items measure overlapping dimensions of learning behaviour or are influenced by the same task context and presentation method. Thus, the covariance relationship between the error terms is conceptually acceptable as a reflection of the natural interrelationship between indicators within a single learning domain.

Table 2. Recommendations based on modification indices

Error Terms			M.I.	Par Change
Gamification	↔	STEAM	149.051	0.084
e7	↔	e12	51.137	0.076
e 6	↔	e10	6.407	−0.004
e12	↔	e14	29,051	0.053
e11	↔	e14	25.131	0.048
e11	↔	e12	69.253	0.070
e10	↔	e14	14.847	−0.014
e 9	↔	e11	31.984	0.059
e 9	↔	e12	15.673	0.042
e7	↔	e9	4.967	0.014
e6	↔	e9	4.757	−0.012
e5	↔	e14	8.462	0.015

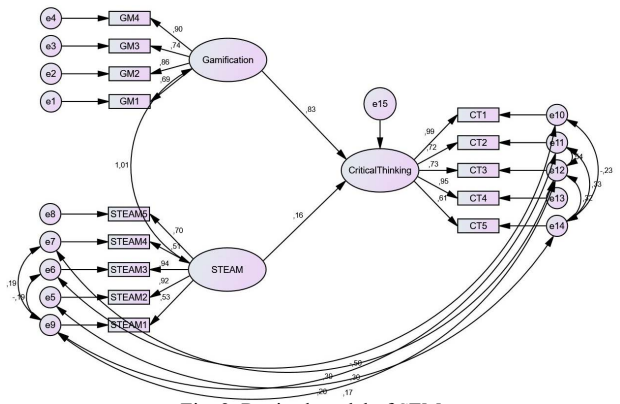

Fig. 2. Revised model of SEM.

Theoretically, this relationship reinforces the assumption that gamification-based learning and STEAM build cognitive competencies and foster affective and social interactions that mutually influence the development of higher-order thinking skills. Therefore, the covariance relationships identified through modification indices are not a deviation from the model, but rather an empirical representation of the complexity of the multidimensional relationships between variables in 21st-century education [76–79]. Model adjustments through these covariance relationships strengthen the structural model's conceptual validity, which depicts the dynamic and interactive reality of learning.

The model significantly improved the feasibility index after modifications based on theoretically relevant MI recommendations (Fig. 2). The model demonstrates goodness of Fit with a CMIN/df value of 1.891, RMSE of 0.069, GFI of 0.914, RMR of 0.011, TLI of 0.970, and CFI of 0.979. These results suggest that the simultaneous integration of gamification and STEAM is an effective model for improving critical thinking skills [80].

The factor loading values (more than 0.5) presented in Table 3 indicate that all indicators in the research variables positively correlate with their respective constructs [81]. Furthermore, the level of validity is determined through convergent validity analysis, which includes the Average Variance Extract (AVE) and the Composite Reliability (CR) values calculated based on the factor loading values. The results state that all research variables are reliable and valid, namely gamification (α = 0.95, CR = 0.88 > 0.7, α = 0.95, AVE = 0.64 > 0.5), STEAM (α = 0.95, CR = 0.85 > 0.7, AVE = 0.55 > 0.5), and Critical Thinking Skills (CR = 0.90 > 0.7, AVE = 0.66 > 0.5) [59]. The AVE value obtained indicates that each variable construct can explain approximately 55% to 66% of the variance of its constituent indicators [82]. Meanwhile, the Cronbach's Alpha value reflects the internal consistency reliability of a construct, with a recommended minimum value range of 0.70 and 0.60 for exploratory research [83, 84]. Other studies have suggested that the CR value can be a substitute for Cronbach's Alpha, as it is more accurate and representative in reflecting construct reliability. In addition, CR considers varying loadings and error variances, thus better aligning with the actual measurement model [55, 85].

Table 3. The results of reliability and validity

Constructs	Indicators	Factor Loading	Information	A	CR	AVE
Gamification	GM1	0.69	Valid	0.95	0.88	0.64
	GM2	0.86	Valid			
	GM3	0.74	Valid			
	GM4	0.90	Valid			
STEAM	STEAM1	0.53	Valid	0.95	0.85	0.55
	STEAM2	0.92	Valid			
	STEAM3	0.94	Valid			
	STEAM4	0.51	Valid			
	STEAM5	0.70	Valid			
Critical Thinking Skills	CT1	0.99	Valid	0.95	0.90	0.66
	CT2	0.72	Valid			
	CT3	0.73	Valid			
	CT4	0.95	Valid			
	CT5	0.61	Valid			

Table 4. The results of the hypothesis

Hypothesis	Results	Evidence	
		B	p
H1: There is a correlation between gamification learning and students' critical thinking skills	Accepted	0.83	＜0.01
H2: There is a correlation between STEAM learning and Students' critical thinking skills.	Accepted	0.16	＜0.01

Based on the analysis results presented in Table 4, it is evident that the H1 and H2 hypotheses can be accepted, indicating that gamification and STEAM learning have a positive impact on students' critical thinking skills in biology learning. The strong correlation between variables is indicated by the β value, which approaches 1 [86]. Gamification learning is considered to be more significantly correlated (β value = 0.83 > 0.5) with students' critical thinking skills compared to STEAM learning (β value = 0.16 < 0.3). In addition, based on the findings on the model fit, it is also confirmed that STEAM and gamification are learning approaches that positively impact each other. In other words, the integration between gamification and STEAM strengthens the influence on improving students' critical thinking skills (β value = 1.01 > 0.5).

B. Correlation of Gamification Learning with Critical Thinking Skills

SEM (Structural Equation Modeling) analysis findings, using AMOS, have shown that gamification elements

significantly correlate with students' critical thinking skills. The β value obtained = 0.83 > 0.5 indicates that gamification significantly impacts students' critical thinking skills [87]. This suggests that gamification has a significant influence, where a one-standard-deviation increase in the variable is followed by a 0.83-standard-deviation increase in critical thinking skills [88]. Gamification elements are used to create fun and accessible learning experiences that increase student engagement and motivation. Previous research [89–91] explain that gamification elements can increase intrinsic motivation and student engagement in learning, facilitating higher-order thinking processes such as analysis, evaluation, and problem-solving.

C. Correlation of STEAM Learning with Critical Thinking Skills

The analysis found that the STEAM variable correlated with improving critical thinking skills, but not as strongly as the contribution of the gamification variable. A β value of 0.16 < 0.3 indicates that the STEAM variable only contributed 0.16 to the increase in the standard deviation of the critical thinking skill variable. This finding suggests further study on the separate effectiveness of this approach in classroom learning applications. However, the researchers analyzed the characteristics of the gamification and STEAM approaches as key contributing factors. Gamification and STEAM have a significant impact on students' cognitive development, particularly in enhancing critical thinking skills. However, gamification tends to provide direct and personal cognitive stimuli that enables the emergence of motivational boosts, self-control, strategy evaluation, and rapid responses, thus triggering critical thinking skills. Meanwhile, STEAM focuses more on collaboration, creativity, and the final product than the cognitive reflective process, so the impact on critical thinking skills is not directly apparent. [92–95] The intrinsically motivated students tend to be more active in evaluating, analyzing, and reflecting on knowledge, which is part of critical thinking skills.

Furthermore, the relatively weaker effect of STEAM compared to gamification can be explained by several contextual factors. From a learning culture perspective, many students, including those in Indonesia, are still accustomed to structured, exam-oriented learning patterns. The STEAM approach, which emphasizes cross-disciplinary exploration and creativity, sometimes aligns with these expectations. Conversely, gamification is more readily accepted due to its close connection to popular digital culture with which students are already familiar [96]. From a curriculum perspective, STEAM demands the integration of areas not always explicitly stated in the syllabus, while teachers are often constrained by time constraints and material achievement targets [97–99]. Regarding implementation, STEAM requires cross-disciplinary skills and additional resources [100]. At the same time, gamification can be implemented more simply through the use of points, badges, and leaderboards, resulting in a more immediate impact on student motivation [101]. Therefore, curriculum policy support, teacher capacity building, and adaptation to local learning cultures are crucial for STEAM to function optimally, and these elements mutually reinforce each other when combined with gamification.

STEAM (Science, Technology, Engineering, Arts, and Mathematics) is a holistic approach designed to develop 21st-century skills, including critical thinking. Project-based learning in the STEAM approach encourages students to solve authentic problems, think analytically, and work collaboratively in a cross-disciplinary environment [102]. STEAM-based projects also require students to integrate knowledge and skills and critically evaluate alternative solutions [48]. A bibliometric and systematic review emphasized that the STEAM learning environment improves technical skills and forms reflective and logical thinking in solving complex problems. This makes STEAM a relevant approach in developing critical thinking skills, mainly when used in the context of challenge-based learning.

D. Correlation of the Integrated Gamification and STEAM Learning with Critical Thinking Skills

With a value of β = 1.01 > 0.5, it indicates that the integration of gamification and STEAM is the strongest contributor in the model, influencing critical thinking skills by 1.01 standard deviations. Gamification and STEAM are a powerful, holistic, and effective combination of approaches to create a contextual and enjoyable learning environment. Gamification enhances students' motivation to engage in STEAM learning, which requires problem-solving and knowledge exploration to complete learning projects. The integration of gamification and STEAM offers students opportunities to collaborate in solving challenges through exploration, analysis, and reflection activities. Gamification elements inserted in STEAM learning can increase students' persistence in completing projects with fun. Therefore, the learning model that integrates gamification and STEAM approaches has a positive correlation with the development and improvement of students' critical thinking skills.

The combination of gamification and STEAM approaches allows students to be more emotionally and cognitively engaged in learning activities, improving their ability to analyze, evaluate, and draw inferences independently [103]. Applying gamification in STEAM learning contributes positively to the development of critical thinking and problem-solving skills, primarily through an experiential learning approach [73]. This combination of approaches can encourage an increase in students' conceptual knowledge abilities to become stronger metacognitive [62].

So far, learning that comprehensively integrates gamification and STEAM into science learning has not been widely discussed. A bibliometric review by Jantakoon *et al.* [39, 48] found only 34 Scopus documents examining gamification and STEAM integration between 2017 and 2023. Almost none explicitly examined the direct correlation with critical thinking skills. Thus, research in this area remains limited, and these findings offer the potential for broad, open scientific exploration.

E. Practical Implications, Limitations and Recommendations for Further Research

Implementing gamification and STEAM learning simultaneously, it was found that the determining factor for its success is the level of school readiness in using it. Not only the availability of facilities and infrastructure, but also the ability of teachers to spearhead success in achieving predetermined goals. Teachers must be equipped with a good

understanding of STEAM learning and the use of technological innovation, so that the knowledge transfer process focuses on meaningful learning, not just competition. Therefore, before implementing this approach, a teacher must ensure that the learning design has been prepared carefully.

The findings of this study offer practical implications, namely that integrating gamification and STEAM approaches can be an effective way to enhance students' critical thinking skills through project-based learning and technology. In other words, it is necessary to enhance teachers' abilities in designing adaptive STEAM and gamification learning through various training programs. One concrete example of the application of the STEAM-Gamification model in biology teaching in the classroom is that teachers can integrate STEAM through activities such as observing the mechanism of breathing: inspiration and expiration (Science), creating interactive e-posters (Technology), designing simple lung models (Engineering), creative visualization of air travel to the body through comics or posters (Art), and calculating the average respiratory frequency before and after the activity (Mathematics). All activities are packaged in a gamification system with mission levels, points, badges, leaderboards, and prizes to make the learning process more interesting and competitive.

The findings also have the potential to provide a reference in the world of education to develop learning innovations relevant to the needs of the 21st century. However, this study has limitations, namely, its implementation is still in a local context involving a limited number of samples and has not integrated technology further. In addition, this study only examines the correlation between gamification learning, STEAM, and critical thinking skills; it has not empirically tested the effectiveness of gamification and STEAM learning approaches in improving students' critical thinking skills. Therefore, further research is recommended to explore the integration of various approaches by considering a wider sample and examining the latest technology in relation to other high-level abilities.

The findings of this study indicate that integrating gamification-based learning with the STEAM approach significantly improves students' critical thinking skills in biology learning. These results align with previous studies that confirmed the effectiveness of STEAM in strengthening critical thinking skills through interdisciplinary learning [104], as well as research showing that gamification can improve students' motivation and metacognition [105]. However, unlike previous studies that examined the two approaches separately, this study presents an integrated conceptual model that combines the motivational power of gamification and the cognitive-reflective dimension of STEAM within a single empirical framework. Thus, these results confirm the research's scientific novelty, specifically empirical evidence that integrating the two approaches produces a stronger synergistic effect on developing critical thinking skills and provides new directions for designing more interactive and meaningful 21st-century biology learning experiences.

IV. Conclusion

The learning model, which integrates gamification, STEAM, and critical thinking skills, has been confirmed as valid and reliable through the Structural Equation Modeling (SEM) approach. This finding suggests that each variable in the model makes a significant contribution to strengthening students' critical thinking skills. Furthermore, the findings have also supported the research hypothesis that gamification and STEAM learning are positively correlated with critical thinking skills. In addition, this study also highlights the finding that integrating the two provides a stronger correlation with critical thinking skills. This explains that combining gamification and STEAM learning can have a greater impact than if applied separately. This integration has been proven to create a learning environment that encourages student engagement and motivation through gamification and develops the ability to analyze and solve problems through project learning contained in STEAM.

However, this study has limitations, namely: (1) implementation is still limited to the local educational context, high school level with participants who are already familiar with technology and biology learning, (2) the sample size is relatively small so that the generalizability of the results is limited, and (3) the focus of the study only on correlational relationships has not tested the direct effectiveness of the combination of gamification and STEAM in improving critical thinking skills. Therefore, further research is recommended to involve larger and more diverse samples and test the effectiveness of the intervention experimentally.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jayanti Syahfitri contributed to the article's drafting, conceptualization, and data interpretation. Meti Herlina collected the data and reviewed the final manuscript. Muntanah designed and processed the data. Furthermore, Kasmiruddin and Mivtha Citraningrum helped validate the data and compiled the results table. All authors had approved the final version.

Funding

The authors would like to express sincere gratitude to the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology for funding this research through the Fundamental Research Grant Program, under the grant number: 123/C3/DT.05.00/PL/2025, and Agreement/Contract Number: 158/LL2/DT.05.00/PL/2025, 126/LPPM/II.3.AU/I/2025.

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