



Deep Learning-Based Instruction on Ecosystem Topics to Enhance Students' Critical Thinking Skills

Lulu Royani Hamidah*, Meti Maspupah, Hadiansah

Universitas Islam Negeri Sunan Gunung Djati Bandung, Indonesia

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*Correspondence Address:

royanhl655@gmail.com

Abstract:

This study aimed to analyze the improvement and differences in seventh-grade students' critical thinking skills in ecosystem learning through deep learning-based instruction. A quantitative approach with a quasi-experimental method and non-equivalent control group design was employed. The sample consisted of 56 seventh-grade students at Junior High School, comprising 28 students in the experimental class and 28 students in the control class. The experimental class received deep learning-based instruction, while the control class received conventional instruction. Data were collected using a tiered multiple-choice critical thinking test administered before and after instruction. The data were analyzed using descriptive statistics, N-Gain, the Shapiro-Wilk test, and an independent-samples t-test. The mean score of the experimental class increased from 66.21 to 84.54, while the control class increased from 70.14 to 82.07. The N-Gain scores were 0.54 for the experimental class and 0.39 for the control class, both categorized as moderate. The independent-samples t-test indicated significant differences between the classes in the pretest ($p < 0.001$) and posttest ($p = 0.035$). The highest N-Gain in the experimental class was found in the inference indicator (0.67), whereas the lowest was found in the focus indicator (0.42). These findings indicate that deep learning-based instruction supported the development of students' critical thinking skills and resulted in descriptively higher improvement than conventional instruction. However, differences in initial ability between the groups should be considered when interpreting the findings.

INTRODUCTION

Critical thinking is an essential competency in science education because it enables students to identify problems, analyze information, evaluate evidence, provide logical reasoning, and draw appropriate conclusions. In science learning, critical thinking is particularly important because students are expected not only to acquire conceptual knowledge but also to apply that knowledge to explain phenomena and address problems encountered in everyday life (Ennis, 2015). Conceptualizes critical thinking through several dimensions, including focus, reason, inference, situation, clarification, and overview. These dimensions reflect the cognitive processes required for students to examine information systematically and make reasoned judgments. The development of critical thinking is important because science learning should not merely emphasize the acquisition of factual knowledge but also enable students to analyze phenomena and solve problems in meaningful contexts. A meta-analysis by Abrami et al. (2015) further

demonstrated that critical thinking can be developed through deliberate instructional strategies, particularly when learning activities explicitly engage students in reasoning, problem solving, and reflection. Thus, science instruction needs to provide learning experiences that actively stimulate students' higher-order thinking processes. Recent evidence from Indonesian science education also indicates that critical thinking is a central learning outcome that requires instructional models and media to be aligned with students' characteristics, learning contexts, and the nature of the scientific content (Arda et al., 2024). This reinforces the need to design science learning experiences that move students beyond recall toward analysis, reasoning, and evidence-based judgment.

Despite the importance of critical thinking, science instruction at the secondary school level does not always provide sufficient opportunities for students to develop these skills. Based on an initial interview with a science teacher at SMP Muhammadiyah 8 Bandung, ecosystem learning in Grade VII was still conducted through a combination of lectures, assignments, and relatively simple discussions. Students had limited opportunities to analyze problems, articulate arguments, and formulate conclusions based on information or evidence. This condition is consistent with findings reported by Harahap et al. (2020a), who found that students' critical thinking skills and mastery of ecosystem concepts still require strengthening, particularly because students experience difficulties in understanding and applying ecosystem concepts. Therefore, learning approaches that provide opportunities for students to analyze information, construct arguments, and connect concepts with real-world situations are needed. A recent review of science learning research similarly shows that teacher-centered practices may provide fewer opportunities for students to engage in inquiry and higher-order reasoning, whereas active and contextual learning models can create more space for critical thinking development (Amrullah et al., 2024). Therefore, the instructional context identified at the research site provides a relevant basis for examining an approach that explicitly emphasizes deeper cognitive engagement.

One approach that may support the development of critical thinking is deep learning-based instruction. In educational contexts, deep learning emphasizes meaningful understanding through contextual exploration, conceptual elaboration, reflection, collaboration, and application of knowledge. Rather than positioning students as passive recipients of information, this approach encourages students to actively construct knowledge and reflect on their learning experiences. Taqiyya et al. (2025) explain that deep learning strategies based on meaningful, mindful, and joyful learning emphasize contextual exploration, conceptual elaboration, reflection, and action, while also supporting the development of critical thinking, creativity, collaboration, and adaptability. Similarly, Andayanie et al. (2025) describe deep learning as a pedagogical approach that promotes mindful, meaningful, and joyful learning experiences. These characteristics provide a theoretical basis for connecting deep learning with the development of students' critical thinking skills. Recent literature conceptualizing deep learning in education further emphasizes the integration of meaningful, mindful, and joyful learning. When these dimensions are implemented contextually and connected with students' experiences, they may support critical, creative, reflective, and engaged learning processes (Nafi'ah & Faruq, 2025). Thus, deep learning is relevant not simply because it is a new instructional label, but because its principles are compatible with learning activities that require students to interpret, connect, reflect, and apply knowledge.

The ecosystem topic is particularly relevant to the implementation of deep learning because it involves complex relationships among biotic and abiotic components, energy flow, food chains, population changes, and environmental disturbances. Understanding these concepts requires students to interpret relationships, analyze environmental problems, evaluate possible consequences, and formulate appropriate conclusions. Harahap et al. (2020b) demonstrated that ecosystem learning can be used to develop students' critical thinking through learning activities that require students to analyze information and construct explanations. Similarly, Setiyanika et al. (2023) reported that ecosystem learning supported by local-potential-based learning materials could improve students' critical thinking, with the learning intervention producing a moderate N-Gain. These findings indicate that ecosystem learning provides an appropriate context for integrating activities that promote analysis, reasoning, and problem solving. The relevance of ecosystem learning is also supported by recent studies showing that ecosystem topics can be used as contexts for developing critical thinking through problem solving, inquiry, and evidence-based discussion (Handayani & Adlini, 2026; Ibrahim et al., 2026). Such contexts allow students to examine relationships among organisms and environmental factors while considering the consequences of changes within an ecosystem.

Previous studies have also reported positive findings regarding the implementation of deep learning in science education. Safitri et al (2025) found that the implementation of deep learning was associated with improvements in students' critical thinking skills in IPAS learning. Panjaitan & Muhammad (2025) reported improvements in science learning outcomes following the implementation of deep learning, while Nurdiana & Pradana (2025) showed that the approach supported students' cognitive learning outcomes. More broadly, Taqiyya et al. (2025) reported that deep learning strategies can promote active engagement, reflection, collaboration, and critical thinking, strengthening the theoretical rationale for applying this approach in science education. In addition, Taufik et al. (2025) reported the effectiveness of deep learning-based project learning in developing students' scientific and critical thinking skills. These studies suggest that deep learning has considerable potential to support higher-order thinking, although its application may produce different outcomes depending on the subject matter, instructional design, educational level, and learning context. The accumulating evidence therefore suggests that deep learning and active science learning share several pedagogical characteristics, particularly student engagement, contextual problem solving, collaboration, and reflection. A meta-analysis of deep-learning-based project learning in Indonesia also reported a positive overall effect on scientific and critical thinking skills, although the magnitude of effects may depend on the instructional model and learning context (Taufik et al., 2025). These findings provide additional justification for examining deep learning specifically within ecosystem instruction.

Nevertheless, previous research has largely examined deep learning in relation to general learning outcomes, cognitive achievement, IPAS learning, or broader learning competencies. Research specifically examining the development of critical thinking among Grade VII students through deep learning-based instruction on ecosystem topics remains limited. Previous ecosystem studies have generally focused on other instructional approaches, such as project-based learning, guided inquiry, or local-potential-based learning materials (Harahap et al., 2020b; Khafah et al., 2023; Setiyanika et al., 2023). Therefore, further investigation is needed to examine whether deep

learning-based instruction can support the development of critical thinking in ecosystem learning at the junior secondary school level. At the same time, a recent systematic review of critical thinking research in Indonesian science education highlights that no single instructional model is universally appropriate; the selection of an approach should consider students, subject matter, learning objectives, available time, and classroom conditions (Arda et al., 2024). This supports the need for context-specific empirical research rather than assuming that findings from other subjects or educational levels will automatically transfer to Grade VII ecosystem learning.

Based on this research gap, this study aims to analyze the improvement of Grade VII students' critical thinking skills before and after participating in deep learning-based instruction on ecosystem topics. The improvement is examined based on six critical thinking indicators: focus, reason, inference, situation, clarification, and overview. The findings are expected to contribute empirical evidence regarding the application of deep learning in science education, particularly for ecosystem learning and the development of students' critical thinking skills.

RESEARCH METHODS

This study employed a quantitative approach using a quasi-experimental method with a non-equivalent control group design. This design was selected because the study involved experimental and control classes that had already been established prior to the research; therefore, students were not randomly assigned individually. The use of a quasi-experimental design allows researchers to examine differences in learning outcomes between groups under naturally occurring classroom conditions (Anastasia & Rindrayani, 2025; Nofirda, 2025). The experimental class received deep learning-based instruction, whereas the control class received conventional instruction. Both groups were administered a pretest before the learning intervention and a posttest after the intervention. The research design was represented as O_1-X-O_2 for the experimental class and O_3-C-O_4 for the control class.

The study was conducted at SMP Muhammadiyah 8 Bandung during the second semester of the 2025/2026 academic year. The population consisted of 140 Grade VII students distributed across five classes. The sample was selected using cluster sampling. Class VII Ibnu Thufail was designated as the experimental class, while Class VII Ibnu Bathutah was designated as the control class. Each class consisted of 28 students, resulting in a total sample of 56 students.

The primary data were obtained using a critical thinking skills test administered before and after the learning intervention. The instrument was developed based on six critical thinking indicators: focus, reason, inference, situation, clarification, and overview (Susanti et al., 2022).

The instrument consisted of tiered multiple-choice questions with four response options (A–D). Each response was assigned a score ranging from 1 to 4 according to its level of correctness, from the least appropriate to the most appropriate response. Thirty items were initially tested to examine validity, reliability, item discrimination, and difficulty level (Pradita et al., 2023; Widodo et al., 2023). Based on the item analysis, 20 items were selected for use in the pretest and posttest. The instrument obtained a Cronbach's alpha coefficient of 0.951, indicating very high reliability. The raw scores were subsequently converted to a 100-point scale. Supporting data were obtained through an observation sheet assessing the implementation of the learning process.

The learning intervention was conducted over two meetings. In the experimental class, deep learning-based instruction consisted of contextual problem analysis, information exploration, group discussion, reflection, presentation, and conclusion drawing. These activities were designed to provide students with opportunities to process information, exchange reasoning, reflect on their understanding, and formulate conclusions. The control class received conventional instruction as normally implemented by the teacher. Both groups studied the same ecosystem topic and were directed toward the same learning objectives, but the instructional approaches differed.

The data were analyzed using descriptive statistics, including the mean, standard deviation, minimum score, and maximum score. Improvements in critical thinking skills were analyzed using N-Gain to describe the relative improvement between pretest and posttest scores. The Shapiro-Wilk test was employed to examine data normality, while Levene's test was used to assess homogeneity. Differences in achievement between the experimental and control classes were analyzed using an independent-samples t-test at a significance level of 0.05. If the assumptions for parametric analysis were not met, the Mann-Whitney test was planned as an alternative.

RESULTS AND DISCUSSION

Results

Descriptive Statistics of Pretest and Posttest Scores

The descriptive statistics of students' critical thinking skills in the experimental and control classes are presented in Table 1.

Table 1. Descriptive Statistics of Pretest and Posttest Scores

Measurement	N	Mean	Standard Deviation	Minimum	Maximum
Experimental Pretest	28	66.21	3.281	58	71
Control Pretest	28	70.14	3.352	64	75
Experimental Posttest	28	84.54	3.795	76	91
Control Posttest	28	82.07	4.705	69	90

As shown in Table 1, the mean score of the experimental class increased from 66.21 on the pretest to 84.54 on the posttest, representing an increase of 18.33 points. The minimum score increased from 58 to 76, while the maximum score increased from 71 to 91. In the control class, the mean score increased from 70.14 to 82.07, representing an increase of 11.93 points. Thus, both groups demonstrated improvements in critical thinking skills, although the experimental class showed a descriptively greater increase.

The comparison of initial and final achievement indicates that the experimental class initially had a mean score 3.93 points lower than the control class. Following the learning intervention, however, the mean posttest score of the experimental class was 2.47 points higher than that of the control class. This change indicates substantial development in the experimental class during the learning process. Nevertheless, the difference in initial ability between the two groups should be taken into account when interpreting the posttest results.

The activities implemented in the experimental class, including contextual problem analysis, information exploration, group discussion, reflection, presentation, and conclusion drawing, provided opportunities for students to process information and connect scientific concepts with problems. Such activities are consistent with the

characteristics of deep learning, which emphasizes active, meaningful, and reflective learning experiences (Andayanie et al., 2025). Active learning also provides opportunities for students to engage directly in learning processes that promote critical thinking (Hidayat et al., 2023).

N-Gain Analysis

N-Gain analysis was conducted to determine the relative improvement in students' critical thinking skills following instruction.

Table 2. N-Gain Results

Analysis	Value	Category
Experimental N-Gain	0.54	Moderate
Control N-Gain	0.39	Moderate

As presented in Table 2, the experimental class obtained an N-Gain value of 0.54, whereas the control class obtained 0.39. Both values were categorized as moderate. These findings indicate that improvements in critical thinking skills occurred in both groups. However, the experimental class demonstrated a higher N-Gain value descriptively than the control class.

The higher N-Gain observed in the experimental class suggests that deep learning-based instruction provided a learning environment that was conducive to greater development of critical thinking skills. Students were involved in analyzing problems, exchanging reasoning, reflecting on learning outcomes, and drawing conclusions. These activities provide opportunities for students to move beyond the simple reception of information and engage in deeper cognitive processing.

This finding is consistent with (Andayanie et al., 2025), who emphasized that deep learning promotes mindful, meaningful, and joyful learning experiences. It is also in line with (Taufik et al., 2025), who found that deep learning-based Project-Based Learning can support the development of scientific and critical thinking skills.

Nevertheless, the higher N-Gain in the experimental class should be interpreted as a descriptive finding rather than definitive evidence of a statistically significant difference in improvement. The present study did not conduct an inferential test specifically comparing the N-Gain values between the two groups. Furthermore, the pretest analysis revealed a statistically significant difference in initial ability. Therefore, the N-Gain results should be interpreted together with the pretest and posttest findings.

Improvement Across Critical Thinking Indicators

The analysis of individual indicators was conducted to identify which aspects of critical thinking demonstrated the greatest improvement in each group.

Table 3. Improvement Across Critical Thinking Indicators

Indicator	Experimental Pretest	Experimental Posttest	N-Gain	Category	Control Pretest	Control Posttest	N-Gain	Category
Focus	67.56	81.25	0.42	Moderate	68.45	81.85	0.42	Moderate
Reason	66.96	80.65	0.41	Moderate	65.18	82.74	0.50	Moderate
Inference	66.74	89.06	0.67	Moderate	66.29	79.91	0.40	Moderate
Situation	61.01	81.85	0.53	Moderate	63.39	83.33	0.54	Moderate
Clarification	68.30	85.27	0.54	Moderate	65.63	81.92	0.47	Moderate
Overview	65.18	86.31	0.61	Moderate	66.07	82.74	0.49	Moderate
Mean	66.16	84.37	0.53	Moderate	65.84	81.96	0.47	Moderate

As shown in Table 3, all critical thinking indicators increased in both groups, and all N-Gain values were categorized as moderate. In the experimental class, the average indicator score increased from 66.16 to 84.37, with an average N-Gain of 0.53. In the control class, the average indicator score increased from 65.84 to 81.96, with an average N-Gain of 0.47. These results demonstrate that improvement occurred not only in the overall critical thinking score but also across the individual indicators measured in the study.

Discussion

The findings demonstrate that students who participated in deep learning-based instruction experienced an increase in critical thinking skills. The improvement can be associated with the characteristics of the learning activities implemented in the experimental class, particularly contextual problem analysis, information exploration, group discussion, reflection, presentation, and conclusion drawing. These activities provided students with opportunities to actively process information and construct understanding rather than simply memorize concepts. The pattern is also compatible with recent reviews of science learning, which emphasize that critical thinking develops when students are given structured opportunities to interpret information, solve problems, communicate reasoning, and reflect on their learning processes (Arda et al., 2024). In the present study, these processes were embedded in the sequence of classroom activities rather than treated as separate exercises.

This finding is consistent with (Andayanie et al., 2025), who characterized deep learning as an approach that promotes mindful, meaningful, and joyful learning experiences. The learning activities in the present study reflect these principles by requiring students to engage with problems, exchange ideas, reflect on their understanding, and formulate conclusions. The findings also support (Hidayat et al., 2023), who emphasized the relevance of active learning in fostering critical thinking. Thus, the present findings provide further empirical support for the potential application of deep learning in science learning. This interpretation is also consistent with recent conceptual work describing deep learning as a combination of meaningful understanding, mindful engagement, and joyful participation. Such integration is intended to make learning more connected to students' experiences while maintaining attention and reflection during the learning process (Nafi'ah & Faruq, 2025).

The findings are also consistent with (Safitri et al., 2025), who reported an improvement in students' critical thinking skills following the implementation of deep learning in IPAS learning. The similarity between the findings suggests that instructional approaches emphasizing active information processing and meaningful learning experiences may contribute to the development of students' critical thinking. However, the present study provides a more specific contribution by focusing on Grade VII students, ecosystem topics, and six dimensions of critical thinking. The present finding is also in line with broader evidence that active and student-centered science learning can facilitate higher-order thinking when students are required to work with evidence and explain their reasoning (Chen & Chen, 2025). The specificity of the current study lies in its focus on ecosystem learning and the six critical-thinking indicators used in the instrument.

The inference indicator demonstrated the highest improvement in the experimental class, with an N-Gain of 0.67. This result suggests that students showed substantial development in their ability to connect information and formulate relevant conclusions. The learning activities may have contributed to this improvement because students were repeatedly engaged in analyzing problems, discussing information, reflecting on their reasoning, and drawing conclusions. The relatively strong development of inference may be related to the repeated requirement for students to connect information before reaching a conclusion. This is particularly relevant to ecosystem concepts, where relationships among components cannot always be understood from isolated facts. Recent ecosystem research similarly shows that structured learning activities can support students in examining biological problems, discussing evidence, and making reasoned decisions (Ibrahim et al., 2026).

This finding is consistent with (Aras et al., 2024), who found that guided inquiry learning can support students' critical thinking through activities involving investigation and information processing. It is also consistent with (Khafah et al., 2023), who demonstrated the relevance of project-based learning to the development of students' critical and creative thinking skills in ecosystem topics. Both studies reinforce the importance of learning activities that require students to investigate information, analyze relationships, and formulate conclusions. These findings also suggest that the critical-thinking gains observed in the present study are compatible with a broader pattern in which inquiry-oriented activities encourage students to investigate information and construct explanations. Recent ecosystem learning research has likewise reported improvements in critical thinking when students engage with structured problem-solving activities (Handayani & Adlini, 2026).

The overview indicator also demonstrated relatively high improvement in the experimental class, with an N-Gain of 0.61. This finding indicates that students developed their ability to integrate information and construct a broader understanding after participating in the learning activities. Group discussions and reflection may have encouraged students to connect information obtained during the learning process and develop a more comprehensive understanding of ecosystem relationships. Such learning processes are compatible with the deep learning orientation toward meaningful and reflective learning (Andayanie et al., 2025). The result is also consistent with the reflective dimension of deep learning. Reflection allows students to revisit information obtained during discussion, compare different explanations, and integrate separate pieces of knowledge into a more coherent understanding (Nafi'ah & Faruq, 2025). This may help explain why the overview indicator showed a relatively high improvement in the experimental class.

In contrast, the focus indicator demonstrated the lowest N-Gain in the experimental class, at 0.42, although it remained within the moderate category. This finding indicates that students' ability to identify or concentrate on the central issue improved, but the magnitude of improvement was lower than that observed for inference and overview. The variation among indicators suggests that different aspects of critical thinking may respond differently to the same instructional experience. Therefore, future implementation of deep learning could provide more explicit scaffolding for identifying the core of a problem, such as through structured problem

statements, focused guiding questions, and activities requiring students to distinguish relevant from irrelevant information. The lower gain on focus also indicates that improvement in critical thinking is not necessarily uniform across indicators. Recent reviews emphasize that instructional strategies should be matched to the specific cognitive processes that students need to develop (Arda et al., 2024). Consequently, deep learning activities may need to include explicit prompts that help students identify the central question before they move to more complex reasoning.

In the control class, the highest N-Gain occurred in the situation indicator, at 0.54, whereas the lowest occurred in the inference indicator, at 0.40. This pattern differs from that of the experimental class and indicates that conventional instruction can also contribute to improvements in critical thinking. However, the aspects showing the greatest improvement were not identical between the two groups. This finding suggests that critical thinking development may be influenced by multiple factors, including instructional approach, learning activities, content characteristics, students' initial abilities, and classroom learning experiences. The improvement observed in the control class is important because it shows that critical-thinking development can occur under conventional classroom conditions as well. This is consistent with evidence that different active or structured science-learning strategies can contribute to critical thinking, while their effects vary according to instructional design and context (Arda et al., 2024). Therefore, the difference between groups should not be interpreted as meaning that conventional instruction is incapable of supporting critical thinking.

Overall, the average N-Gain across the critical thinking indicators was 0.53 in the experimental class and 0.47 in the control class. Although both values were categorized as moderate, the experimental class demonstrated a descriptively higher average improvement. This finding is consistent with (Safitri et al., 2025), who reported the potential of deep learning to improve critical thinking skills, and with (Taufik et al., 2025), who found that deep learning-based Project-Based Learning can support scientific and critical thinking skills. The descriptive difference should nevertheless be considered alongside the characteristics of the intervention. Deep-learning approaches emphasize active engagement, meaningful connections, and reflection, while related project-based implementations have also reported improvements in scientific and critical thinking skills (Taufik et al., 2025). The present results extend this discussion to ecosystem learning at the junior secondary level, while the moderate N-Gain in both groups indicates that substantial room for further development remains.

From a pedagogical perspective, these findings indicate that deep learning can serve as an alternative instructional approach for developing critical thinking in science education. Ecosystem topics provide an appropriate context because they are closely connected to environmental phenomena and real-world problems. Teachers can therefore formulate contextual problems that require students to analyze information, provide evidence-based reasoning, identify relationships among ecosystem components, and formulate conclusions. In ecosystem learning, contextualization can be strengthened by using environmental issues that students can observe in their own surroundings, such as waste accumulation, changes in local biodiversity, water quality, or disturbances to food webs. Such contextual problems can encourage students to connect scientific concepts with observable phenomena and develop explanations based on evidence,

which is consistent with the broader emphasis on contextual and student-centered science learning (Chen & Chen, 2025).

The statistically significant posttest difference further strengthens the descriptive findings. The independent-samples t-test produced a t-value of 2.157 with 54 degrees of freedom and $p=0.035$, indicating a statistically significant difference in posttest achievement between the two groups. The experimental class obtained a higher mean posttest score (84.54) than the control class (82.07).

However, the interpretation of this finding requires caution because the pretest analysis also revealed a statistically significant difference between the two groups ($p<0.001$). The control class began with a higher mean score than the experimental class. Therefore, the posttest difference cannot be interpreted solely as evidence that the instructional treatment was entirely responsible for the observed difference. In addition, because the study did not conduct an inferential test comparing N-Gain values or an analysis explicitly controlling for the initial difference, the findings are more appropriately interpreted as demonstrating a significant difference in final achievement accompanied by descriptively greater improvement in the experimental class. This caution is consistent with the broader principle that quasi-experimental findings should be interpreted in relation to baseline differences between groups. Because the present study used intact classes and the pretest scores differed significantly, the observed posttest difference should be understood as an association within the study context rather than as an unqualified causal estimate.

This limitation is important for maintaining an appropriate level of causal interpretation. Nevertheless, the fact that the experimental class initially had a lower mean score but subsequently achieved a higher mean posttest score, together with its higher descriptive N-Gain, provides an empirical indication of the potential value of deep learning-based instruction. Future studies should employ larger samples, longer intervention periods, and statistical procedures capable of controlling for baseline differences, such as analysis of covariance or other appropriate approaches, to provide stronger evidence regarding the effect of deep learning on critical thinking. The methodological limitation does not negate the descriptive pattern observed in the data, but it defines how strongly the findings can be generalized. Future studies could combine longer interventions with larger samples and baseline-adjusted analyses, while also examining classroom processes in greater detail. Such work would help determine whether the observed pattern can be replicated across different schools, teachers, and ecosystem-learning contexts.

CONCLUSION

Deep learning-based instruction on ecosystem topics supported the improvement of Grade VII students' critical thinking skills. The mean score of the experimental class increased from 66.21 on the pretest to 84.54 on the posttest, while the control class increased from 70.14 to 82.07. The N-Gain values were 0.54 for the experimental class and 0.39 for the control class, both of which were categorized as moderate. Thus, the experimental class demonstrated descriptively greater improvement than the control class. All critical thinking indicators in the experimental class increased within the moderate category. The highest improvement occurred in the inference indicator, with

an N-Gain of 0.67, whereas the lowest occurred in the focus indicator, with an N-Gain of 0.42. The independent-samples t-test indicated statistically significant differences between the two groups in both the pretest ($p < 0.001$) and posttest ($p = 0.035$). The findings indicate that deep learning-based instruction has potential to support the development of critical thinking skills in science education, particularly in ecosystem learning. However, the interpretation should consider the significant difference in students' initial abilities between the two groups and the absence of an inferential comparison of N-Gain values. Accordingly, the findings should not be interpreted as definitive evidence that the observed differences were solely attributable to the deep learning intervention. Future research should involve larger samples, longer interventions, and statistical analyses that explicitly control for baseline differences to provide stronger evidence regarding the effectiveness of deep learning-based instruction.

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