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Effects of Ecosystem Balance Simulation Games within a Problem-Based Learning Model on High School Students' Critical Thinking Skills

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ABSTRACT

This study aims to evaluate the effectiveness of integrating the Problem-Based Learning (PBL) model with an ecosystem balance simulation game in enhancing senior high school students' critical thinking skills. A quasi-experimental method with a matching-only posttest-only control group design was employed, involving 90 purposively selected students divided into three groups. The critical thinking instrument consisted of 12 validated essay items. Data analysis included the Kolmogorov–Smirnov normality test, Levene's homogeneity test, and ANOVA followed by the LSD post hoc test. The results indicate a significant difference among the groups (Sig. = 0.019), with post hoc analysis showing that the experimental group performed significantly better than the conventional group, but did not differ significantly from the PBL-only group. These findings suggest that integrating simulation games into the PBL framework is associated with improved critical thinking outcomes compared to conventional instruction, while yielding results comparable to PBL without simulation support. This indicates that simulation-based PBL may serve as a complementary instructional approach that supports student engagement and conceptual understanding. The study's implications highlight the importance of integrating interactive digital media in ecology instruction to support the development of students' 21st-century competencies.

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1. INTRODUCTION

Biology learning at the secondary school stage is instrumental in developing students' ability [1] to understand natural phenomena scientifically [2], [3]. However, Biology learning is often still oriented towards memorizing concepts [4], which limits the meaningfulness of the learning experience. In ecosystem material, for example, students are required to understand concepts such as interaction, population dynamics [5], and ecosystem balance [6], which are complex and dynamic, making them difficult to observe directly in the classroom. This condition makes it difficult for many students to develop high-level thinking skills, especially critical thinking, which is an important demand in 21st-century learning.

The capacity for critical thinking is among the main competencies in science learning [7], [8] because it involves analyzing, evaluating, concluding, and making decisions based on evidence. Unfortunately, several studies indicate that critical thinking among high school students remains relatively low [9], [10]. This fact indicates the need for learning innovations that provide an active, contextual, and challenging learning experience for students. One pedagogical strategy that is believed to be able to effective in developing these abilities is the Problem-Based Learning (PBL) model [11], [12], [13], [14], [15], collect information [16], analyse data [17], and formulate solutions [18], thereby theoretically improving their critical thinking skills [19], [20], [21]. Nevertheless, despite its theoretical strengths, implementing PBL in classroom practice often encounters several constraints, including limited access to engaging, contextually rich learning resources and difficulties in representing complex ecological processes in ways that are accessible to students [22], [23].

The development of educational technology presents new opportunities through the use of interactive media, such as simulation games [24], [25]. Digital simulations of ecosystem concepts allow students to explore relationships between biotic and abiotic components [26], manipulate variables [27], and directly observe the impact [28] of changes on ecosystem balance. One relevant form of innovation is the use of ecosystem balance simulation games that model the dynamics of interactions among producers, top consumers, and predators, such as grasses, rabbits, and tigers [29]. Through these simulation games, students not only learn visually and experientially but are also encouraged to perform cause-and-effect analysis [30], make predictions [31], and make decisions [32]. These processes closely align with the core dimensions of critical thinking, particularly reasoning, inference, and evidence-based decision-making, making ecosystem simulation especially well-suited as a medium for fostering higher-order thinking skills [33]. In addition, the dynamic, interactive nature of simulation allows students to test multiple scenarios and receive immediate feedback, further strengthening reflective and analytical thinking. The integration of simulation games into the PBL model is seen as capable of overcoming the weaknesses of pure PBL by providing a more concrete, interactive, and challenging learning environment [34].

Although research on the effectiveness of PBL and educational games has been conducted separately, as done by Bayley et al., Chang et al., Marbun, Martins et al., and Moradi & Noor. [35], [36], [37], [38], [39]. Most of these studies examine the two approaches in isolation and primarily focus on general learning outcomes such as engagement or achievement, rather than explicitly analyzing their combined effects on specific higher-order thinking skills. Furthermore, existing studies tend to adopt single-treatment designs and do not provide direct comparative analyses across multiple instructional conditions within the same research context. As a result, while both PBL and simulation-based learning are recognized as beneficial, there is limited empirical evidence on whether integrating simulation games into PBL offers additional pedagogical value

31 beyond PBL alone, particularly in the context of ecosystem learning at the secondary school level. More importantly, the absence of studies that simultaneously compare simulation-supported PBL, PBL without simulation, and conventional instruction creates a gap in understanding the relative effectiveness of these approaches in promoting students' critical thinking skills.

3 Based on this gap, the present study aims to examine the effects of integrating 29 ecosystem balance simulation games within a Problem-Based Learning model on high school students' critical thinking skills. This study specifically compares three instructional approaches: (1) PBL supported by simulation games, (2) PBL without simulation, and (3) conventional learning methods. It is expected that both PBL-based approaches will be 59 associated with higher critical thinking performance than conventional learning. At the same time, the inclusion of simulation games is anticipated to provide additional cognitive support through enhanced visualization, interactivity, and dynamic feedback, though this may not yield statistically significant differences compared to PBL alone. By addressing this issue, 16 the study seeks to provide a more precise, evidence-based understanding of the role of 3 simulation in strengthening inquiry-based biology instruction and in supporting the development of students' critical thinking skills in complex ecological contexts.

2. METHOD

23 This study employed a quasi-experimental design, specifically a matching-only posttest-only control group design. This design was selected due to the constraints of classroom settings, which did not permit full random assignment of individual students. Instead, equivalence among groups was established through a matching procedure conducted prior to the intervention.

The matching process was based on students' prior academic achievement, specifically their midterm examination (UTS) scores in Biology, obtained from the subject teacher. A descriptive comparison of mean scores and variances across classes indicated relatively similar academic characteristics, suggesting baseline equivalence among the selected groups. These classes were then assigned into three groups using a simple random allocation (web-based spinner) at the class level: (1) an experimental class receiving Problem-Based Learning (PBL) supported by an ecosystem balance simulation game, (2) a positive control class receiving PBL without simulation, and (3) a negative control class receiving conventional instruction. Although this procedure strengthens internal comparability, the absence of pretest data limits the ability to make strong causal claims regarding improvement.

The study population consisted of 401 students from 10 senior high school classes, of whom 90 were purposively selected. The selection was based on the similarity of academic characteristics, teacher recommendations, and class readiness to implement the intervention. The sample was divided equally into three classes, each consisting of 30 students. While purposive sampling is appropriate for school-based experimental research, 13 it may limit the generalisability of the findings to broader populations.

43 The intervention was conducted over four instructional sessions, each lasting approximately 90 minutes, within the ecosystem topic. The same Biology teacher taught all

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three groups to control for teacher-related variability. The experimental class engaged in PBL activities integrated with an ecosystem balance simulation game, allowing students to manipulate variables such as population size and environmental factors. The positive control class followed the same PBL procedures, but without using simulation media, relying instead on text-based and discussion-based problem-solving. The negative control class received conventional instruction characterized by teacher-centered explanations and limited student interaction. To maintain implementation fidelity, lesson plans were standardized across groups, and the learning procedures were monitored using observation checklists.

40 The instrument used to measure students' critical thinking skills was an essay-based test consisting of 12 items, developed based on Ennis's critical thinking framework, which
3 includes five indicators: elementary clarification, basic support, inference, advanced clarification, and strategy and tactics. The items were constructed to align with these indicators, with each indicator represented by 2–3 questions. The instrument underwent
56 content validity testing through expert judgment, involving two experts: one in Biology
12 content and one in critical thinking assessment. Items that did not meet validity criteria were revised or removed.

The scoring process employed a rubric ranging from 0 to 3, where 0 indicated no response, and 3 indicated a complete and accurate response. To ensure consistency in scoring, an inter-rater reliability procedure was conducted involving two independent scorers. The instrument's reliability was further assessed using internal consistency analysis,
46 yielding a Cronbach's alpha coefficient exceeding 0.70, indicating acceptable reliability for research purposes.

28 Prior to hypothesis testing, the posttest data were analyzed using the Kolmogorov–
21 Smirnov test to assess normality and the Levene's test to examine homogeneity of variance. After these assumptions were met, one-way Analysis of Variance (ANOVA) was conducted
14 to identify differences in critical thinking skills among the three groups. To further examine
47 pairwise differences, a Least Significant Difference (LSD) post hoc test was applied.

Ethical considerations were addressed prior to data collection. Permission to conduct
12 the study was obtained from the school administration, and informed consent was secured
6 from students and teachers. Participants were assured that their responses would be kept confidential and used solely for research purposes.

4 3. RESULTS AND DISCUSSION

3.1. Results

1 Results. The study's analysis focused on the effect of using Problem-Based Learning (PBL) assisted by ecosystem balance simulation games compared to PBL without games and conventional learning, based on statistically analyzed post-data to assess the significance
5 of differences between groups, as shown in Table 1.

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Table 1. Description of the research results

No	Statistics	Skor		
		Experiments	Positive control	Negative Control
1	Maximum score	36	34	34
2	Score minimum	11	11	4
3	Range	25	23	30
4	Mean	24	23	18
5	Median	25	23	19
6	Standard Deviation	7.62	7.05	9.28
7	Varians	58.05	49.72	86.05

Table 1 presents the results of the descriptive statistical analysis, which provide an overview of students' critical thinking skills across the three treatment groups: the experimental class (PBL + simulation game), the positive control class (PBL without games), and the negative control class (conventional learning). The analysis showed that the experimental group achieved a maximum score of 36, higher than those of the positive control (34) and negative control (34) groups. Meanwhile, the minimum score in both the experimental and positive control groups was 11, while the negative control had a lower minimum score of 4. The score range in the experimental class was 25, lower than in the negative control class (30) but slightly higher than in the positive control class (23), which showed moderate score variation.

Based on the mean value, the experimental class showed a mean of 24, higher than the positive control class (23) and much higher than the negative control class (18). These findings indicate that PBL learning, combined with ecosystem balance simulation games, contributes more to improving students' critical thinking skills than either PBL or conventional learning alone. The median score also showed the same pattern: 25 in the experimental class, 23 in the positive control, and 19 in the negative control, which emphasized the tendency to achieve higher scores in the class with the integration of simulation games.

In terms of data dissemination, the standard deviation in the experimental class was 7.62, slightly larger than in the positive control class (7.05) but smaller than in the negative control class (9.28). This value shows that the variation in students' critical thinking abilities in the experimental class is relatively moderate and more stable than in the conventional class. The variance value also showed a similar pattern: 58.05 in the experimental class, 49.72 in the positive control, and 86.05 in the negative control. The high variance in the negative control indicates a fairly wide range of ability among students in the class.

Overall, the statistical descriptions show that students in PBL classes with simulation games achieved better, more consistent results in critical thinking skills than the other two groups. Next, a normality test is performed to assess whether the data are normally distributed as a pre-study for the ANOVA test. The results of the normality test are shown in Table 2.

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Table 2. Description of the normality test

Kelas		Kolmogorof-Smirnov			Conclusion
		Statistic	df	Sig.	
Critical Thinking	Posttest experiment	0.117	30	0.200*	Normally distributed data
	Posttest positive control	0.138	30	0.127	Normally distributed data
	Posttest negative control	0.130	30	0.200*	Normally distributed data

a. Liliefors Significance Correction

2 Table 2 presents the results of the normality test to determine whether the data on
critical thinking skills within each treatment group are normally distributed. The test used
8 the Kolmogorov-Smirnov method with a Lilliefors correction at the 0.05 significance level.
2 The test results showed that the experimental class had a significance value of 0.200, the
positive control class had a value of 0.127, and the negative control class had a value of
0.200. All of these values are greater than 0.05. Thus, the three groups of postes data have a
45 normal distribution. For the next time, a homogeneity test was carried out to determine
5 whether the third data set had homogeneous variants. The results of the homogeneity test are
shown in Table 3.

Table 3. Description of homogeneity test results

		Levene Statistic	Df1	Df2	Sig
Posttest Critical Thinking	*Based on the mean*	1.546	2	87	0.211

2 The variance homogeneity test (Table 3) was conducted to determine whether the
variances of the data postes critical thinking skills across the three treatment groups were
44 equal. The test was carried out using the Levene Test based on mean comparisons. The test
9 results showed a Levene statistic of 1.546 (df1 = 2, df2 = 87) and a significance value of
0.211. The significance value is greater than 0.05, so the three groups have homogeneous
52 variances. With the assumptions of normality and homogeneity of variance satisfied, the
8 ANOVA test can proceed, as the data meet the basic assumptions for parametric analysis.
The results of the hypothesis test are shown in Table 4.

Table 4. Description of the hypothesis test results

		ANOVA				
24		*Sum of Squares*	df	*Mean Square*	F	Sig.
Critical Thinking	*Between groups*	535.022	2	267.511	4.141	0.019
	Within groups	5620.800	87	64.607		
	Total	6155.822	89			

41 Table 4 shows the results of the one-track ANOVA Test, which was conducted to
14 find out if there was a significant difference in critical thinking skills between three groups
1 of students, namely the experimental class (PBL + simulation game), the positive control
38 class (PBL only), and the negative control class (conventional learning). The results of the
9 analysis showed that the F value was calculated as 4.141 with a significance value (p =

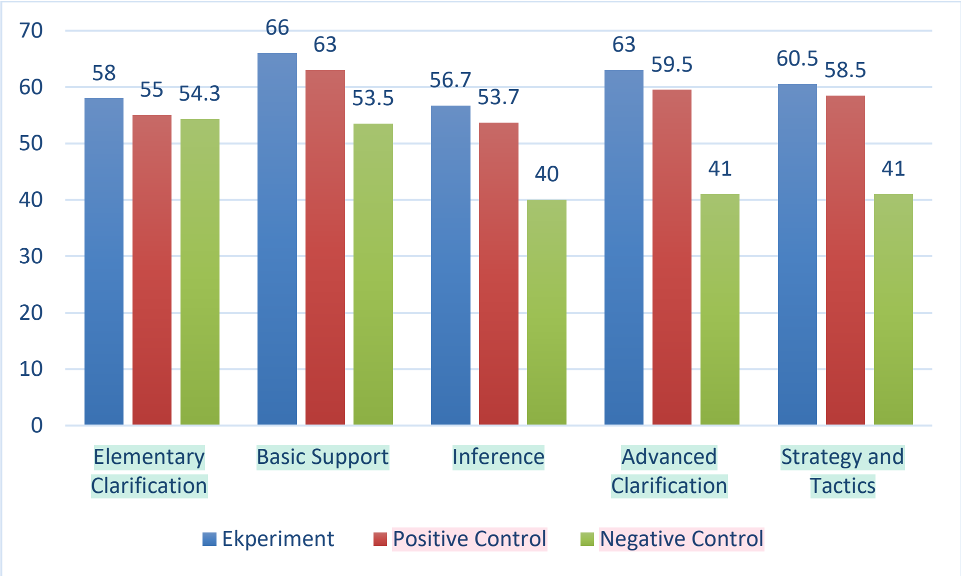
0.019). The significance value was less than 0.05, indicating a significant difference in critical thinking skills between at least two treatment groups.

Statistically, these results indicate that the learning models are associated with differences in students' critical thinking skills across groups. However, given the posttest-only design, these findings reflect differences in performance after treatment rather than direct improvement from baseline conditions. Thus, both PBL-based approaches (with and without simulation) are associated with higher critical thinking scores than conventional learning, while simulation-supported PBL does not show a statistically significant difference compared to PBL without simulation. To identify which groups differ specifically, the analysis can be continued with post hoc tests. The results of the post hoc test are shown in Table 5.

Table 5. Description of LSD test results

(I) Critical Thinking Classroom	(J) Class	Mean difference (I-J)	Std. Error	Sig.
Experiment	Positive Control	3.033	5.770	0.600
	Negative Control	15.333*	5.770	0.009
Positive Control	Experiment	-3.033	5.770	0.600
	Negative Control	12.300*	5.770	0.036
Negative Control	Experiment	-15.333*	5.770	0.009
	Positive Control	-12.300*	5.770	0.036

Table 5 presents the results of the post hoc test using the Least Significant Difference (LSD) to determine which group pairs show significant differences in critical thinking skills. The analysis showed that the experimental class differed significantly from the negative control class, indicated by a mean difference of 15.333 and a p-value of 0.009, which is significant at the 0.05 level. Similarly, the positive control class also differed significantly from the negative control class, with a mean difference of 12,300 and a significance value of 0.036. In contrast, there was no significant difference between the experimental and positive control classes, as indicated by a mean difference of 3.033 and a p-value of 0.600, which was greater than 0.05. These findings show that both the experimental and positive control classes had higher critical thinking abilities than the negative control classes. However, the levels of critical thinking between the experimental and positive control classes were relatively equal. Furthermore, the acquisition of critical thinking skills, as indicated in Figure 1, is evident.



39
1 Figure 1. Graph of the average acquisition of critical thinking skills based on indicators

19 Figure 1 shows a comparison of the average critical thinking skills of students in three classes, namely the experimental class, the positive control class, and the negative control class, based on five main indicators. Overall, the experimental class consistently
1 achieved the highest average score across all indicators, followed by the positive control class, and the negative control class was at the lowest.

The scores are derived from a validated 12-item essay test assessed using a rubric ranging from 0 to 3, and represent the average score for each indicator, calculated by summing students' scores across items within the same indicator and dividing by the number of items.

In the elementary clarification indicator, the experimental class obtained an average
1 of 58, higher than the positive control class (55) and the negative control (54.3). The basic support indicator shows a similar pattern, with the experimental class achieving the highest
1 score (66), followed by the positive control class (63), and the negative control being far
30 below (53.5). The inference indicator showed a striking difference between the experimental class (56.7) and the positive control class (53.7). In contrast, the negative control class reached only 40, showing a significant weakness in the ability to conclude.

In the advanced clarification indicator, the experimental class again dominated, with
1 an average score of 63, followed by the positive control class at 59.5, while the negative control class remained low at 41. Finally, in the strategy and tactics indicator, the
1 experimental class achieved 60.5, the positive control class 58.5, and the negative control class remained the lowest at 41. This data indicates that PBL-based learning models are associated with higher critical thinking performance than conventional learning, and that adding simulation games yields outcomes comparable to PBL without simulation.

7 3.2. Discussion

The findings of this study indicate that implementing Problem-Based Learning
17 (PBL), with or without simulation games, positively enhances students' critical thinking

13 skills compared to conventional instruction. The statistical analysis shows that student-centered learning plays a significant role in enhancing higher-order thinking. However, the lack of a statistically significant difference between the experimental and PBL-only classes suggests that both approaches are comparably effective.

This result implies that the primary contribution to critical thinking development lies in the PBL process itself, particularly through problem orientation, collaborative inquiry, and active engagement. The integration of simulation games may enrich the learning experience, especially through visualization and interactivity, but their effectiveness should be seen as a complementary enhancement rather than a definitive improvement over standard PBL.

When viewed through the lens of critical thinking indicators, the experimental class consistently demonstrated strong performance. Nevertheless, given the comparable outcomes between the two PBL-based groups, these findings should be understood as indicative patterns rather than conclusive evidence of superiority. To examine in depth how this simulation game affects critical thinking skills, an explanation will be presented for each critical thinking indicator.

Elementary Clarification

The improvement in Elementary Clarification skills in PBL classes, combined with simulation games, seemed more pronounced than in the other two classes because students gained a learning experience that enabled them to identify problems concretely through visual and dynamic representations [42]. In PBL+ game classes, the problem orientation stage does not stop at the text description, but is reinforced by the phenomenon of changing populations of grass, rabbits, and tigers moving in real time. This situation makes it easier for students to clearly establish the problem's focus, for example, by observing the pattern of rabbit mortality as grass declines or by describing the causal relationship between rainfall and grass availability. The process encourages students to craft more incisive basic questions in group discussions, such as "What factors are the most likely to disrupt the balance of the population?" or "How can the role of predators maintain the stability of the system?"

This power of visualization is not limited to PBL classes, so the clarification of problems in conventional PBL classes often depends on imagination and interpretation of static texts or illustrations. Although students can still identify problems, the accuracy and depth of their clarifications are lower because they do not directly observe the ecosystem's dynamics. In the conventional class, clarification activities take place more passively because the teacher is more dominant in explaining, so students are not much involved in independently identifying the core of the problem. Thus, integrating PBL and simulation games provides an authentic context that strengthens students' ability to identify issues, understand basic concepts, and formulate initial questions more accurately and meaningfully.

Basic Support

Basic Support skills, including the use of reason, preliminary evidence, and supporting facts [43], tended to show higher performance in the PBL class combined with the simulation game than in the other two classes. In this class, students are not only asked to search for data from texts or reference sources, but also to obtain direct empirical evidence from the results of manipulating variables in the game. When students change the reproductive rate of rabbits or the rainfall rate, they can quantitatively observe how those conditions affect grass and tiger populations. This evidence-gathering process makes them more skilled at connecting phenomena to relevant reasons. For example, students could state that the decline in grass populations is not only due to rabbits being eaten but also to low rainfall, and they can point to population graphs as evidence [29]. Verifiable visual and numerical evidence provides a stronger foundation for argumentation [44], making group discussions more weighty and directed.

In contrast, in a PBL class without a game, evidence support is mainly sourced from literature studies or worksheets provided by the teacher [45]. Students can still craft arguments based on ecological concepts, such as the relationships among predators, herbivores, and producers. However, the evidence used is abstract and does not undergo dynamic verification. As a result, the arguments that emerge tend to be normative rather than drawing on the wealth of empirical data from PBL classes using games. Meanwhile, in conventional classes, the preparation of evidence support is very limited because students often receive explanations from teachers without the opportunity to explore the data independently. Dependence on the teacher's information makes students' reasons and evidence less developed [46]. Thus, the combination of PBL and simulation games appears to provide an exploratory space that allows students to build arguments based on actual data, improving their ability to structure rationale and basic evidence in a more logical, accurate, and measurable manner.

Inference

Inference is the ability to conclude, predict consequences, and identify the implications of data or phenomena [47]. Inference increases significantly in PBL classes combined with simulation games, as students gain a learning experience that allows them to test hypotheses directly by changing variables in virtual ecosystems [48]. In this class, students not only read or discuss cause-and-effect relationships, but actually see how small changes to one component of an ecosystem can produce complex follow-up impacts. When students raise the reproductive rate of rabbits, for example, they can predict that grass populations will decline before finally seeing a further impact in the form of increased rabbit mortality due to lack of feed. When tiger populations increase, they can predict that a decline in the rabbit population will be followed by instability in the tiger population. The fast-paced, feedback-driven process of prediction testing allows students to build more accurate, consistent, pattern-based inferences that they actually observe.

In a non-gaming PBL class, the ability to infer is still developed thanks to structured problem-based discussions, but the inference process is more conceptual and speculative [49]. Students use their ecological knowledge to estimate the consequences of a variable change, but they do not get empirical confirmation of those predictions. This often makes their conclusions general, lacking detail, and not always accounting for the ecosystem's simultaneous dynamics. Meanwhile, in conventional classrooms, inference skills develop

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the least because students tend to receive causal explanations from teachers without the opportunity to conduct independent predictive exploration [50]. The conclusions that emerge are more reproductive than analytical. Overall, the use of simulation games within the PBL framework creates a learning experience that challenges students to actively predict, test, and revise their inferences, thereby providing the greatest improvement in Inference indicators compared to other learning models.

Advanced Clarification

Advanced Clarification skills, which include in-depth concept analysis, assumption identification, and evaluation of definitions and relationships between concepts [47], tended to show higher performance in the PBL class combined with simulation games. In this class, students gain an authentic experience that demands not only that they understand the basic relationships among producers, herbivores, and carnivores, but also that they analyze more complex conceptual structures in ecosystem dynamics. When students observed that increased rainfall did not always have a linear impact on grass growth, for example, they were encouraged to reevaluate their initial assumptions regarding abiotic factors. Similarly, when tiger populations are stable despite fluctuating rabbit numbers, students learn that ecosystems do not always respond simply as predicted by the theories usually explained statistically in class. This kind of reflection process arises because games allow students to test various scenario-based assumptions, enabling them to question the validity of concepts better, compare ideal conditions with real dynamics, and interpret the relationships between variables more critically.

In a non-gaming PBL class, this ability continues to evolve, but the depth of student analysis depends on the problem scenario and the quality of the group discussion. Without visualization and direct empirical data, students tend to rely on the theoretical schema they have learned, so the clarification process becomes more abstract and lacks the complexity of the actual ecological system [49]. Students can identify assumptions or analyze concepts, but are not always able to validate the results of those analyses through real observations. Meanwhile, in the conventional classroom, the advanced clarification process develops the least because students receive more linear explanations from the teacher, without being allowed to re-examine the limitations of the concept or question the assumptions inherent in ecological theory. Thus, integrating PBL and simulation games provides the richest learning experience, as it goes beyond aiding students' comprehension of concepts by also training them to test, revise, and restructure their conceptual understanding in a more critical and in-depth way.

Strategy and Tactics

The skills of strategy and tactics involve the ability to choose problem-solving strategies [29], plan analytical steps [51], and make effective data-based decisions [52]. They showed the most significant improvement in PBL classes combined with simulation games. In this class, students are directly involved in the strategic decision-making process when managing variables in the ecosystem, such as determining when to reduce the rabbit population, when to increase the tiger population, or how to manage rainfall to keep the grass stable. Each intervention they carry out immediately provides visual and numerical feedback, so that students learn to evaluate whether the chosen strategy is effective or actually creates a new imbalance. Through this iterative process, students become more skilled at designing measurable tactical measures, revising strategies based on simulation results, and predicting the long-term risks of each decision. This dynamic, problematic situation moves students from simply understanding the concept of ecology to the ability to manage the complexity of systems. This skill is very relevant to Strategy and Tactics indicators.

In PBL classes without games, strategy planning still occurs through group discussions, but it is more speculative and relies on purely conceptual understanding [45]. Students can propose strategies to maintain ecosystem balance, but cannot see firsthand the impact of those strategies [53], so their ability to correct or refine plans is limited [54]. The resulting strategies tend to be normative, such as "adding predators to control herbivore populations," without accounting for the quantitative dynamics that arise in real-world conditions. In the conventional classroom, this ability develops least because students are not given space to design strategies independently. Teachers usually explain the ecosystem's balance linearly, so students are not trained to make decisions, assess risks, or optimize solutions. Thus, the combination of PBL and simulation games is the most effective approach for developing Strategy and Tactics indicators because it provides an authentic, data-driven problem-solving experience and allows students to apply strategies directly in complex, dynamic systems.

20 This study has several limitations that should be acknowledged. First, the use of a posttest-only design limits the ability to assess initial differences and measure learning gains. 34 Second, purposive sampling may reduce the generalizability of the findings. Third, the relatively small sample size may limit statistical power. In addition, the matching procedure between groups was not fully controlled, which may introduce potential bias. The use of essay-based assessments also allows for possible scorer subjectivity, despite the use of scoring guidelines. Future research is recommended to address these limitations through more rigorous designs, larger samples, and more objective assessment methods.

48 Despite these limitations, this study contributes to the existing literature by providing a direct comparison between simulation-supported PBL, PBL without simulation, and conventional instruction within the same experimental context. The findings highlight that 6 PBL-based approaches play a central role in supporting students' critical thinking skills, while simulation games may serve as a complementary tool to enrich learning experiences rather than as a standalone determinant of learning effectiveness. This study, therefore, offers 16 a more nuanced understanding of the role of digital simulation in inquiry-based biology learning, particularly in complex topics such as ecosystem dynamics.

4. CONCLUSION

7 This study indicates that implementing Problem-Based Learning (PBL), with or without ecosystem balance simulation games, positively enhances students' critical thinking 35 skills compared to conventional instruction. The findings show that both the experimental group and the PBL-only group performed better than the conventional class, highlighting the importance of student-centered learning in fostering higher-order thinking. Although the

54 experimental group achieved the highest descriptive scores, the difference between simulation-supported PBL and PBL-only was not statistically significant. This suggests that while simulation games may enrich the learning experience, particularly through visualization, interactivity, and engagement, their role should be viewed as complementary rather than as a significantly more effective approach than PBL alone. These results imply that the primary contribution to students' critical thinking development lies in the PBL process itself, which emphasizes inquiry, collaboration, and active knowledge construction. Simulation tools can support this process by providing a more dynamic, context-rich learning environment, especially for complex topics such as ecosystem balance. Future research is recommended to apply more rigorous designs, including pretest–posttest approaches, larger sample sizes, and random assignment where possible. Additionally, further validation of assessment instruments is needed to ensure a more objective measurement of critical thinking skills.

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