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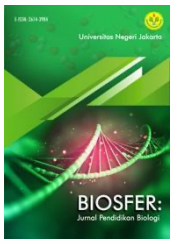

Gamification-assisted project-based learning in biology education: Critical thinking and collaboration among students in urban Medan, Indonesia

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ABSTRACT

In 21st-century learning, students are required to develop critical thinking and collaboration skills. Project-Based Learning (PjBL) integrated with gamification is considered a potential approach to support these competencies. This study aimed to examine the effect of gamification-assisted PjBL on Grade X students' critical thinking and collaboration skills in the biodiversity topic at SMAN 21 Medan. The study employed a quasi-experimental method using a Non-Equivalent Control Group design, involving class X5 as the experimental group and class X7 as the control group selected through random sampling. Critical thinking skills were measured using ten essay questions representing five indicators, while collaboration skills were assessed through an observation sheet based on four indicators. The results showed a significant difference between the experimental and control groups. The t-test analysis of critical thinking skills yielded a significance value of 0.016 (< 0.05), with the experimental group achieving a higher posttest mean score (75.25) than the control group (61.60). Similarly, collaboration skills showed a significant difference with a significance value of < 0.001. These findings indicate that gamification-assisted PjBL has a positive effect on improving students' critical thinking and collaboration skills compared to PjBL without gamification. Therefore, it is recommended that biology teachers integrate gamification elements such as points, badges, and challenges into project-based learning to enhance students' critical thinking and collaboration skills.

INTRODUCTION

The rapid advancement of digital technologies in the 21st century has transformed various sectors, including education, necessitating a fundamental shift in instructional strategies to foster students' cognitive and social competencies (UNESCO, 2021; Voogt & Roblin, 2012). Biology education, in particular, has undergone a substantial paradigm shift as learning objectives now extend beyond the memorization of factual knowledge to the development of essential 21st-century skills such as critical thinking, collaboration, communication, creativity, and digital literacy (Dewi & Arifin, 2024). Despite these expectations, many students still struggle to reach the desired level of competence. High school students' critical thinking skills remain low, as shown by an average pretest score of 38.30, which falls into the "low" category (Mukrimah et al., 2023). High school students' collaboration skills remain low, particularly in coordinating roles and communicating ideas during group work (Sari et al., 2025).

Critical thinking and collaboration skills among senior high school students in Medan City still require reinforcement through structured instructional designs oriented toward 21st-century skills. A study conducted on Grade X students at SMA Negeri 7 urban Medan revealed that students' critical thinking and collaboration skills were not yet optimal when learning activities remained conventional and teacher-centered, resulting in limited student engagement in inquiry processes and meaningful discussions (Sipayung et al., 2019). Consistent with these findings, Simatupang et al. (2023) reported that critical thinking and collaboration skills of senior high school students in Medan had not yet been optimally developed, as classroom practices were still predominantly focused on cognitive achievement rather than higher-order thinking processes. Therefore, the implementation of active and student-centered learning models such as Project-Based Learning, which are systematically designed to promote critical thinking and collaboration skills, is essential for senior high school students in Medan.

The problem becomes more prominent in the biodiversity topic, which is frequently perceived by students as abstract and disconnected from their daily experiences. Students often rely heavily on rote memorization of classifications and scientific terms without fully understanding the underlying concepts or their real-world applications. Research from a secondary school context reveals that students exhibit limited biodiversity knowledge, even when attitudes about biodiversity are generally high, indicating challenges in achieving comprehensive biodiversity literacy (Aslan & Efe, 2022). At the same time, collaboration—another essential 21st-century competency—has not been developed optimally. The results indicated that the collaboration skills of senior high school or equivalent students in Indonesia were predominantly at a developing level, with a substantial proportion demonstrating good collaboration skills, while a smaller group remained at an emerging level (Mardian et al., 2023).

Factors such as facilities, learning media, and teacher readiness also influence the learning process, but recent studies indicate that pedagogical approaches are the most decisive component in developing students' critical thinking and collaboration skills. Therefore, PjBL becomes a strategic choice because it has been proven to significantly enhance both critical thinking and collaboration skills (Aifah & Astriani, 2024). Meta-analytic evidence suggests that project-based learning is generally more effective than traditional instruction in improving complex skills such as critical thinking and collaboration (Strobel & Van Barneveld, 2018). Research indicates that PjBL contributes to students' critical thinking development by situating learning in real-world contexts, encouraging deeper exploration, and enabling students to construct meaningful knowledge through active participation (Surahman et al., 2019; Ary et al., 2023). However, in practice, the potential of PjBL is not always fully realized. Teachers often encounter obstacles such as limited instructional time, varying student motivation, inconsistent group participation, and challenges in sustaining engagement throughout the project duration.

Limitations in student involvement indicate the need for additional strategies to strengthen engagement in project-based tasks. Gamification—through elements such as points, badges, and challenges—leverages motivational principles to increase participation, persistence, and enjoyment, making it particularly effective in project-based learning contexts that require sustained effort and collaboration (Sailer & Homner, 2020; Subhash & Cudney, 2018). Gamification integrates game elements such as points, badges, and challenges into learning environments to enhance student motivation, engagement, and persistence, particularly in instructional contexts that demand sustained effort and active participation (Dichev et al., 2015). Research by Fazarini et al. (2024) demonstrated that the G-PjBL model (Project-Based Learning integrated with gamification) significantly enhances student engagement, collaboration among group members, and learning outcomes compared to conventional

PjBL alone. Gamification can help maintain student enthusiasm, encourage equal contribution among group members, and provide immediate feedback that supports improvement. Previous research by Rasyid & Khoirunnisa (2021) indicates that PjBL alone can already improve collaboration skills, suggesting that the addition of gamification may further strengthen group dynamics, communication, and shared responsibility.

Although Project-Based Learning (PjBL) has been shown to improve students' critical thinking and collaboration skills (Kokotsaki et al., 2016; Han et al., 2015), student engagement and motivation often remain challenging. Integrating gamification into PjBL has been proven to enhance motivation, engagement, and group dynamics (Khuluq et al., 2023; Ekaputra, 2025). Therefore, this study is important to examine the effectiveness of gamified PjBL in improving students' collaboration and critical thinking skills compared to conventional PjBL. Based on these considerations, this study aims to investigate the effect of Project-Based Learning assisted by gamification strategies on students' critical thinking and collaboration skills in the biodiversity topic. The research seeks to fill the existing gap by providing empirical evidence on whether the combined approach can enhance both cognitive and interpersonal competencies more effectively than non-modified PjBL implementations. In addition to determining its effectiveness, the study also explores how gamification supports students' motivation and engagement, both of which are crucial in ensuring meaningful involvement in project activities.

While previous research suggests that PjBL can improve collaboration (Rasyid & Khoirunnisa, 2021), integrating gamification into this model is proven to further strengthen group responsibility and provide immediate feedback that sustains student enthusiasm (Khuluq et al., 2023). Previous research synthesizing studies on gamified project-based learning demonstrates that gamification elements embedded in PjBL environments can enhance student motivation, engagement, and overall learning experience, which supports the theoretical rationale for integrating gamification into PjBL in this study (Wang & Huang, 2023). This study is novel because it specifically integrates gamification into PjBL within the context of 10th-grade biodiversity topics—an area where these combined approaches are rarely explored. By explicitly measuring the synergy between higher-order thinking and team-based dynamics, this research seeks to fill the existing gap in biology education. Consequently, this study aims to investigate the effect of gamification-assisted PjBL on students' critical thinking and collaboration skills, providing empirical evidence on how structured game mechanics can transform the learning experience into a more effective and engaging process.

METHODS

Research Design

This study employed a non-equivalent control group design, which is a type of quasi-experimental design used to examine the effects of an intervention in natural settings where random assignment of participants is not feasible (Capili, 2024). In this study, pretest and posttest measurements were administered to both the experimental and control classes to examine the effect of gamified Project-Based Learning (PjBL) on students' critical thinking and collaboration skills.

Population and Samples

The population of this study consisted of all tenth-grade students at SMA Negeri 21 Medan in the 2024/2025 academic year, totaling 281 students distributed across eight classes. The sample used in this study comprised two classes. The study employed a cluster random sampling technique applied to the existing class groups, resulting in the selection of two classes: X5 as the experimental class and X7 as the control class, each consisting of 30 students.

Table 1
Population and Sample Characteristics

Group	Class	Number of Students	Treatment
Experimental	X-5	30	PjBL with Gamification
Control	X-7	30	PjBL
Total Sample		60	

Instrument

The critical thinking test consisted of ten essay questions developed based on Ennis's (1985) critical thinking indicators, including elementary clarification, basic support, inference, advanced clarification, and strategy and tactic. Collaboration skills were assessed using an observation sheet

adapted from Greenstein's (2012) collaboration indicators, covering productive work, valuing others' opinions, compromise, and shared responsibility, measured using a four-point rating scale.

Content validity of both instruments was established through expert judgment conducted by two expert lecturers. The essay test obtained average expert scores of 2.9 and 2.5 on a four-point scale, indicating that the items were valid and appropriate for measuring students' critical thinking skills. Meanwhile, the collaboration observation sheet achieved a content validity score of 87.5%, which falls into the very valid category, demonstrating strong alignment with the learning objectives and collaboration indicators. Consistent with Haladyna & Rodriguez (2013), constructed-response tests emphasize content validity based on expert review rather than item-level statistical analysis. Instrument reliability was ensured through consistent assessment procedures, including the use of clear scoring rubrics for the observation sheet and predefined scoring guidelines for the essay test to maintain stable and consistent measurement across assessments.

Procedure

The research instruments, consisting of a critical thinking test and a collaboration observation sheet, were developed by the author based on the learning objectives and indicators of critical thinking and collaboration skills. Validity was assessed by two expert lecturers who evaluated the content, construct, and clarity of the instruments. The learning module was developed by integrating gamification strategies into Project-Based Learning (PjBL). The development process included defining learning objectives and skill indicators, designing project-based activities embedded with gamification elements such as challenges, points, badges, and leaderboards, and preparing step-by-step guidelines for students and teachers. The module was validated by subject matter and instructional design experts to ensure clarity, relevance, and appropriateness for the intended learning context.

In the implementation phase, the experimental class applied the gamified PjBL module, where students actively engaged in projects, completed challenges, earned points or badges, and received continuous feedback. The control class applied PjBL without gamification, following the same project procedures but without additional motivational elements. Both classes were taught by the author to minimize instructional bias and ensure consistent delivery. Data were collected through pretest-posttest critical thinking assessments and collaboration observation sheets completed by observers during the project-based learning activities.

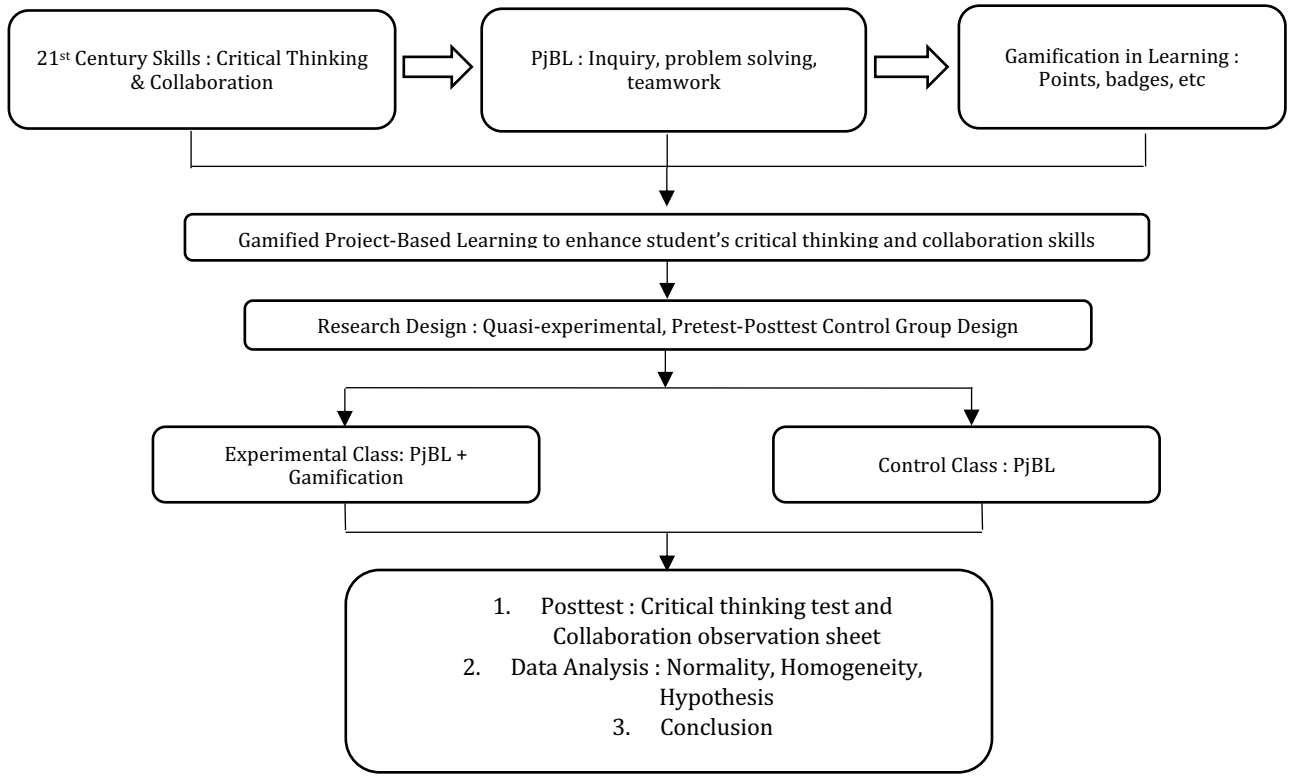

Figure 1. Conceptual framework and research design

Data Analysis Techniques

The data in this study consisted of pretest and posttest scores of critical thinking skills for both the control and experimental classes, as well as scores from collaboration observation sheets for both classes. The data analysis began with prerequisite tests, including normality and homogeneity tests. The normality test was conducted using the Kolmogorov–Smirnov test in SPSS version 30 to determine whether the data were normally distributed, where a significance value greater than 0.05 indicated normal distribution. Homogeneity was tested using Levene's Test to assess whether both groups had equal variances; a significance value greater than 0.05 indicated homogeneous variance.

Hypothesis testing for critical thinking skills was performed using an independent samples t-test to examine the mean differences between groups. A significance value less than 0.05 indicated a significant effect. For collaboration skills, the Mann–Whitney U test was used because the data were not normally distributed. As a nonparametric alternative to the t-test, this test requires no assumptions of normality or homogeneity. A significance value below 0.05 indicated that the null hypothesis was rejected. All data were collected quantitatively and presented in tables to compare the outcomes between the experimental and control classes.

RESULTS AND DISCUSSION

The results of this study include the description of pretest and posttest scores as well as observational data from the experimental and control classes. These data were used to examine the effect of the project-based learning model assisted by gamification strategies on the critical thinking and collaboration skills of tenth-grade students in the biodiversity topic at SMAN 21 Medan. Previous studies have reported that the critical thinking and collaboration skills of senior high school students in Medan have not yet been optimally developed, particularly when learning is dominated by conventional, teacher-centered approaches that provide limited opportunities for inquiry and collaborative interaction (Sipayung et al., 2019). In this context, the implementation of gamification-assisted project-based learning in the present study offered a learning environment that actively engaged students in problem solving, discussion, and teamwork, which is reflected in the observed improvement of students' critical thinking and collaboration skills in the experimental class.

Critical Thinking Skill

The results indicate that the experimental and control classes had comparable initial levels of critical thinking skills, as shown by the non-significant difference in pretest scores ($p > 0.05$). This confirms that both groups started from a relatively equal baseline before the intervention.

Table 2
The effect of PjBL assisted by gamification strategies on students' critical thinking skills

Indicators	Average		Sig (2-tailed)
	Experiment	Control	
Elementary Clarification	77.4±10	72.2±6.8	0.156
Basic Support	82.0±0.9	65.8±1.1	0.711
Inference	81.2±7.7	50.4±4.9	<0.001
Advanced Clarification	87.0±0.7	63.3±1.0	0.125
Strategies and Tactics	70.8±7.0	51.6±1.4	<0.001
Total (Posttest)	75.2±6.8	61.6±8.9	0.016

After the implementation of the learning models, a clear difference emerged between the experimental and control groups. The experimental class, which experienced Project-Based Learning integrated with gamification strategies, achieved a higher posttest mean score ($M = 75.2$) compared to the control class ($M = 61.60$). The independent samples t-test revealed a statistically significant difference between the two groups ($p < 0.05$), indicating that the gamified PjBL intervention had a significant effect on students' critical thinking skills.

From an instructional perspective, these findings suggest that the integration of gamification elements within the PjBL framework enhanced students' engagement in higher-order cognitive processes. Gamification components such as points, badges, and leaderboards functioned as motivational reinforcements that encouraged students to actively analyze problems, evaluate evidence, and justify their reasoning during project activities. These cognitive processes align closely with Ennis's

(1985) conception of critical thinking, which emphasizes analysis, inference, and strategic decision-making as core components of critical reasoning.

The findings of this study are consistent with previous research demonstrating the positive impact of Project-Based Learning on higher-order thinking skills. Studies by Fitriani et al. (2022) and Fatah (2025) reported that PjBL fosters critical thinking by engaging students in inquiry-oriented tasks that require argument construction and evidence-based reasoning. Similarly, Holm (2011) emphasized that PjBL facilitates higher-order cognitive skills through complex, inquiry-driven learning activities. Furthermore, the integration of gamification has been shown to strengthen this effect by sustaining students' motivation and cognitive persistence, as reported by Wijayanti and Kurniawan (2023) as well as Wang and Tahir (2020).

From a contextual standpoint, previous studies have indicated that senior high school students in Medan, tend to demonstrate relatively low levels of critical thinking skills when learning remains teacher-centered and focused primarily on content mastery rather than cognitive processes (Sipayung et al., 2019). Although urban students are generally familiar with digital technology, interactive media, and fast-paced information environments, these characteristics do not automatically translate into strong critical thinking skills without structured learning designs that explicitly train analytical and evaluative reasoning. The gamification-assisted PjBL model implemented in this study provided a learning context that aligned with students' urban characteristics while simultaneously offering systematic cognitive scaffolding through project tasks and reflective activities.

Theoretically, these results support the view that learning environments combining meaningful cognitive challenges with motivational stimuli create optimal conditions for developing critical thinking skills. As argued by Kokotsaki et al. (2016), PjBL encourages learners to formulate authentic problems and generate solutions through reflective thinking. The present findings extend this perspective by demonstrating that the integration of gamification enhances the effectiveness of PjBL, enabling students to engage more deeply in analytical and evaluative reasoning processes. The observed improvement in posttest scores indicates that students in the experimental class became more capable of analyzing information, evaluating alternatives, and drawing logical conclusions within the context of biodiversity learning.

Collaboration Skill

The analysis of collaboration skills revealed a significant difference between the experimental and control classes. Because the collaboration data were not normally distributed ($p < 0.05$), the Mann–Whitney U test was applied.

Table 3
The effect of PjBL assisted by gamification strategies on students' collaboration skills.

Indicators	Average		Sig (2-tailed)
	Experiment	Control	
Working productively	2.43±0.56	1.70±0.46	<0.001
Respecting others' opinions	3.36±0.49	2.43±0.62	<0.001
Compromising	2.36±0.49	1.60±0.49	<0.001
Shared responsibility	2.80±0.57	1.70±0.46	<0.001
Total (Posttest)	2.73±0.39	1.83±0.30	<0.001

The results of this study revealed a highly significant difference in collaboration skills between the experimental and control groups ($p < 0.001$), indicating that the gamification-assisted Project-Based Learning (PjBL) intervention had a strong effect on students' collaborative abilities. Descriptively, students in the experimental class achieved a higher mean collaboration score ($M = 2.73$, good category) compared to those in the control class ($M = 1.83$, fair category). This finding demonstrates that students who learned through gamified PjBL exhibited more effective cooperative behaviors, including shared responsibility, productive teamwork, and mutual respect during learning activities.

The improvement in collaboration skills can be explained by the social and motivational mechanisms embedded within gamified project-based learning. Gamification elements such as group points, leaderboards, and team-based rewards promoted positive interdependence, where students' success depended on collective effort rather than individual performance. This condition encouraged students to communicate more effectively, negotiate roles, and support one another throughout the

project completion process, as described in gamification theory (Deterding et al., 2011). As a result, collaboration was not only encouraged but became an essential component of task achievement.

From a contextual perspective, previous studies have indicated that collaboration skills among senior high school students in Medan, tend to be underdeveloped when learning remains teacher-centered and focuses primarily on individual academic achievement (Sipayung et al., 2019). Although urban students are generally familiar with digital media, interactive environments, and social networking in their daily lives, these experiences do not automatically translate into effective academic collaboration without structured learning designs. The findings of this study suggest that gamified PjBL provided a learning environment that aligned with students' urban characteristics while simultaneously scaffolding meaningful collaborative interactions.

These findings are consistent with prior research showing that gamified project-based learning environments foster collaboration by motivating students to actively contribute to group success (Hidayat & Nugraha, 2023). Furthermore, the results support the theoretical framework proposed by Trilling and Fadel (2009), who emphasize collaboration as a core 21st-century skill that develops optimally through authentic, project-oriented learning experiences. In science education contexts, PjBL has been shown to positively influence students' learning outcomes while facilitating higher-order skills, including collaboration and critical thinking (Peng et al., 2023).

Overall, the combination of PjBL and gamification created a cooperative learning environment that strengthened students' social interaction and teamwork skills. Project tasks required coordination in planning, execution, and evaluation, while gamification increased students' motivation to engage meaningfully within their groups. This finding aligns with Surahman and Alamsyah (2024), who reported that gamification enhances social interaction and team performance through challenge-based motivation. Collectively, these results demonstrate that gamified project-based learning is an effective instructional approach for improving collaboration skills in secondary biology education, particularly for urban students in Medan whose collaborative potential requires structured and purposeful instructional support.

CONCLUSION

This study concludes that Project-Based Learning integrated with gamification strategies significantly enhances students' critical thinking and collaboration skills. The experimental class demonstrated higher posttest scores than the control class, with mean critical thinking scores of 75.25 compared to 61.60 and collaboration scores of 2.58 compared to 1.84, indicating statistically significant differences between groups ($p < 0.05$). These results confirm that the integration of gamification elements within a PjBL framework effectively supports higher-order cognitive processes and cooperative learning by increasing student engagement and active participation during project-based activities.

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