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STEM-Based Biology Learning Assisted by Virtual Lab Gizmos to Enhance Critical Thinking Skills of Students' with Different Academic Abilities

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Abstract. The critical thinking skills (CTS) of students with different academic abilities is still low. Therefore, STEM-based biology learning assisted by virtual lab gizmos can be implemented to improve students' CTS. This study aims to determine whether STEM-based biology learning assisted by virtual lab gizmos can enhance students' CTS with different academic abilities. This study employed a quasi-experimental design with a pretest-posttest control group design. The population consisted of twelfth-grade science students from SMA Negeri 3 Bantaeng. The sample was selected using simple random sampling, with a total of 60 students divided into two learning groups: XII MIPA 1 and XII MIPA 2. Data collection techniques included a CTS skills test. Data analysis was conducted using two-way analysis of covariance. The results showed STEM-based biology learning asissted by the virtual lab gizmos significantly enhances students' CTS, with a significance value of 0.00 < 0.05. Additionally, the study reveals that academic abilities also influences students' CTS. Furthermore, there is an interaction effect between STEM-based learning with the virtual lab gizmos and academic abilities on students' CTS. Further post hoc LSD analysis shows that STEM-based biology learning with the virtual lab gizmos is more effective in improving students' CTS across different academic abilities compared to contextual learning without the virtual lab gizmos. These findings suggest that STEM-based biology learning supported by the virtual lab gizmos can serve as an effective teaching strategy to enhance students' CTS, particularly in addressing the challenges of 21st-century education.
Keywords: Academic abilities; biology learning; critical thinking skill; STEM; virtual lab gizmos

Introduction

Education plays an essential role in enhancing the quality of human life by developing skills, abilities, and character. The 21st-century education paradigm requires students to possess competencies in various domains, including cognitive, interpersonal, and intrapersonal skills (Bahri, et al., 2021). Among these, cognitive competence often referred to as the 4Cs includes higher-order thinking skills (HOTS), particularly critical thinking (Febril & Alberida, 2023; Wulansari & Sunarya, 2023). Critical thinking is the ability to analyze, evaluate, and solve problems systematically, making it a crucial skill for academic success and career readiness (Ramadhani, et al., 2023; Ardiansyah, et al., 2024).

However, despite its importance, the development of critical thinking skills (CTS) among students remains suboptimal.

Empirical studies and national assessments indicate that Indonesian students' CTS are still relatively low. The Program for International Student Assessment (PISA) results show that Indonesia ranks below the global average in scientific and mathematical literacy, which are closely linked to CTS (OECD, 2022). Similarly, research conducted by Bahri et al. (2023) highlights that many high school students struggle with analytical thinking due to the predominant use of teacher-centered learning approaches. These methods limit students' opportunities to engage in discussions, problem-solving activities, and inquiry-based learning, all of which are essential for developing CTS (Muzainah et al., 2024). Consequently, the quality of education is affected, necessitating the implementation of more effective teaching strategies.

A potential solution to this issue is the implementation of the science, technology, engineering, and mathematics (STEM) approach in learning. STEM-based education integrates multiple disciplines to develop students' analytical and problem-solving skills (Nugroho, et al., 2019). This approach fosters active student participation, which in turn enhances CTS. Studies by Yaki (2022) and Astawan, et al. (2023) indicate that STEM-based learning enables students to connect scientific concepts with real-world applications, facilitating deeper understanding and HOTS. Additionally, Wahono et al. (2020) and Sari et al. (2022) found that STEM-based learning significantly improves students' CTS by providing hands-on experiences and encouraging the application of knowledge in various contexts. However, despite its benefits, the implementation of STEM learning in Indonesia faces significant challenges, including limited access to laboratory facilities and the lack of teacher readiness to integrate interdisciplinary learning effectively (Martawijaya et al., 2023).

To overcome these challenges, technology-based learning tools such as gizmos can be utilized to enhance STEM-based instruction. Gizmos is an interactive virtual lab that allows students to conduct simulations, manipulate variables, and visualize scientific concepts in a realistic manner (Noris et al., 2022; Alnaser & Forawi, 2024). In biology learning, one of the topics taught in grade XII at SMA Negeri 3 Bantaeng is photosynthesis. This topic is often difficult for students to understand due to its complex microscopic processes, such as light and dark reactions, enzymatic activities, and environmental interactions. By using gizmos, students can experiment with different conditions affecting photosynthesis, promoting a deeper conceptual understanding and improving their CTS (Baris, 2022).

Despite its effectiveness, the implementation of STEM-based learning with virtual labs must consider students' diverse academic abilities. Research suggests that students with high academic achievement tend to grasp STEM concepts more quickly, while those with lower academic performance may require additional guidance (Bahri et al., 2020). Without adaptive teaching strategies, the disparity in academic abilities can result in unequal learning outcomes. Therefore, designing inclusive STEM-based learning that accommodates students' varying levels of understanding is crucial.

Based on the issues discussed, this study aims to determine the influence of STEM-based biology learning assisted by virtual lab gizmos on students' CTS with different academic abilities. This research is expected to contribute to the improvement of STEM implementation in Indonesian classrooms, particularly in addressing the challenges associated with CTS development and academic diversity.

Methods

The approach used in this research is quantitative. This study employs a quasi-experimental method with a 2×2 factorial pretest-posttest control group design. It involves two classes, each of which is given a test before the learning process (pretest) and a test after the learning activities (posttest). The population in this study were all students of clas XII SMA Negeri 3 Bantaeng, consisting of four classes with a total of 119 students.

Table 1. 2×2 factorial pretest-posttest control group research design

Academic ability [K]	Classroom learning [A]	
	Learning based on STEM assisted by virtual lab gizmos [A1]	Contextual learning without virtual lab gizmos [A2]
Upper [K_A]	[$A1K_A$]	[$A2K_A$]
Lower [K_B]	[$A1K_B$]	[$A2\ K_B$]

(Source: Sugiyono, 2021)

The procedure for implementing the learning treatment is based on the research design.

Table 2. Treatment class based on vriables

Pretest	Treatment	Posttest
O_1	A_1K_A	O_2
O_3	A_1K_B	O_4
O_5	A_2K_A	O_6
O_7	A_2K_B	O_8

The sampling technique in this study was simple random sampling. This technique was carried out by randomly selecting two classes out of four. After that, another random selection was conducted to determine which class would be assigned as the experimental group and which as the control group. The selected sample consisted of class XII MIPA 1 (experimental group) and class XII MIPA 2 (control group), with each class consisting of 30 students.

The data collection technique used in this study was a test, specifically a CTS test in the form of an essay test consisting of 10 questions. The test included questions that measured CTS based on Ennis' indicators, such as elementary clarification, basic support, inference, advanced clarification, and strategies and tactics. The data obtained from this test were then analyzed to compare the differences between the pretest and posttest results to determine the effectiveness of the applied learning method.

The data analysis techniques used in this study consist of two types: descriptive statistical analysis and inferential statistical analysis (two-way ancova). Descriptive statistical analysis to describe students' CTS data. CTS scores are categorized into five modified categories.

Table 3. Categories of CTS

Score interval	Categories
$81.25<X\leq100$	Very high
$71.50<X\leq81.25$	High
$62.50<X\leq71.50$	Moderate
$43.75<X\leq62.50$	Low
$0<X\leq43.75$	Very low

(Source: Priawasana & Waris, 2019)

Before conducting inferential statistical analysis, prerequisite tests were carried out, namely normality and homogeneity tests. The decision-making provisions for the analyzed data are based on the significance value. If the α value > 0.05, the research data is normally distributed and homogeneous. However, if the α value < 0.05, the research data is considered not normally distributed and not homogeneous. The decision-making provisions in the two-way ancova test are as follows: if the significance (sig) value > α, then H0 is accepted, meaning that there is no significance difference; whereas if the significance (sig) value < α, then H1 is accepted, meaning that there is a significance difference at the α level of 0.05.

Results and Discussion

The assessment of CTS before and after learning was conducted using a critical thinking essay test instrument. The test consisted of 10 questions, which students answered, and each response was given a score. The results of the CTS data acquisition can be seen in Table 4.

Table 4. Descriptive analysis results of students' cts in the experimental and control classes

Statistics	Experiment (STEM-based learning assisted by virtual lab gizmos)		Control (Contextual learning without virtual lab gizmos)	
	Pretest	Posttest	Pretest	Posttest
Sample size	30	30	30	30
Average	50.75	84.92	48.42	70.92
Std. deviation	6.63	2.97	6.10	6.61
Lowest score	38	80	38	55
Highest score	58	90	58	85

Table 4 shows that before participating in STEM-based learning with virtual lab gizmos, the average CTS of students was 50.75, which increased to 84.92 after the learning process. The lowest score before treatment was 38, and the highest was 58, with a standard deviation of 6.63. After the treatment, the lowest score increased to 80, and the highest to 90, with a standard deviation of 2.97. Meanwhile, in contextual-based learning, the initial average score was 48.42, which increased to 70.92. Before the treatment, the lowest score was 38, and the highest was 58, with a standard deviation of 6.10. After the treatment, the lowest score increased to 55, and the highest to 85, with a standard deviation of 6.61.

Table 5. Frequency distribution and percentage of CTS categories in the experimental and control classes

Interval value	Categories	Class							
		Experiment (STEM-based learning assisted by virtual lab gizmos)				Control (Contextual learning without virtual lab gizmos)			
		Pretest		Posttest		Pretest		Posttest	
		F	%	F	%	F	%	F	%
81.25<X≤100	Very high	0	0	26	86.7	0	0	0	0
71.50<X≤81.25	High	0	0	4	13.3	0	0	13	43.3
62.50<X≤71.50	Moderate	24	80	0	0	0	0	11	36.7
43.75<X≤62.50	Low	6	20	0	0	23	76.7	6	20
0<X≤43.75	Very low	0	0	0	0	7	23.3	0	0
Total		30	100	30	100	30	30	100	30

The frequency distribution and percentage data of pretest and posttest CTS scores of students in the experimental and control classes can be seen in Figure 1.

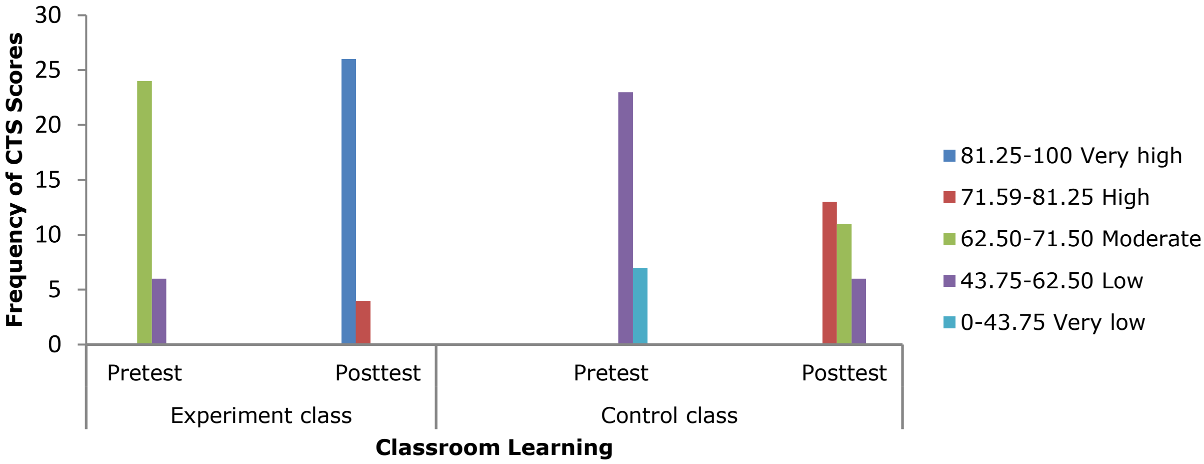

Figure 1. Frequency distribution diagram of CTS of experimental and control class students

In Figure 1, prior to receiving STEM-based biology instruction assisted by the virtual lab gizmos, 24 students (80%) were categorized as moderate, while 6 students (20%) were in the low category. Following the learning process, no students remained in the low or moderate categories. Instead, 4 students (13.3%) were classified in the high category, and 26 students (86.7%) were in the very high category. Meanwhile, in the control class, before undergoing context-based biology instruction, 23 students (76.7%) were classified as low, and 7 students (23.3%) were categorized as very low. After the learning process, no students remained in the very low category. The distribution shifted, with 6 students (20%) falling into the low category, 11 students (36.7%) in the moderate category, and 13 students (43.3%) in the high category. Notably, no students reached the very high category. Based on these findings, it can be concluded that the CTS of students in the experimental class were superior to those in the control class.

The descriptive statistical values of students' CTS in the experimental and control classes are presented based on different academic abilities.

Table 6. Descriptive statistical analysis results of students' CTS in the pretest and posttest of the experimental and control classes based on differences in academic abilities

No	Learning approach	Academic abilities	Average		Difference	Conclusion
			Pretest	Posttest		
1	STEM Assisted by VLG	KA upper	56.00	87.00	31.00	Increased
		KA lower	45.50	83.17	37.67	Increased
		Total	50.75	85.08	34.33	Increased
2	Contextual without VLG	KA upper	49.50	73.33	23.83	Increased
		KA lower	47.67	65.33	17.66	Increased
		Total	48.58	69.33	20.76	Increased
Total		KA upper	52.75	80.16	27.41	Increased
		KA lower	46.58	74.25	27.67	Increased

Table 6 above presents the CTS of students before and after being taught using STEM-based biology instruction assisted by virtual lab gizmos and context-based biology instruction, categorized by high and low academic abilities. The data indicate an increase in students' average scores, with varying differences depending on the instructional method and academic ability.

A diagram illustrating the average CTS scores, as measured by the critical thinking test, is provided in Figure 2.

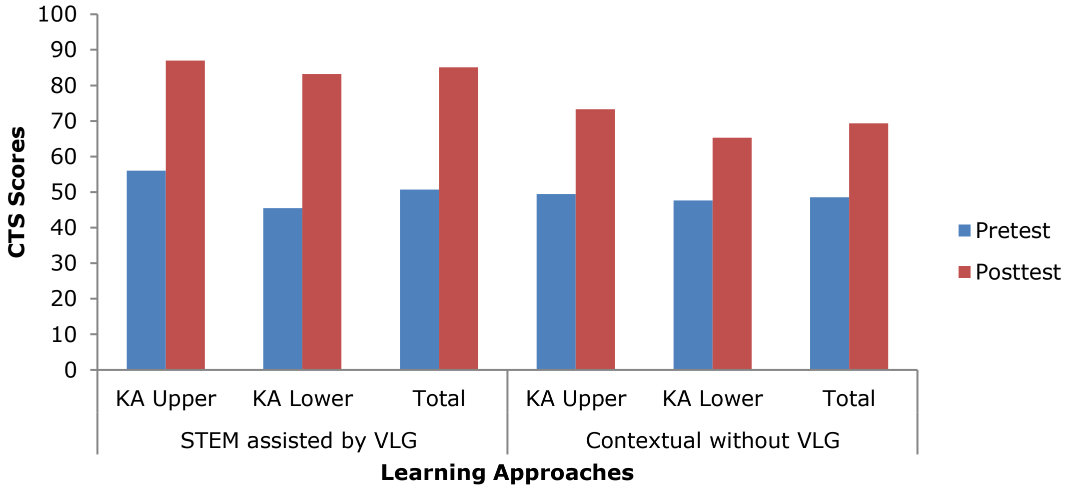

Figure 2. Diagram of students' CTS categories in pretest and posttest for experimental and control classes based on different academic abilities

Based on Figure 2, it can be seen that students who received STEM-based biology instruction assisted by virtual lab gizmos experienced a greater improvement compared to those who received context-based biology instruction. It is also evident that the high academic ability group showed a higher increase compared to the low academic ability group.

Before conducting this inferential statistical test, several prerequisite tests were carried out, namely the normality and homogeneity tests. The provisions for making decisions from the data that havebeen analyzedare by looking at the significance value if the ɑ value> 0.05,then the research data is normally distributed, but if the ɑ value <0.05,then the research data is declared not normally distributed. The results of the normality test in this study can be seen in Table 7.

Table 7. Results of pretest and posttest normality test of CTS

One sample kolmogorov smirnov test				
Variables	Data	Sig.	Sig level (ɑ)	Conclusion
CTS	Pretest experiment	0.230	> 0.05	Normal
	Posttest experiment	0.160		Normal
	Pretest control	0.290		Normal
	Posttest control	0.200		Normal

Based on Table 7, the results of the normality test for students' CTS from the pretest and posttest scores in the experimental and control classes show a significance value above 0.05, indicating that the CTS data of XII grade students at SMA Negeri 3 Bantaeng, using STEM-based biology learning assisted by virtual lab gizmos, are normally distributed.

The homogeneity test was conducted to determine whether the samples used, namely class XII MIPA 1 (experimental class) and XII MIPA 2 (control class), came from a population with homogeneous variance. The decision-making criteria based on the analyzed data are determined by examining the significance value. If the ɑ value > 0.05, the research data is considered homogeneous. However, if the ɑ value < 0.05, the research data is considered not homogeneous. The results of the homogeneity test in this study can be seen in Table 8.

Table 8. Results of pretest and posttest homogeneity test of CTS

Variables	Sig.	Sig level(ɑ)	Conclusion
Critical thinking pretest	0.526	> 0.05	Homogeneous
Critical thinking posttest	0.140		Homogeneous

Based on Table 8, it can be seen that in the calculation of data management for testing the homogeneity of variance using SPSS for Windows 23.0 the data obtained can be described as the value of the CTS test on the pretest shows that sig 0.526> 0.05 while the posttest shows that sig 0.140> 0.05 It can be concluded that CTS through STEM-based biology learning assisted by virtual lab gizmos and contextual learning are homogeneous.

Based on the results of hypothesis testing it shows that the significance value is <0.000. This shows the sig value < ɑ (0.05), so it can be concluded that H_0 is rejected and H_1 is accepted. This means there are differences in the CTS of students taught with STEM-based biology learning assisted by virtual lab gizmos and contextual learning on photosynthesis material.

Table 9. Results of hypothesis test (two-way ancova) CTS

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	4311.146[a]	3	1437.049	168.533	0.000
Intercept	357667.604	1	357667.604	41946.358	0.000
Class	3720.938	1	3720.938	436.382	0.000
Academic abilities	525.104	1	525.104	61.583	0.000
Class*Academic abilities	65.104	1	65.104	7.635	0.008
Error	477.500	56	8.527		
Total	362456.250	60			
Corrected total	4788.646	59			

Based on Table 9, the significance value of 0.000 < 0.05 indicates a difference in CTS between students who learned through STEM-based biology instruction assisted by virtual lab gizmos and those who received contextual learning, demonstrating the influence of STEM-based learning on students' CTS. Additionally, the significance value of 0.000 < 0.05 also indicates a difference in CTS between students with high and low academic abilities, signifying the impact of academic ability on critical thinking. The interaction significance value of 0.008 < 0.05 shows the influence of the interaction between the learning approach and academic ability on students' CTS. Further test results can be seen in Table 10.

Table 10. Least significant difference (LSD) test results on the interaction influence of learning approach and academic ability on students' CTS

Learning approach	Academic abilities	Pretest	Posttest	Difference	Adjusted mean	LSD notation
STEM+VLG	Upper	56.00	87.00	31.00	86.67	a
STEM+VLG	Lower	45.50	83.17	37.67	83.48	b
Contextual	Upper	49.50	73.33	23.83	73.24	c
Contextual	Lower	47.67	65.33	17.66	65.41	d

Based on Table 10, the lowest adjusted mean score of CTS is found in the contextual-lower academic ability group (65.41), while the highest is in the STEM+VLG - Higher Academic Ability group (86.67). The LSD test results indicate significant differences among all combinations, with STEM+VLG-higher academic ability having the highest score.

The research results indicate that STEM-based biology instruction assisted by virtual lab gizmos has an impact on students' CTS. These findings align with the study conducted by Yasifa et al. (2023), which stated that the implementation of STEM influences students' CTS. STEM-based learning enhances CTS by integrating four key aspects STEM which require active student engagement in the learning process (Ratnasari & Sulistyaningrum, 2023). STEM-based learning significantly influences students' CTS, as evidenced by hypothesis testing with a significance value of 0.00 < 0.05. This indicates that STEM-based biology learning assisted by virtual lab gizmos and contextual learning significantly impact CTS.

STEM-based learning consists of four aspects that contribute to developing CTS. Science trains students to analyze phenomena and draw conclusions based on scientific evidence through observation and experimentation. Technology enables students to use digital platforms to simulate, evaluate, and solve problems innovatively. Engineering encourages students to design solutions to address problems. Meanwhile, mathematics teaches students to process quantitative data, evaluate results, and interpret information in graphical form (Fatimah & Fanni, 2022). This learning approach fosters students' ability to understand problems, seek solutions, and utilize information to make informed decisions.

The integration of STEM-based learning with virtual lab gizmos stimulates students' critical thinking by combining scientific exploration, interactive technology use, problem-solving through design, and data analysis, helping students comprehend concepts through virtual experiments (Rahma & Irma, 2024). This aligns with Ismail et al. (2023), who stated that virtual lab gizmos benefits students by enhancing their understanding of materials, fostering creativity, and improving learning outcomes. The use of virtual lab gizmos connects students' cognition and creativity by activating cognitive functions, increasing focus, and deepening material comprehension through virtual simulations, enabling the transfer of information from short-term to long-term memory (Sumadevi, 2023).

Virtual lab gizmos is chosen for its alignment with 21st-century learning, integrating technology into education. Technology integration helps students develop essential digital skills, such as conducting virtual experiments. Additionally, virtual lab gizmos offers various visual features that facilitate problem-solving and comprehension. Its features include interactive experiment simulations that allow students to manipulate variables and observe their effects in real time, visualization of experimental results in graphs and diagrams, and step-by-step instructions to clarify concepts. These features enable students to conduct experiments that may be challenging in physical labs, thereby enhancing their understanding of the subject matter (Hartanto & Suryani, 2022).

The combination of STEM-based learning with virtual lab gizmos has strong potential to enhance students' CTS. This is supported by Tauran and Wibowo (2021), who stated that virtual lab gizmos allows students to conduct virtual experiments, deepening their understanding of scientific concepts through interactive simulations and precise data analysis. STEM-based learning assisted by virtual lab gizmos effectively focuses students' minds on problem-solving by integrating science, technology, engineering, and mathematics, creating a comprehensive and real-world-based learning experience. Through direct interaction with virtual experiments, students develop CTS by engaging in problem-solving activities that involve analysis, synthesis, and in-depth evaluation of results.

The study also reveals that students with higher academic ability demonstrate better CTS than those with lower academic ability. This finding aligns with Putra et al. (2024), who stated that students with higher academic performance tend to have stronger CTS due to their frequent success in academic tasks. Strong academic achievement enhances students' ability to tackle academic challenges. Additionally, students with high academic ability usually possess strong intrinsic motivation, which further strengthens their CTS.

The academic ability used as a reference in this study is the students' raw scores from the previous semester. This is consistent with research by Bahri et al. (2020), Elfaladonna & Indra (2022), and Asda (2024), who also used raw scores to determine students' academic ability. Raw scores refer to the direct measurements or observations recorded without modification or additional interpretation. In the context of data, raw scores are the initial figures obtained during measurement before further analysis or interpretation (Sugiyono, 2021). This approach allows for an objective and comprehensive assessment of students' academic abilities by enabling direct comparisons among students.

Students' academic abilities are categorized into high and low groups based on the average raw scores. The average score is calculated by summing all individual scores and dividing by the number of students in the group. Students with scores above the average are classified as having high academic ability, while those with scores below the average are categorized as having low academic ability. The number of students in the high academic ability group is equal to those in the low academic ability group. Creswell (2018) highlights the importance of balancing groups in quantitative research to minimize bias. Ensuring equal group sizes based on academic ability helps control variables that might influence experimental outcomes. This balanced grouping ensures fairness in representation, preventing dominance by one group, which could lead to biased results and less valid research conclusions.

The study findings indicate that STEM-based learning assisted by virtual lab gizmos is highly effective in enhancing students' CTS, particularly among students with high academic ability. Meanwhile, contextual learning shows nearly equivalent improvement in critical thinking among students with low academic ability compared to STEM-based learning. This suggests that both STEM-based learning with virtual lab gizmos and contextual learning significantly impact students' CTS across different academic ability levels.

Conversely, contextual learning often struggles to present abstract concepts effectively, as it relies on real-world experiences that may not always be accessible to all students (Johnson, 2019). This approach tends to prioritize experiential understanding without the support of simulations or advanced technology-based exploration. As a result, students with limited exposure or less supportive learning environments may find it difficult to connect theoretical concepts with practical applications. Therefore, STEM-based learning, supported by virtual lab gizmos, offers a more flexible, interactive, and data-driven learning experience, making it more effective in enhancing students' CTS compared to contextual learning.

Students with higher academic ability taught using STEM-based learning assisted by virtual lab gizmos exhibit greater improvements in critical thinking, as they possess a stronger initial ability compared to other groups. On the other hand, students with lower academic ability in the STEM-based learning group show significant differences when compared to high-achieving students in the contextual learning group. Similarly, students with high academic ability in the contextual learning group demonstrate notable differences from those with lower academic ability in the same learning approach. This variation highlights the effectiveness of STEM-based learning assisted by virtual lab gizmos in fostering CTS, especially among high-achieving students.

Conclusion

The implementation of STEM-based biology learning assisted by virtual lab gizmos has a significant effect on the CTS of Grade XII students at SMA Negeri 3 Bantaeng. The CTS score in the class that applied STEM-based biology learning assisted by virtual lab gizmos was 19.74% higher than the class that applied contextual learning. There is a significant influence of academic ability level on students' CTS, where students with higher academic ability had a CTS score that was 7.96% higher than students with lower academic ability. The two-way ancova test results for CTS showed a significance value of 0.008 < 0.05, meaning that H1 is accepted, indicating an interaction effect between STEM-based biology learning assisted by virtual lab gizmos and academic ability on the CTS skills of grade XII students at SMA Negeri 3 Bantaeng.

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