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# The Effect of Implementing STEAM-Based Learning on Students' Critical Thinking Skills in the 11th Grade Biology at SMAN 14 Makassar

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**ABSTRACT**
This study aims to determine the effect of STEAM-based learning on students' critical thinking skills regarding the digestive system topic in Grade 11 at State Senior High School 14 Makassar. A quasi-experimental approach with a pretest–posttest control group design was applied. The study population consisted of all 360 Grade 11 students, and the sample comprised two classes (72 students) selected using purposive sampling. Class XI.5 was designated as the experimental class, which employed STEAM-based learning, while Class XI.6 served as the control class, which used conventional teaching methods. The research instrument was an essay test of 12 items developed based on Ennis's indicators of critical thinking. The data obtained were analyzed using descriptive and inferential statistical analysis with the aid of SPSS; analysis of covariance (ANCOVA) was applied to the posttest scores, with the pretest scores entered as the covariate. The results of the analysis of student scores showed that the critical thinking skills of students taught using STEAM-based learning were better than those taught using conventional learning. The mean score of the STEAM class climbed from 23.86 to 86.36 (N-gain = 0.82), whereas that of the conventional class moved from 22.39 to 60.00 (N-gain = 0.49). The ANCOVA confirmed that the learning approach had a significant and large effect once the pretest was controlled ($F(1, 69) = 518.14$, $p < .001$, partial $\eta^2 = .88$).

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## INTRODUCTION

Technological advancements in the 21st century have brought significant changes to the world of education. Educational systems are now expected not only to transfer knowledge but also to equip students with skills relevant to global challenges, such as critical, creative, and innovative thinking, as well as the ability to utilize digital technology in the learning process (Mardhiyah, 2021).

Without innovative learning, students tend to become passive, focusing solely on formal grades, and lacking the ability to think deeply. This renders the learning process meaningless for both students and teachers (Shabrina, 2022). Quality education must be directed toward developing higher-order thinking skills to produce human resources capable of competing in the global marketplace (Sartono, 2020).

One of the 21st-century skills that needs to be emphasized is critical thinking. This skill encompasses the ability to evaluate information objectively, question assumptions, and

devise creative solutions to complex problems ((Ngatminiati & Hidayah, 2024). Teachers play a crucial role in fostering a culture of critical thinking from an early age so that students can solve problems in a reflective and innovative manner (Risandy, 2024). This can be achieved through learning strategies that engage students in discussions, analysis, solving real-world problems, and utilizing technology to enrich the learning experience (Maulidia, 2023).

Results from the Programme for International Student Assessment (PISA) survey indicate that Indonesian students' critical thinking skills remain low. In PISA 2022, Indonesian students obtained a mean of 366 in mathematics, 359 in reading and 383 in science, all well below the OECD averages of 472, 476 and 485, respectively (OECD, 2023), even though the country's relative position improved slightly compared with 2018 (Serina, 2024). These figures are relevant to biology learning even though PISA does not assess biology as a separate subject. The science domain, which covers living systems, asks students to explain phenomena scientifically, evaluate the design of an inquiry and interpret data and evidence, while the mathematics domain asks them to reason from quantitative information. Both domains therefore draw on the same operations that (Ennis, 2011) places at the heart of critical thinking, namely clarifying a problem, judging the credibility of information, drawing inferences and deciding on a reasonable course of action. Low results across these domains signal a general weakness in reasoning with evidence, a weakness that also constrains students' performance in biology. This fact highlights the urgency of changing the current learning approach, which has placed too much emphasis on rote memorization, particularly in science subjects such as Biology.

To address these challenges, an innovative learning approach is needed, one of which is STEAM (Science, Technology, Engineering, Arts, and Mathematics). This approach integrates five disciplines and encourages students to conduct investigations, generate ideas, be creative, and produce real-world solutions to complex problems (Anizal, 2022). Previous research has also demonstrated the effectiveness of STEAM. (Ningsih, 2023) found a significant improvement in the critical thinking skills of Biology students at SMAN 3 Bone following the implementation of STEAM-based learning. Similar findings were reported by (Sulastri & Cahyani, 2021), who integrated STEAM with Project-Based Learning (PjBL) and observed a significant improvement in critical thinking skills among vocational school students.

Despite these encouraging results, the available evidence still leaves several gaps. (Ningsih, 2023) documented the improvement mainly through changes in students' category distribution, (Sulastri & Cahyani, 2021) worked with vocational accounting students in online classes, and (Fazriyah & Nuraeni, 2024) studied elementary pupils. Studies that compare STEAM with conventional instruction in senior high school biology while statistically adjusting for students' initial ability remain scarce. In addition, most reports treat STEAM as a single package, so it is seldom clear which activity within the five disciplines strengthens which aspect of critical thinking. The present study responds to these gaps in three ways. First, the five STEAM components are embedded in a four-meeting project in which students design, build, test and present a working model of the human digestive system. Second, each phase of the project is deliberately linked to one or more of (Ennis, 2011) five indicators and twelve sub-indicators, and each test item represents one sub-indicator, so that the effect can be traced at the indicator level rather than only through a total score. Third, the effect is estimated with ANCOVA using the pretest as a covariate and is reported together with its effect size.

SMAN 14 Makassar was selected because preliminary observation and discussion with the biology teacher showed that Grade XI biology lessons were still dominated by teacher-centred lectures, and students seldom asked questions or defended their opinions during class discussion. A comparable picture has been reported in another public senior high school in the same city, where 50.82% of students were classified in the poor and very poor categories of critical thinking (Almunawarah & Bahri, 2023). The digestive system was chosen as the learning context for three reasons. It is part of the Grade XI biology content in the Merdeka Curriculum; it is closely connected to students' everyday experiences, such as eating habits and common complaints like gastritis or indigestion, which makes it easy

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to frame as authentic problems; and its organs and processes can be represented physically, so students can observe, measure, construct and evaluate a model rather than merely memorise organ names and functions. These features make the topic well suited to a STEAM project and to test items that demand reasoning instead of recall.

Therefore, this study was conducted to examine the impact of STEAM-based learning on the critical thinking skills of 11th-grade students at SMAN 14 Makassar on the digestive system topic.

## METHOD

This study employed a quasi-experimental method with a pretest-posttest control group design. This design involved two groups: an experimental class and a control class. Both groups took the same critical thinking test before the treatment (pretest) and after it (posttest). The pretest therefore served as the baseline measure of the dependent variable and was later entered as the covariate in the analysis. The study population consisted of all 11th-grade students at SMAN 14 Makassar during the 2024/2025 academic year, totaling 360 students distributed across ten classes. The sample was determined using purposive sampling, based on similar average Biology scores in the previous (odd) semester, as reported by the biology teacher. After the two classes had been identified, their roles as experimental and control classes were assigned by random draw. From the selection results, Class XI.5 (36 students) was chosen as the experimental class and Class XI.6 (36 students) as the control class, for a total of 72 students. Equivalence of the two classes on the dependent variable was then checked with an independent-samples *t*-test on the pretest scores. The difference was not significant ($t(70) = 1.43$, $p = .158$), confirming that both groups started from a comparable level of critical thinking before the treatment was given.

**Table 1.** Research Sample

| Class | Average Score | Number of Student |
|---|---|---|
| XI. 5 | 78 | 36 |
| XI. 6 | 77 | 36 |
| **Total** | | **72** |

### Instructional Procedure

Both classes studied the same digestive system content with the same learning objectives over four meetings (8 lesson hours, each meeting lasting 2 × 45 minutes), and the study ran from 15 to 30 April 2025. In the experimental class, STEAM was carried out through a project-based learning sequence guided by a teaching module and student worksheets that had been reviewed by an expert validator. In the first meeting (introduction and planning), the teacher opened the lesson with a triggering question, “What happens to food after we swallow it?”, showed videos and pictures of the digestive system and its disorders, and asked each group to use Worksheet 1 to plan the design, materials, tools and procedure for a digestive system model. In the second meeting (construction), groups began building the model according to their plan, while the teacher observed, guided and helped them identify and resolve difficulties. In the third meeting (testing and evaluation), groups completed the model, ran a simple simulation of how food passes through the tract, evaluated the weaknesses of their product and discussed how a disorder in one organ would affect the whole digestive process. In the fourth meeting (presentation and reflection), each group presented its model, the other groups offered comments and suggestions, and the teacher reinforced the key concepts and led a reflection on the learning process.

The five disciplines were integrated into this sequence as follows. Science covered identifying the digestive organs and their functions, explaining the stages of digestion and analysing related health problems. Technology covered the use of videos, images and digital sources, together with the tools and materials used to build the model and to document the simulation. Engineering covered designing, assembling and improving the model on the basis of evaluation. Arts covered choosing the visual design and colouring and decorating the model so that it was both attractive and informative. Mathematics covered measuring

the organs, determining the size ratio between the model and the real organs, and analysing data from the simulation.

The control class followed conventional instruction for the same number of meetings and lesson hours. In the first meeting, the teacher explained the digestive system directly while students took notes; in the second, students completed worksheets and presented their answers; in the third, the teacher lectured on digestive disorders while students recorded the material; and in the fourth, students worked on practice questions and discussed them with the teacher. No project, model construction or design activity took place in this class.

**Research Instrument**

Critical thinking skills were measured with an essay test of 12 items, each representing one of the 12 sub-indicators grouped under (Ennis, 2011) five indicators: elementary clarification (three items), basic support (two items), inference (three items), advanced clarification (two items), and strategies and tactics (two items). Every item was built around a contextual case related to digestive health, for example a student who habitually eats in a hurry and later complains of stomach pain, and the test was completed in 60 minutes. The same test was administered as the pretest and the posttest. Answers were scored with an analytic rubric ranging from 0 to 5 per item: 5 for an accurate, comprehensive and logically argued answer; 4 for an accurate answer with minor gaps in detail or depth; 3 for a partly accurate answer with a shallow explanation; 2 for an answer showing limited understanding or basic misconceptions; 1 for an inaccurate or irrelevant answer; and 0 for an unanswered item. The total score (maximum 60) was converted to a 0–100 scale by dividing the obtained score by 60 and multiplying the result by 100.

The test, rubric, teaching module and worksheets were reviewed by an expert in biology education, who rated each component on content, construction and language using a four-point scale (1 = not valid to 4 = highly valid). The test was declared usable after minor revision, and the item on source credibility was revised as the validator suggested, while the teaching module and worksheets were declared usable without revision. The study relied on this expert judgement of content validity; an empirical try-out to estimate internal-consistency reliability was not carried out, and this is discussed as a limitation.

**Data Analysis**

Descriptive statistics, namely the mean, standard deviation and lowest and highest scores, were used to summarise the pretest and posttest results. Each score was also classified into five levels adopted from (Arikunto, 2002): 90–100 (excellent), 80–89 (good), 75–79 (fair), 60–74 (less) and 0–59 (very low). Before hypothesis testing, normality was examined with the Shapiro–Wilk test and homogeneity of variance with Levene's test at $\alpha = .05$. The hypothesis was then tested with one-way ANCOVA, with posttest scores as the dependent variable, learning approach as the fixed factor and pretest scores as the covariate. Partial eta squared ($\eta^2p$) was reported as the effect size and interpreted with (Cohen, 1988) benchmarks of .01 (small), .06 (medium) and .14 (large). The normalised gain (N-gain) was also calculated to describe the size of improvement in each class, with $g \geq 0.70$ classified as high, $0.30 \leq g < 0.70$ as moderate and $g < 0.30$ as low (Hake, 1998). All analyses were conducted with SPSS 27.0 for Windows.

**RESULT AND DISCUSSION**

Based on the research findings and the data analyzed, it can be concluded that STEAM-based learning has an impact on students' critical thinking skills in the 11th-grade biology at SMAN 14 Makassar.

**Research Results**

**Descriptive Statistical Analysis**

This study aims to analyze the effect of STEAM-based learning on students' critical thinking skills regarding the digestive system in the 11th-grade biology course at SMAN 14

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Makassar. Data were collected through pre-tests and post-tests in the experimental class (XI.5) and the control class (XI.6).

**Table 2.** Descriptive Statistics of Pretest and Posttest Critical Thinking Scores

| Descriptive Statistic | STEAM Class | | Conventional Class | |
|---|---|---|---|---|
| | Pretest | Posttest | Pretest | Posttest |
| Lowest Score | 16 | 75 | 15 | 46 |
| Highest Score | 33 | 95 | 31 | 78 |
| Average | 23.86 | 86.36 | 22.39 | 60.00 |
| Standard Deviation | 4.499 | 5.530 | 4.251 | 7.664 |
| Sample Size | 36 | 36 | 36 | 36 |

The results of the descriptive statistical analysis show that the average critical thinking skills score of students in the experimental class increased significantly from 23.86 (pretest) to 86.36 (posttest). In contrast, the control class only saw an increase from 22.39 (pretest) to 60.00 (posttest). Additionally, the standard deviation in the experimental class was relatively smaller (5.53 versus 7.66), indicating a more even distribution of score increases compared to the control class. In terms of normalised gain, the STEAM class reached a mean N-gain of 0.82, which falls in the high category, whereas the conventional class reached 0.49, which falls in the moderate category (Hake, 1998).

**Table 3.** Categories of Critical Thinking Skills: Pretest and Posttest

| Score Range | Category | Conventional Class | | STEAM Class | |
|---|---|---|---|---|---|
| | | Pretest | Posttest | Pretest | Posttest |
| | | F | F | F | F |
| 90-100 | Excellent | 0 | 0 | 0 | 12 |
| 80-89 | Good | 0 | 0 | 0 | 19 |
| 75-79 | Fair | 0 | 1 | 0 | 5 |
| 60-74 | Less | 0 | 20 | 0 | 0 |
| 0-59 | Very Low | 36 | 15 | 36 | 0 |

Source: score categories adopted from (Arikunto, 2002).

Based on the assessment categories, prior to the intervention, all students in both classes were in the “very low” category. After the intervention, the posttest results showed that the majority of students in the experimental class were in the “good” to “Excellent” categories (31 of 36 students), and the remaining five students reached the fair category. In contrast, no student in the control class moved beyond the fair category; 20 students were in the less category, 15 remained in the very low category and only one reached fair. The analysis was simplified by grouping the sub-indicators into five main indicators of critical thinking. The following diagram shows a comparison of the control class students’ critical thinking indicator scores on the pretest and posttest.

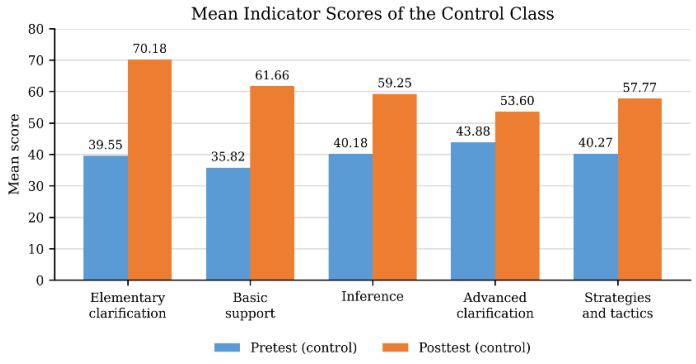



**Figure 1**. Diagram of Average Scores for Critical Thinking Skills Indicators in the Control Class

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There was an improvement in several indicators, although it was not uniform. The largest increase occurred in elementary clarification (39.55 to 70.18), whereas advanced clarification rose only from 43.88 to 53.60, and none of the five indicators reached a mean of 75 after instruction. Posttest scores that were only moderately higher than the pretest scores indicate that conventional instruction has not yet been able to comprehensively strengthen students' critical thinking skills. The presentation of key indicator achievements among STEAM class students was conducted as a comparison with the conventional class. The following diagram shows the average pretest and posttest scores for the five key indicators following the implementation of STEAM-based instruction.

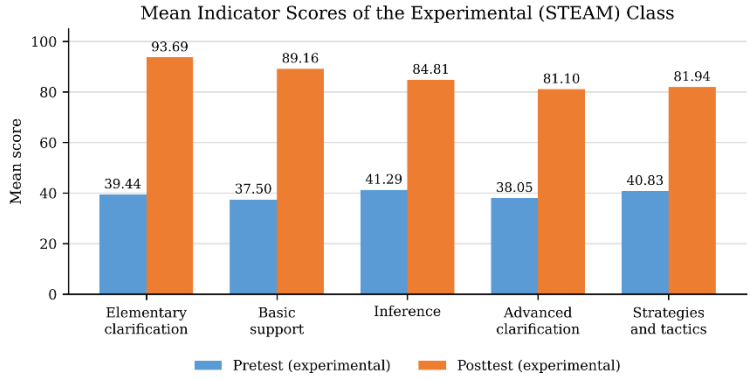



**Figure 2**. Diagram of Average Scores for Critical Thinking Indicators in the STEAM Class

Figure 2 shows a consistent increase across all indicators, with posttest means ranging from 81.10 for advanced clarification to 93.69 for elementary clarification, so that every indicator exceeded the highest indicator mean of the control class (70.18), indicating that STEAM-based learning has a significant positive impact on the overall development of students' critical thinking skills.

**Inferential statistical analysis**

The results of the normality test using the Shapiro-Wilk method indicate that the significance value (sig) for the pretest and posttest data in the STEAM class and the conventional class is above 0.05 (STEAM class: pretest = .329, posttest = .211; conventional class: pretest = .597, posttest = .722), indicating that the data are normally distributed. Meanwhile, the homogeneity test using Levene's test shows that the sig value (.088) is greater than 0.05, meaning the data variances are homogeneous. Thus, it can be concluded that the data in this study meet the assumptions of normality and homogeneity, so that inferential statistical analysis can be conducted validly. Hypothesis testing was performed using an ANCOVA test with the SPSS 27.0 for Windows program. The results of the ANCOVA test for the class implementing STEAM-based learning and the class implementing conventional learning are presented in the following table.

**Table 4.** Results of ANCOVA on Posttest Critical Thinking Scores with Pretest as Covariate

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial $\eta^2$ |
|---|---|---|---|---|---|---|
| Corrected Model | 13885.220 | 2 | 6942.610 | 357.878 | < .001 | .912 |
| Intercept | 4989.036 | 1 | 4989.036 | 257.175 | < .001 | .788 |
| Pretest (covariate) | 1872.720 | 1 | 1872.720 | 96.535 | < .001 | .583 |
| Learning approach (STEAM vs conventional) | 10051.641 | 1 | 10051.641 | 518.142 | < .001 | .882 |
| Error | 1338.558 | 69 | 19.399 | | | |

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| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial η² |
|---|---|---|---|---|---|---|
| Total | 403598.000 | 72 | | | | |
| Corrected Total | 15223.778 | 71 | | | | |

Note. Dependent variable: posttest critical thinking score. $R^2$ = .912 (adjusted $R^2$ = .910). Partial $\eta^2$ = partial eta squared; values of .14 or above indicate a large effect (Cohen, 1988).

Based on the results of the ANCOVA test presented in Table 4, the learning approach had a significant effect on posttest scores, $F(1, 69) = 518.14$, with a significance value below .001, which is smaller than the significance level of 0.05. Thus, H0 is rejected and H1 is accepted, meaning that there is a significant difference between the critical thinking skills scores of students in the STEAM class and the conventional class after controlling for pretest scores. The partial eta squared of .882 shows that the learning approach accounted for about 88% of the variance in posttest scores that remained after the pretest effect was removed, far above the .14 threshold for a large effect (Cohen, 1988). The pretest was also a significant covariate ($F(1, 69) = 96.54$, $p < .001$, partial $\eta^2 = .583$), confirming that adjusting for students' initial ability was appropriate. Together, the pretest and the learning approach explained 91.2% of the variance in posttest scores ($R^2 = .912$).

**Discussion**

The implementation of STEAM-based learning in this study was explicitly designed to facilitate the improvement of students' critical thinking skills, where each component of STEAM (Science, Technology, Engineering, Arts, Mathematics) is integrated and contributes to the development of critical thinking indicators. This aligns with the integrative review by (Perignat & Katz-Buonincontro, 2019), which shows that STEAM practice is commonly organised around interdisciplinary problem solving, inquiry and creative production, the very conditions under which students must clarify problems, weigh evidence and justify decisions. The following paragraphs trace how each component of the project engaged specific Ennis indicators and how these links are reflected in the indicator scores shown in Figures 1 and 2.

In the Science domain, exploratory activities such as learning about the structure and function of the digestive system encourage students to formulate specific and relevant questions. This helps them provide more structured explanations in response to questions. Additionally, in-depth observation and analysis of organ functions and their disorders also help students observe and interpret the results of their observations based on the data they collect, which is a crucial component of Building Foundational Skills. This aligns with the research by (Fazriyah & Nuraeni, 2024), which found that the STEAM approach has been proven to enhance critical thinking skills in the context of basic science learning through exploratory activities and data analysis. The mechanism was direct: during the planning stage, students had to turn an everyday case, such as food that is swallowed without being chewed properly, into a focused question and then check their explanation against what their model and learning resources showed. This rehearsed focusing questions and judging observation reports, the sub-indicators targeted by the first five test items. The pattern is visible in the data, as elementary clarification rose from 39.44 to 93.69 and basic support from 37.50 to 89.16 in the STEAM class (Figure 2), compared with posttest means of 70.18 and 61.66 in the conventional class (Figure 1).

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**Figure 3**. Exploratory Activity: Observing the Structure and Function of the Digestive System

In terms of technology, its application through the use of visual media such as videos and images aims to help students develop strategies and tactics for processing information. Students are trained to determine the most appropriate actions when analyzing visual data and organizing ideas. The use of technology also helps them assess the credibility of sources, thereby strengthening the foundation for building their basic skills. This perspective aligns with research conducted by (Handoyono, 2021), which shows that the use of digital technology in learning can improve students' information literacy as well as their ability to effectively process, analyze, and utilize data for problem-solving. Because groups gathered information from videos, images and digital sources before deciding on the form and function of each organ in their model, they had to consider whether these sources were credible and consistent with one another. This is precisely the sub-indicator of judging the credibility of a source under basic support.



**Figure 4.** Examining Visual Media on the Digestive System

The Engineering aspect trains students to develop strategies and tactics primarily through the design and model-making process. In this process, they learn to determine the most effective actions to solve design problems. Practical model testing reinforces the sub-indicator of drawing conclusions, where students must deduce and consider the results of their deductions from the failure or success of the projects they create. According to (Choirunnisa & Rahmawati, 2023), the engineering design process systematically trains students to identify problems, design solutions, implement, and evaluate prototypes all of which constitute an iterative process to strengthen reasoning and the ability to solve complex problems. Testing was the stage in which inference was exercised most visibly. When a part of the model did not represent the passage of food as intended, groups had to reason backward from the failure to its likely cause, decide on a modification and judge whether the revised design worked better, which matches the deduction and value-judgement sub-indicators of inference. The inference indicator in the STEAM class increased from 41.29 to 84.81, whereas the conventional class reached only 59.25 at posttest.

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**Figure 5.** Process of Creating a Digestive System Model

The integration of arts elements is evident when students draw, decorate, and present models. These activities directly address the sub-indicator of providing further explanation, as students must be able to identify terms and the assumptions underlying the ideas they represent visually. Furthermore, the presentation process encourages them to interact effectively with others to communicate complex ideas, which is part of developing strategies and tactics. This aligns with (Liao, 2016), who argues that integrating the arts into STEAM learning not only enhances creativity but also strengthens students' ability to communicate their ideas and thoughts critically, particularly when conveying complex concepts both visually and verbally. Labelling each organ, choosing colours or shapes to distinguish structures and explaining these choices to classmates required students to define terms precisely and make their assumptions explicit, which is the substance of advanced clarification. Even so, advanced clarification recorded the lowest posttest mean in the STEAM class (81.10), suggesting that defining terms and identifying assumptions remains the most demanding skill and calls for more explicit scaffolding.



**Figur**e **6**. Drawing and Decorating a Digestive System Model

Mathematics plays a crucial role in developing foundational skills through calculations, measurements, and scaling adjustments to models. These activities help students develop logical and systematic thinking. The application of mathematics also serves as the foundation for students to determine precise technical actions when designing functional models, which is an essential component of formulating strategies and tactics. This aligns with (Samosir, 2024) view, who states that in STEAM-based learning, mathematics plays a vital role in building systematic thinking structures through activities such as measurement, estimation, and scale calculations. These skills form the foundation for developing measurable and rational solutions, making them highly relevant for fostering critical thinking and logical problem-solving within a multidisciplinary context. The role of mathematics in this project therefore went beyond routine calculation. To determine the scale, groups had to compare the real dimensions of the organs with the space available for the model, choose a ratio that kept the relative proportions of the organs recognisable and justify the compromises they made between accuracy and feasibility. Such decisions require students to weigh alternatives, check them against evidence and settle on a defensible action, which corresponds to deciding on an action under strategies and tactics and to making value judgements under inference. The strategies and tactics indicator increased from 40.83 to 81.94 in the STEAM class (Figure 2).

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**Figure 7**. Measuring and determining the Scale of the Model Design

The STEAM-based learning stages implemented in this study create a learning environment rich in cognitive challenges and encourage students to develop various aspects of critical thinking skills. Integrated activities focused on solving real-world problems train students to build conceptual understanding, explain ideas systematically, draw conclusions from data, and design problem-solving strategies in a reflective and logical manner. This entire process is central to strengthening critical thinking skills.

STEAM-based learning has a tangible positive impact on improving students' critical thinking skills compared to conventional teaching methods. One of the keys to the success of STEAM learning lies in the stimulation phase. Teachers play a crucial role in sparking students' curiosity by connecting learning materials to everyday life. For example, teachers ask questions such as "What happens to food after we swallow it?" to open up students' thinking. Teachers also utilize visual media such as videos and images of the digestive system and related disorders to provide concrete examples that facilitate students' understanding.

Higher scores on critical thinking skills were observed in the STEAM class compared to the conventional class. The STEAM class also showed a narrower spread of posttest scores (SD = 5.53) than the conventional class (SD = 7.66), and none of its students remained below the fair category. This difference indicates that the STEAM approach accommodates individual differences in processing and applying knowledge through more open-ended and creative activities, so that lower-achieving students also benefited rather than only a few high performers. (Sulastri & Cahyani, 2021) state that a STEAM-based project-based learning model has a positive effect on improving students' critical thinking skills.

The STEAM-based learning approach positions students as active participants in the learning process. This active role is reflected in their engagement in exploring, designing, reflecting on, and communicating their learning outcomes both independently and collaboratively. This approach aligns with constructivist principles, which emphasize the importance of hands-on learning experiences in building deep and contextual understanding

Several limitations and implementation challenges should be considered when interpreting these findings. First, the study used two intact classes selected purposively from one school, so students were not randomly assigned and unmeasured differences between the classes, such as classroom climate, cannot be ruled out, even though the pretest scores were statistically equivalent and were controlled in the ANCOVA (Shadish, 2002). Second, the treatment lasted only four meetings on a single topic, and the same essay test was used as the pretest and posttest; part of the gain may therefore reflect familiarity with the items, and the durability of the effect was not examined. Third, instrument quality rested on expert judgement of content validity, while internal-consistency reliability and inter-rater agreement in scoring were not estimated. Fourth, the project itself was demanding to implement. Project work generally requires more time, materials and teacher preparation than lecture-based lessons (Nuragnia & Usman, 2021), and in this study the planning, construction, testing and presentation stages had to fit into four meetings, leaving little room for repeated redesign. Finally, the novelty of building a model may have raised students' motivation in the experimental class, which could have contributed to the difference alongside the STEAM design itself.

## CONCLUSION

Based on the data obtained from the analysis and discussion, it can be concluded that the critical thinking skills of 11th-grade students at SMAN 14 Makassar improved following the implementation of STEAM-based learning in biology, as evidenced by a shift in test scores from the low category to the good and very good categories. The mean score of the STEAM class increased from 23.86 to 86.36 (N-gain = 0.82), and every student reached the fair to excellent categories, whereas the conventional class increased from 22.39 to 60.00 (N-gain = 0.49) and no student went beyond the fair category. Furthermore, STEAM-based learning had a greater impact on students' critical thinking skills compared to conventional learning, as confirmed by the ANCOVA after the pretest was controlled ($F(1, 69) = 518.14$, $p < .001$, partial $\eta^2 = .88$). Because the study involved only two intact classes in one school, a single topic and four meetings, these findings should be read as evidence for this context and should not be generalised to all senior high schools without further replication.

These findings carry practical implications for biology teachers. Digestive system lessons can be organised as short model-building projects in which each STEAM component is tied explicitly to a critical thinking indicator, for example by using source comparison in the technology phase to train source evaluation and model testing in the engineering phase to train inference. Teachers are also advised to give more explicit support for defining terms and identifying assumptions, the indicator with the lowest gain in this study. Schools can facilitate such learning by allocating longer time blocks and simple materials for project work. Future studies should involve more schools and topics, use randomised or matched designs, include an empirical reliability analysis and inter-rater scoring, and examine whether the gains persist over time.

## AI DISCLOSURE STATEMENT

The authors used ChatGPT solely for language editing and grammatical improvement. No generative AI tools were used to create, analyze, interpret, or write the scientific content of this manuscript.

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