Enhancing Students' Critical Thinking in Fluid Mechanics through PBL-Based Escape Room Games: Evidence of Significant Improvement

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Abstract: This study aims to examine the effect of escape room games based on Problem-Based Learning on students' critical thinking in fluid mechanics. A quasi-experimental method with a nonequivalent control group design was employed, involving an experimental and a control class. Data were collected through critical thinking tests and student response questionnaires, and analyzed using normality tests, mean difference tests, normalized gain (N-gain), and effect size. The results provide evidence of significant learning gains, with the experimental class achieving a high normalized gain (N-gain = 0.74) and a large effect size (d = 0.82), indicating a statistically significant effect compared to the control class ($p < 0.05$). In addition, student responses were categorized as very good, reflecting increased engagement, motivation, and conceptual understanding. These findings suggest that escape room games based on Problem-Based Learning constitute an effective and innovative instructional approach for enhancing students' critical thinking in physics, particularly in fluid mechanics.

Abstrak: Penelitian ini bertujuan untuk mengkaji pengaruh permainan escape room berbasis Problem-Based Learning terhadap kemampuan berpikir kritis siswa pada materi fluida. Penelitian ini menggunakan metode kuasi-eksperimen dengan desain nonequivalent control group yang melibatkan kelas eksperimen dan kelas kontrol. Data dikumpulkan melalui tes kemampuan berpikir kritis dan angket respons siswa, kemudian dianalisis menggunakan uji normalitas, uji perbedaan rata-rata, perhitungan normalized gain (N-gain), serta effect size. Hasil penelitian menunjukkan adanya peningkatan yang signifikan, dengan kelas eksperimen memperoleh nilai N-gain sebesar 0,74 (kategori tinggi) dan effect size sebesar 0,82 (kategori besar), yang menunjukkan adanya pengaruh signifikan dibandingkan dengan kelas kontrol ($p < 0{,}05$). Selain itu, respons siswa terhadap pembelajaran berada pada kategori sangat baik, yang mencerminkan peningkatan keterlibatan, motivasi, dan pemahaman konsep. Temuan ini menunjukkan bahwa permainan escape room berbasis Problem-Based Learning merupakan pendekatan pembelajaran yang efektif dan inovatif untuk meningkatkan kemampuan berpikir kritis siswa dalam pembelajaran fisika, khususnya pada materi fluida.

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A. Introduction

The transformation of 21st-century education necessitates that pupils have a range of essential skills relevant to the rapid advancement of science and technology. The National Education Association (2010) highlights how crucial it is to develop the 4Cs: communication, creativity, teamwork, and critical thinking. Thinking critically is a rational and reflective thinking skill that helps students analyze information, evaluate arguments, overcome issues and reach reasonable conclusions and based on evidence—a critical requirement in modern science education (Ennis, 1996; National Research Council, 2012). However, numerous studies show that pupils' critical thinking abilities, particularly in physics education, remain relatively low (Fitri et al., 2025; Neswary & Prahani, 2022; Pratama, 2023; Suprapto et al., 2024). This situation is caused by insufficient training in higher-order cognitive abilities and by the continued dominance of conventional approaches and routine problem-solving, resulting in students being less accustomed to analyzing problems in depth (Suprapto et al., 2024).

Thinking critically is a logical, reflective skill that involves analyzing information and evaluating evidence in problem-solving (Ennis, 1996). This ability involves decision-making based on logical, systematic considerations in understanding a problem (Ennis, 1996). Ennis (1996) defines critical thinking as a methodical, introspective process that focuses on choosing what to believe or do.

According to Ennis (2011), Indicators of critical thinking focus on the ability to make logical decisions and encompass five main categories: Strategy and tactics, elementary clarification, advanced clarification, inference, and basic assistance. These five sets of indications systematically describe the stages of students' thinking activities, ranging from understanding problems, analyzing information, and evaluating evidence to formulating rational decisions (Ennis, 2011).

The systematic organization of indicators allows for the evaluation of critical thinking abilities across all stages of reasoning, thereby supporting a more structured measurement of these skills in the context of learning (Ennis, 2011).

Other experts have presented the concept of critical thinking from different perspectives, such as Facione (2015) who emphasizes abilities in self-control, interpretation, analysis, assessment, inference, and explanation; Elder (2005) who emphasizes Intellectual criteria include precision, logic, and clarity in the thinking process; and Brookfield (2012) who highlights the importance of reflecting on experience and considering various perspectives in decision-making. Nevertheless, the critical thinking indicators developed by (Ennis, 1996) They are considered more systematic and operational, making them easier to implement in learning assessments; consequently, they were used as the basis for measuring students' critical thinking skills in this study.

One PBL-based learning approach may enhance critical thinking skills (Dita et al., 2021). By having students tackle real-world contextual challenges, the PBL paradigm puts students at the center of their education (Barrows, 1996). This approach fosters critical thinking in addition to intellectual comprehension, communication, and collaboration skills

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through discussion and investigative activities (Bonafide et al., 2021). This model corresponds with the Merdeka Curriculum's implementation, which places a strong emphasis on contextual and active learning. According to earlier studies, PBL greatly improves pupils' critical thinking abilities (Suhirman & Khotimah, 2020).

Fluid mechanics is one of the key topics in high school physics education, featuring both conceptual and practical applications in daily life, such as hydrostatic pressure, Pascal’s law, and Bernoulli’s equation (Busyairi & Zuhdi, 2024). However, these concepts are abstract and require a high level of analytical ability, so students often struggle to understand the relationships among them and their application in problem-solving (Suherly et al., 2023). Therefore, fluid mechanics was chosen for this study because it is relevant for developing Critical thinking abilities of pupils.

Additionally, the use of innovative learning media is essential to enhance student engagement (Melianti et al., 2020). One such medium is the escape room game. This medium is a game-based learning approach that combines elements of challenge, puzzles, and teamwork to solve learning problems (Manojlovic, 2022; Nicholson, 2022; Nicholson & Cable, 2020). It has been demonstrated that using escape rooms in science classes increases students' cognitive engagement and aids conceptual understanding through a more interactive and engaging educational experience (Sánchez-Martín et al., 2020).

However, despite these developments, previous studies have predominantly examined Problem-Based Learning and escape room games separately, particularly in physics education. While PBL has been shown to enhance critical thinking skills, its integration with digital game-based learning environments remains limited. Conversely, escape room-based studies tend to emphasize engagement and collaboration rather than specifically measuring critical thinking outcomes. Furthermore, the application of such integrated approaches in fluid mechanics at the high school level is still rarely explored. Therefore, a clear research gap exists in integrating PBL and escape room games to enhance students’ critical thinking skills in physics learning.

Research on PBL and escape room games has been extensive, but most studies still examine the two separately. Research by Sánchez-Martín et al (2020) and Veldkamp et al (2020) shows that escape room games generally focus on improving student motivation and collaboration (Taraldsen et al., 2022), but their specific impact on critical thinking skills in physics learning has not yet been examined. On the other hand, research by Farah et al (2024) and Suhirman & Khotimah (2020) indicates that PBL effectively enhances students’ critical thinking skills, yet has not integrated digital game-based learning media. Furthermore, research on integrating PBL-based escape rooms into physics instruction, particularly in high school fluid mechanics, remains limited. Bibliometric analysis indicates that research on escape rooms, PBL, and critical thinking is still developing in isolation and has not yet been widely combined in digital media-based physics instruction.

This study addresses this gap by integrating a Problem-Based Learning framework within a digital escape room environment specifically designed for fluid mechanics instruction. In addition, this study employs the Ennis critical thinking framework as a

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structured basis for measuring students' critical thinking skills. This combination of instructional model, game-based learning media, and cognitive assessment represents a novel contribution that has not been widely implemented in previous studies.

Results from interviews with 11th-grade physics teachers indicate that students still struggle to understand fluid concepts such as pressure and Bernoulli's equation, their critical thinking skills remain low, and instruction is still dominated by lecture-based methods with limited use of instructional media.

Based on these considerations, this study seeks to examine whether implementing a PBL-based digital escape room significantly improves students' critical thinking skills in fluid mechanics and to determine the magnitude of its effect relative to conventional learning. It is hypothesized that implementing a PBL-based digital escape room has a significant positive effect on students' critical thinking skills compared with conventional instruction.

In response to these issues, this study aims to examine how an escape room game based on Problem-Based Learning affects 11th-grade students' critical thinking skills. The findings of this study are expected to contribute to the development of technology-based physics learning and support the integration of instructional models with game-based learning to improve higher-order thinking skills.

B. Method

The method used was a quasi-experimental study with a nonequivalent control group design, in which the experimental and control groups were not selected randomly (Creswell, 2014; Sugiyono, 2022). This design allows researchers to compare learning outcomes between classes receiving the treatment and those using the standard teaching methods typically employed by teachers in the classroom, even though the groups are not randomly equivalent (Creswell, 2014; Sugiyono, 2022). This quasi-experimental design is frequently used in educational contexts because class assignments are often predetermined by the school and do not allow for full randomization, yet it still provides information on the effectiveness of the intervention (Sugiyono, 2022). This research design is illustrated in greater detail in Table 1.

Table 1. Research Design: Nonequivalent Control Group Design

Group	Pretest	Treatment	Posttest
Experimental	O_1	X	O_2
Control	O_3	–	O_4

Notes:
O_1: Critical thinking pretest (experimental group)
O_2: Critical thinking posttest (experimental group)
O_3: Critical thinking pretest (control group)
O_4: Critical thinking posttest (control group)

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X: PBL-based Escape Room game

The study was conducted at State Senior High School 4 Bengkulu City, Indonesia. The population consisted of all Grade 11 students enrolled in physics classes during the 2025/2026 academic year, totaling 119 students. Purposive sampling was employed to select two classes with similar characteristics in terms of teacher, curriculum, learning materials, class schedule, and number of students. Class XI E was assigned as the experimental group (n = 39), while Class XI F served as the control group (n = 39). The assignment of the classes was determined through a random draw conducted by the teacher to ensure objectivity.

Data were collected using three instruments: a critical thinking skills test, a critical thinking assessment rubric, and a student response questionnaire. The critical thinking test consisted of 17 essay items developed based on Ennis's critical thinking indicators. The assessment rubric was used to evaluate students' critical thinking performance, while the questionnaire was administered to obtain students' perceptions of the learning process. Prior to implementation, all instruments underwent expert validation involving two university lecturers and one physics teacher. Reliability testing was conducted to ensure the consistency of the instruments before they were administered to the research participants (Kimberlin & Winterstein, 2008).

The research procedure consisted of several stages. First, instrument development and validation were conducted. Second, a pretest was administered to both groups to determine students' initial critical thinking skills. Third, the experimental group received instruction through a PBL-based escape room game on fluid mechanics, whereas the control group received conventional teacher-centered instruction involving lectures, discussions, and problem-solving activities. The intervention was implemented during the regular learning schedule for the selected topic. After the instructional treatment was completed, a posttest was administered to both groups to measure students' critical thinking skills. Finally, students in the experimental group completed a response questionnaire regarding their learning experiences. The overall research procedure is illustrated in Figure 2.

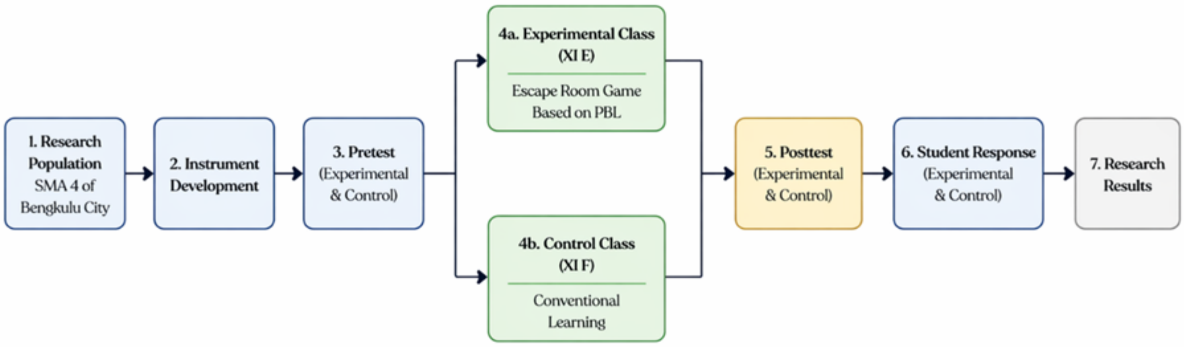

Figure 2. Research Flow

The escape room game was developed using the Genially platform and implemented as an interactive learning medium integrated with the stages of Problem-Based Learning.

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The game contained contextual problems and collaborative challenges related to fluid mechanics concepts, requiring students to analyze information, discuss solutions, and complete tasks to progress through the activities.

Data were analyzed using descriptive and inferential statistics. Descriptive statistics were employed to summarize students' critical thinking scores and questionnaire responses. The Shapiro Wilk test was used to assess data normality. For normally distributed data, paired-samples t-tests and independent-samples t-tests were conducted, whereas Wilcoxon signed-rank and Mann–Whitney tests were used for non-normally distributed data (Inayah et al., 2025). In addition, normalized gain and effect size analyses were performed to evaluate students' learning improvement and the magnitude of the intervention effect. All statistical analyses were conducted using SPSS software (Ghozali, 2018).

C. Result

The instrument was tested on 10 essay questions, each with sub-questions (a, b, c), yielding 30 test items that assessed pupils' capacity for critical thought. Tests were used to assess each test item independently in terms of empirical validity, reliability, discriminative power, and difficulty. The validity test results showed that 17 items met the validity criteria and were used as research instruments (Lukman et al., 2023). The test items were deemed valid because they had a significance value (Sig.) < 0.05 at the 5% significance level with a total of 32 student respondents, indicating that the items accurately measured critical thinking skill indicators. The complete Table 3 displays the findings of the validity test for the assessment items.

Table 3. Empirical Validity Results of the Critical Thinking Skills Instrument

Dimensions of Critical Thinking	Indicators	Concepts	No	Item Validation			
				Koef r (criteria)	p-value (criteria)	DP (criteria)	TK (criteria)
Elementary clarification	Formulating questions	hydrostatic pressure	1 A	0.467** (Enough)	0,007 (Valid)	0,419 (Good)	0,9 (Easy)
			1 B	0.695** (high)	< 0,001 (Valid)	0,665 (Good)	0,832 (Easy)
Advanced clarification	Identifying hidden assumptions	Pascal's law	2	0.483** (Enough)	0,005 (Valid)	0,234 (Enough)	0,68 (medium)
Strategy and Tactics	Formulating problems & solutions	continuity equation	3 A	0.624** (high)	<0,001 (Valid)	0,578 (Good)	0,568 (medium)
	Determining Solution Criteria		3 B	0.777** (high)	<0,001 (Valid)	0,744 (Very Good)	0,512 (medium)

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Dimensions of Critical Thinking	**Indicators**	**Concepts**	**No**	**Item Validation**			
				Koef r (criteria)	**p-value (criteria)**	**DP (criteria)**	**TK (criteria)**
	Identifying errors		3 C	0.770** (high)	<0,001 (Valid)	0,734 (Very Good)	0,506 (medium)
Elementary clarification	Formulating questions	Archimedes' law	4 A	0.603** (Enough)	<0,001 (Valid)	0,543 (Good)	0,632 (medium)
	Identifying claims		4 B	0.602** (Enough)	<0,001 (Valid)	0,569 (Good)	0,695 (medium)
	Identifying reasons		4 C	0.585** (Enough)	<0,001 (Valid)	0,534 (Good)	0,522 (medium)
Basic support	Assessing the credibility of sources	buoyancy	5 A	0.698** (high)	<0,001 (Valid)	0,657 (Good)	0,556 (medium)
	Assessing observation reports		5 B	0.663** (high)	<0,001 (Valid)	0,628 (Good)	0,5 (medium)
	Assessing the appropriateness of evidence		5 C	0.523** (Enough)	0,002 (Valid)	0,474 (Good)	0,47 (medium)
Inference	Making logical conclusions	Viscosity	6	0.675** (high)	<0,001 (Valid)	0,634 (Good)	0,562 (medium)
Advanced clarification	Defining concept boundaries	Capillarity and surface tension of	7 A	0.635** (high)	<0,001 (Valid)	0,577 (Good)	0,568 (medium)
	Distinguishing examples of concepts	liquids	7 B	0.594** (Enough)	<0,001 (Valid)	0,536 (Good)	0,5 (medium)
	Identifying hidden assumptions		7 C	0.734** (high)	<0,001 (Valid)	0,691 (Good)	0,438 (medium)
Strategy and Tactics	Formulate problems and alternative solutions	Applications of fluids in life	8	0.484** (Enough)	0,005 (Valid)	0,417 (Good)	0,756 (Easy)

Description: DP=Discriminating Power, TK=Difficulty Level

Cronbach's Alpha was used to assess the instrument's reliability (Zakariya, 2022). The reliability test indicated a reliability coefficient of 0.894, which falls in the very high category; Consequently, the instrument was judged reliable and appropriate for use.

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After the instrument was deemed valid and reliable, descriptive statistical analysis was carried out to characterize the distribution of students' pretest results for critical thinking skills and posttest scores in the experimental and control classes, including the skewness, kurtosis, mean, standard deviation, minimum, and maximum. An initial indication that learning through PBL-based escape room games can improve students' critical thinking skills in the experimental class is provided by Table 4, which displays differences in score distributions between the pretest and posttest results for the experimental and control groups.

Table 4. Descriptive Statistical Analysis (n=39)

Test	group	Min	Max	Mean	Std.Deviation	Skewness	Kurtosis
Pre	Control	11.76	22.35	18.40	2.046	- 1.024	1.930
	Experiment	11.76	31.76	21.56	4.860	-0.258	- 0.427
Post	Control	50.59	83.53	60.51	5.376	1.912	8.098
	Experiment	75.29	85.88	80.30	2.775	0.120	- 0.779

An overview of students' critical thinking abilities in the control and experimental courses before to and during the intervention was generated based on Table 4 presents the results of the descriptive statistical analysis. The average score for the control group during the pretest period was lower than that of the experimental class, with a narrower spread, whereas the experimental class showed greater variation in scores. In the posttest phase, both groups showed improvement; however, the experimental class exhibited a higher mean and a smaller standard deviation, indicating more consistent learning outcomes. Furthermore, the skewness and kurtosis values revealed differences in the allocation characteristics of the information between the parties. During the pretest, the control class had a skewness of -1.024 (left-skewed) and the experimental class -0.258 (slightly left-skewed), whereas in the posttest, the control class had a skewness of 1.912 (right-skewed) and the experimental class 0.120 (approaching symmetrical). The kurtosis values for each group also indicate variations in the shape of the data distribution. Overall, these findings imply that the distribution of data in the experimental class tends to be more even and consistent compared to the control class.

Before conducting a comparative analysis of the results of the pretest and posttest, a Shapiro-Wilk test was initially used for the normality test since the sample size was less than 50 (Korkmaz & Demir, 2023; Shapiro & Francia, 1972). According to the test findings, the pretest (0.194) and posttest (0.275) in the experimental class scores had significance values > 0.05, so the data were declared normal. Conversely, the pretest (0.008) and posttest (0.001) results in the control group had significance values < 0.05, so the data were declared non-normal. The normality test data are shown in Table 5.

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Table 5. Normality Test

Group	Test	Shapiro-Wilk*		
		Statistic	df	Sig.
Experiment	Pretest	0.961	39	0.194
	Posttest	0.966	39	0.275
Control	Pretest	0.918	39	0.008
	Posttest	0.830	39	<0.001

Note: *SPSS output

After conducting a normality test, Levene's Test was used to conduct a homogeneity of variance test. to determine whether the variance in critical thinking skill scores across classes was homogeneous. Based on the mean, Sig. = 0.040 (< 0.05), indicating that the variance is not homogeneous, whereas based on the median or trimmed mean method, the Sig. value is above 0.05 (0.053–0.055), indicating that the variance is nearly homogeneous. Under these conditions, the assumption of homogeneity is not fully met, or the data are not homogeneous.

The ensuing study compared the posttest scores on critical thinking abilities, depending on the results of the homogeneity and normality tests, the nonparametric Mann-Whitney U test was used to compare the experimental and control courses. The results of the Mann-Whitney U test showed a significant difference between the two groups ($p < 0.05$), particularly at the <0.001 level, indicating that the growth in critical thinking skills among students in the experimental class was significantly different from that of the control class. This suggests that PBL-based escape-room game-mediated learning improves students' critical thinking abilities. Table 6 displays the Mann-Whitney U-test findings.

Table 6. Mann-Whitney U' Test

Description	Value
Mann-Whitney U'	33.000
Wilcoxon W	813.00
Z	-7.286
Asymp. Sig. (2-tailed)	<0.001

The results of the Mann-Whitney U test reveal a significant difference between the posttest scores of the experimental and control classes. The effect size was 0.82, indicating $r \geq 0.5$, placing the effect in the large category. This means that the intervention—a PBL-based escape room game—is practically effective in enhancing students\' critical thinking abilities. This can be understood because students are encouraged to actively address issues using the PBL technique systematically, while the escape room game provides an engaging and challenging learning experience; thus, the combination of both strengthens student engagement and maximizes the transfer of students\' critical thinking abilities to fluid mechanics material.

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To assess an N-gain analysis was carried out for each class and indicator to examine the deeper development of critical thinking skills (Wahab & Azhar, 2021; Borle et al., 2025; Gustati et al., 2025). The experimental group's average N-gain was 0.74 (high category), but the control group was just 0.51 (moderate category). The N-gain analysis per indicator is shown in Figure 4.

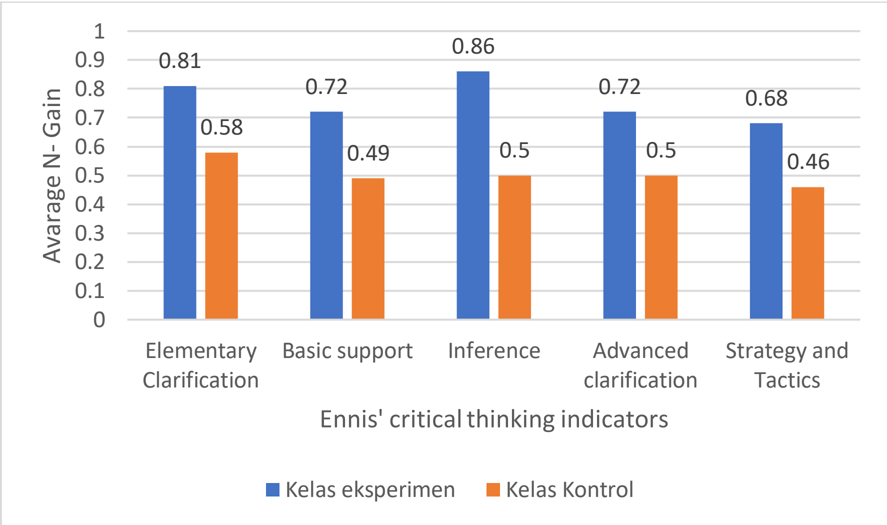

Figure 4. N-Gain Analysis Results of Ennis' Critical Thinking Indicators

Analysis by indicator revealed different patterns of improvement. The Inference indicator showed the greatest improvement in the experimental class, with an N-gain of 0.86, while the Strategy and Tactics indicator showed a lower improvement (0.68). This confirms that PBL-based escape room games effectively enhance critical thinking skills.

Furthermore, following the observed increase in N-gain, the student response questionnaire results indicate a notable distinction between the control and experimental groups regarding the implemented learning. The experimental class achieved a response rate of 90.44%, It is classified as "very good.", but the control group's rate of 70.32% is in the "good" range. This difference indicates that the experimental class provided a more effective learning experience for developing students' critical thinking abilities compared to what was normally taught in the control class, as Table 7 illustrates.

Table 7. Survey Results from the Experimental and Control Classes

Class	Response (%)	Category
Experiment	90.44	Very good
Control	70.32	good

The experimental class responded well to putting in place a digital escape room game based on PBL for the fluid mechanics module. Through this medium, students were presented with contextual problems requiring them to identify key information, analyze relationships among concepts, and formulate systematic problem-solving strategies. This

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activity aligns with the markers of critical thinking abilities in accordance with Ennis (2011), namely the ability to provide elementary clarification, build basic support, make inferences, provide advanced explanation, and arrange techniques and strategies.

In addition, solving puzzles and challenges at each level of the game motivates students to assess their answers and make revisions to strategies when they are not yet correct. This indicates that learning not only requires students to understand fluid concepts conceptually but also trains their reasoning, decision-making, and reflective thinking skills. Thus, PBL-based escape room games serve as a learning tool that facilitates higher-order thinking activities more effectively.

D. Discussion

The variation between the critical thinking abilities of the experimental and control groups shows the influence of the learning treatment provided. Pedagogically, this difference can be explained by the characteristics of the intervention applied to the experimental class, namely the integration of PBL with a digital escape room game mechanism that requires active student involvement in the problem-solving process (Makri et al., 2021). Learning that places students as the center of thinking activities tends to provide more space for the process of analysis, evaluation and reflection compared to learning that is oriented towards delivering material (Ghafar, 2023; Muganga & Ssenkusu, 2022). The study's findings show that using a PBL-based virtual escape room game to learn is useful for enhancing pupils' flexible critical thinking abilities. This effectiveness can be interpreted as meaning that a learning design that integrates contextual problem-solving with game mechanics is able to create deeper cognitive engagement compared to teacher-centered learning (Boom-Cárcamo et al., 2024; Kakos et al., 2024).

Empirically, in the class under experimentation, the learning process was active and collaborative. To finish each task in the escape room game, students worked in small groups. (Papadopoulos & Tenta, 2021). They discussed available information, identified relevant physics concepts, and assigned roles in completing necessary calculations or analyses. The classroom environment demonstrated intense interaction among group members, the emergence of scientific arguments, and clarification processes when disagreements arose. This contrasted with the control group, which frequently concentrated on the teacher's explanations, casual discussions, and individual practice problems.

In practice, each level of the game starts by outlining a contextual issue, such as a floating ship or a hydraulic system. This problem serves as a trigger, requiring students to clarify information and formulate initial questions. When the answer given is incorrect, students do not receive an immediate final correction; instead, they are encouraged to review their thinking. This process demonstrates independent reflection and strategic evaluation, which are key characteristics of developing critical thinking.

The conceptual and applied characteristics of fluid materials further strengthen these dynamics. Concepts such as hydrostatic pressure and Archimedes' law are understood not only as formulas but also as tools for solving real-life problems presented in the game. This

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demonstrates that learning does not stop at procedural understanding, but develops toward analytical and evaluative skills.

The dominant development in the ability to draw conclusions indicates that the contextual puzzle-solving activities in the game consistently train students to connect data with relevant concepts (Zapata-Cardona, 2023). Meanwhile, the ability to design alternative strategies shows a development that requires further practice, because this skill is related to more complex planning and evaluation (Borzyh, 2024).

The students' excellent response to the learning process demonstrates that the learning environment designed through a PBL-based escape room game facilitates more active and reflective thinking (Pearcy et al., 2022). Student engagement during the game extends beyond simply participating in a fun activity, but is also reflected in their ability to identify important information, evaluate relationships between concepts, and revise problem-solving strategies when faced with errors (Veldkamp, Grint, et al., 2020). This indicates that interactive and problematic learning experiences contribute to strengthening critical thinking indicators more optimally (Liu & Pásztor, 2022; López-Pernas et al., 2023).

Thus, the students' excellent response can be interpreted as an acceptance of a learning model that allows for exploration, argumentation, and logical evaluation. This demonstrates that learning designs that consistently demand intellectual engagement help develop critical thinking skills, not simply increase interest in learning.

Theoretically, these findings reinforce the constructivist view that firsthand experience is the foundation of expertise in resolving issues. The integration of Learning Through Problems with an escape room game provides an authentic context that allows students to construct their understanding while enhancing higher-order physics thinking abilities.

E. Implication

The findings indicate that a Problem-Based Learning (PBL)- scaffolded digital escape room intervention significantly enhances eleventh-grade students' critical thinking skills in fluid mechanics, including hydrostatic pressure, Pascal's law, and Archimedes' principle. Theoretically, these findings reinforce constructivist learning theory, emphasizing that knowledge is actively constructed through meaningful problem-solving experiences. The integration of PBL within a digital escape room environment provides empirical support for Vygotsky's sociocultural perspective, where learning is mediated through interactive tools, collaboration, and guided inquiry. Furthermore, this study extends constructivist principles into game-based learning contexts, demonstrating that immersive, feedback-rich environments can effectively foster higher-order thinking skills, particularly critical thinking as conceptualized by Ennis (2011).

From a pedagogical perspective, embedding the PBL syntax within an escape room environment moves students beyond rote formula application toward authentic problem solving, requiring them to analyse situational cues, identify relevant variables, develop solution strategies, and evaluate their responses. The game mechanics, which require correct

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answers to unlock each stage, promote cognitive engagement and metacognitive reflection, strengthening critical thinking components such as advanced clarification and strategy and tactics. For physics teachers, this approach offers an innovative and practical alternative to conventional lecture-based instruction. The use of platforms such as Genially has the potential to enhance student motivation, support collaborative interaction, and improve the quality of classroom discourse, all of which are essential for developing 21st-century skills. Teachers can adopt the PBL cycle—problem presentation, investigation, resolution, and reflection—when designing escape room activities tailored to specific physics concepts.

In terms of policy implications, the results highlight the importance of integrating game-based learning approaches, particularly those aligned with PBL, into formal physics curricula. Educational policymakers and curriculum developers are encouraged to incorporate structured, technology-enhanced learning activities that promote critical thinking skills. This integration should be supported by the provision of adequate technological infrastructure and professional development programs that equip teachers with the skills to design and implement PBL-based digital learning environments effectively. Such efforts may contribute to broader educational goals related to 21st-century competencies and student-centered learning reforms.

Regarding research implications, further studies are needed to examine the long-term effectiveness of PBL-based escape room interventions through longitudinal designs with delayed post-tests. Future research should also investigate the individual and combined effects of PBL and game-based learning elements to better understand their respective contributions to learning outcomes. Importantly, there is a need to explore hybrid learning models that integrate digital escape rooms with blended or hybrid instructional approaches, allowing for greater flexibility and scalability across diverse educational contexts. Additionally, examining mediating variables such as self-efficacy, achievement motivation, and metacognitive awareness would provide deeper insight into the mechanisms through which this intervention enhances students' critical thinking skills.

F. Limitation and Suggestion for Further Research

Several limitations should be acknowledged. First, the study involved a single experimental class and a single control class from one senior high school in Bengkulu (n = 39), which limits the generalisability of the results to the broader senior high school population and requires replication in more diverse settings. Second, the class assignment was not fully randomised, allowing possible class - or teacher-level confounding effects. Third, the intervention lasted only three sessions (≈ 4 hours of contact time), so the findings do not speak to long-term retention of critical-thinking gains.

Based on these limitations, future investigations could employ a randomised controlled trial (RCT) with three conditions: (1) PBL combined with an escape room, (2) escape room without the PBL scaffold, and (3) conventional instruction. Longitudinal study designs with delayed post-tests are also recommended to examine the durability of learning outcomes over time. In addition, mixed-method research integrating quantitative and

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qualitative data would provide deeper insights into students' learning processes and experiences. Furthermore, conducting multi-school experimental studies across diverse educational contexts would enhance the external validity and generalisability of the findings. Including mediators such as self-efficacy or achievement motivation would help elucidate the mechanisms through which the intervention influences critical thinking.

G. Conclusion

This study demonstrates that the Problem-Based Learning (PBL)-scaffolded digital escape room intervention significantly improves eleventh-grade students' critical thinking skills in fluid mechanics. Students in the experimental group achieved a high normalized gain (N-gain = 0.74) and a large effect size (d = 0.82), indicating that the intervention was substantially more effective than conventional instruction in promoting higher-order thinking skills. The integration of contextual problem-solving activities with escape room game mechanics successfully enhanced students' engagement, reasoning, collaboration, and reflective thinking processes.

The main contribution of this study lies in the integration of a PBL framework with digital escape room learning as an innovative instructional strategy for physics education. This approach not only strengthens students' critical thinking competence but also creates meaningful and interactive learning experiences that support 21st-century learning demands. Therefore, PBL-based digital escape rooms have strong potential to be implemented as an alternative learning model for improving critical thinking skills in physics classrooms.

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