Jurnal Pijar MIPA
https://jurnalfkip.unram.ac.id/index.php/JPM

ISSN 1907-1744 (Print)
ISSN 2460-1500 (Online)

Analysis of STEAM PBL-Based E-Worksheet to Improve Critical Thinking Skills

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Received: xxx. Accepted: xxx. Published: xxx

Abstract: The 21st-century learning paradigm emphasizes critical thinking and problem-solving skills as essential competencies that must be developed to equip students to address increasingly complex global challenges and demands. Therefore, learning in schools should be designed to be innovative and contextual. This study aimed to evaluate the validity, practicality, and effectiveness of a problem-based learning e-worksheet incorporating the STEAM approach to enhance critical thinking skills in biology at State Senior High School 11 Palembang. The research model used the 4D development model, consisting of define, design, develop, and disseminate. The analysis techniques used include the Wilcoxon test, the Mann-Whitney test, and the N-gain analysis. Data collection techniques were interviews, questionnaires, and observations. The research population was students of grades X.2 and X.5. The analysis of the define stage showed that teachers and students need an e-worksheet based on the PBL model with the STEAM approach. The design stage included designing an e-worksheet. In the develop stage, the feasibility of the developed teaching materials was assessed at 90% from the aspects of language, materials, media, learning tools, and evaluation, so that it was categorized as very good. The practicality of the teaching tools was categorized as practical by teachers, with a percentage of 91.25% and the teaching materials could be read very well by students, with a percentage of 81%. The effectiveness of the e-worksheet based on the PBL model with the STEAM approach showed that the N-gain value for the control class was 0.33 (low criteria), while the experimental class was 0.78 (high criteria). In conclusion, an e-worksheet based on the PBL model with the STEAM approach can improve students' critical thinking skills.

Keywords: Biotechnology; Critical Thinking Skills; E-Worksheet; Problem-Based Learning.

Introduction

In the 21st century, technological developments have propelled the world into an era of massive digitalization, namely the 4.0 industrial revolution. This phenomenon has made technology and information the main pillars of every aspect of human life. The shift towards a knowledge-based society requires the mastery of global competencies, particularly in information and communication technology literacy. Therefore, the education sector plays a significant role in producing individuals who not only understand technology but also possess critical thinking skills, problem-solving abilities, effective communication, and collaboration skills [1].

Critical thinking is the ability to develop a mindset accompanied by self-awareness, as well as the ability to utilize information to enhance creativity and courage in decision-making. In line with [2], critical thinking underpins a person's ability to analyze arguments and develop a mindset. This cognitive aspect requires sharpness in recognizing problems in order to produce conclusions or solutions based on logical and objective thinking [3].

Based on a survey conducted at SMA Negeri 11 Palembang on teaching systems that encourage students to think critically, 83% reported that these systems are often monotonous. The dominance of textbook use at 67% at SMA Negeri 11 Palembang indicates that the teaching materials remain conventional. As a result, teaching and learning activities tend to be monotonous and are not yet optimal in actively engaging students in critical thinking. Although there is 14% use of E-modules, 14% use of worksheets, 3% use of YouTube, and 1% use of e-worksheet, these percentages indicate the need for more adaptive and interactive teaching materials.

The lack of innovative teaching materials significantly contributes to declining student learning outcomes, leading to student boredom during learning activities and affecting their critical thinking skills. Based on the acknowledgement from educators at SMA Negeri 11 Palembang, students' critical thinking skills are still categorized as low. This is reflected in the students' difficulty in analyzing, solving, and evaluating problems, which are key indicators of critical thinking. This condition is related to the application of a learning model that is still conventional and teacher-centered. In addition, the lack of problems that are relevant to real life causes students to tend to only memorize concepts without having the space to explore solutions independently.

The biology learning process at SMA Negeri 11 Palembang shows the following results: 56% assignments, 19% presentations, 16% discussions, 9% lectures, and 0% problem/case solving. Meanwhile, the application of the STEAM approach in the learning process resulted in the application of science elements at 33%, technology elements at 28%, engineering elements at 19%, art elements at 12%, and mathematics elements at 8%. Based on the analysis results, the most difficult material in biology was biotechnology (76%).

One effort to achieve the goal of education to develop science and technology is to implement digital-era learning

How to Cite:
R. M. Bonet, A. S. W. Sumah, and W. Saputri, "Analysis of STEAM PBL-Based E-Worksheet to Improve Critical Thinking Skills", *J. Pijar.MIPA*, vol. 21, no. 4, pp. 826–832, Aug. 2026. https://doi.org/10.29303/jpm.v21i4.12040

through the STEAM (science, technology, arts, and mathematics) approach. The STEAM concept guides students in developing a holistic mindset in facing problems through its five supporting aspects. This strategy is designed to enable students to apply the principles of science and mathematics to the design of innovative solutions. The relevance of the STEAM approach in modern education systems lies in its function of preparing the younger generation to be ready and able to adapt to the dynamics of the times [4].

A solution to this problem is the development of teaching materials, namely an e-worksheet. The main advantage of STEAM-based e-worksheet lies in its ability to integrate technological advances through the presentation of video, image, and animation elements. The presence of these visual and audiovisual components serves as a cognitive stimulant that can accelerate the improvement of students' critical thinking skills in understanding something more concretely [5]. This is supported by Syarifa Nurhalisa on analysis of the STEAM approach in biology learning towards student creativity at the State Senior High School 6 Maros [6]. Research by Umi Muslihah conducted at SMAN 4 Surabaya, analyzed development of electronic student worksheets based on the STEAM approach to improve problem-solving skills in the environmental pollution sub-material [7]. Research by Bimo Aji Nugroho at SMA Negeri 1 Sebatik analyzed about increasing student learning interest using PBL: STEAM [8].

The novelty of this study lies in the systematic integration of PBL syntax with each component of the STEAM approach in biology learning, particularly in biotechnology instruction through eco-enzyme production activities. Based on this review, the authors aimed to develop and analyze a STEAM-integrated, PBL-based electronic worksheet to improve the critical thinking skills of students at State Senior High School 11 Palembang. The development of innovative learning media is essential to enhance the quality of learning.

Research Methods

This study applied the research and development method using the 4D model. The product was an electronic student worksheet on biotechnology material that integrated the PBL model with the STEAM approach. In line with the theory [9], this 4D framework includes four main phases, namely define, design, develop, and disseminate. In the define phase, five analytical activities are conducted to identify the requirements for media development. The first activity, front-end analysis, involves evaluating the existing learning media and instructional methods to determine their limitations and identify areas for improvement. Learner analysis is then conducted to gather information on students' needs and characteristics that will serve as the basis for media development. Task analysis focuses on examining student characteristics and learning requirements. Subsequently, concept analysis is performed to select and organize the subject matter based on the findings of the previous analyses. The final activity in this phase is specifying instructional objectives, which involves formulating clear learning goals. Based on the results of these analyses, the researcher proceeds to develop learning media to enhance the quality of the learning process.

During the development testing phase, the instrument's validity and reliability were examined to ensure its quality and consistency prior to its use in the study. The instrument comprised 10 essay questions, and its reliability was evaluated using Cronbach's alpha coefficient.

The analysis techniques used normality, homogeneity, Wilcoxon, Mann-Whitney, and N-gain analysis. Data collection techniques were interviews, questionnaires, and observations. The research population comprised students in grades X.2 and X.5, one control class of 34 students, and one experimental class of 34 students. The control class was instructed using the method commonly used in their class, namely the lecture method. Meanwhile, the experimental class used the PBL learning method.

Table 1. Test Subject

Class	SMA	Pretest	Treatment	Posttest
Experiment	X.2	0_1	X1	0_2
Conventional	X.5	0_3	X2	0_4

Source :[10]

Explanation:

X1: Treatment in the experimental class (using electronic worksheet)

X2: Treatment in the conventional class (using printed teacher's books)

0_1: Pretest given to the experimental class

0_2: Posttest given to the experimental class

0_3: Pretest given to the control class

0_4: Posttest given to the control class

Results and Discussion

Main Text Paragraph The product developed in this study is an e-worksheet based on Problem Based Learning with a STEAM approach to biotechnology material using the 4D model of [9]. The first stage is Definition. At this stage, the researcher distributed questionnaires or needs assessments, as shown in the appendix, to biology teachers and students at SMA Negeri 11 Palembang. This process was carried out to identify problems that occurred in the learning process.

The second stage was the Design stage. The main objective of this stage was to compile and design teaching materials for use in the learning process. Based on the needs analysis, the selected media developed was an e-worksheet using the PBL model and a STEAM approach, incorporating biotechnology materials, created with the help of the Canva application. The third stage is the development stage in this study, which is realized through two main steps, namely expert appraisal and development testing. This procedure aims to ensure the product's theoretical feasibility through expert validation and to test its effectiveness in the field.

Next is the trial/development testing stage. The series of tests on the product development results is divided into three main stages: 1) the initial stage in the form of e-worksheet readability tests involving 10 students; 2) quantitative testing to measure the level of practicality by teachers and testing the validity and reliability of the instruments; and 3) total package testing carried out in control and experimental classes through pre-tests, post-tests, and response questionnaires. The initial trial was conducted with students from class XI.3 of SMA Negeri 11 Palembang as respondents.

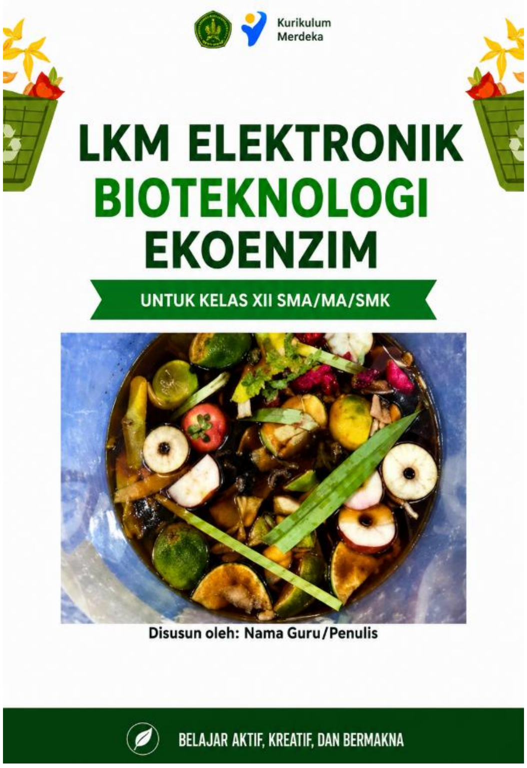

Figure 1. e-worksheet cover

Table 2. Results of expert validator assessment

No	Expert Assessment	Achievement %	Qualification
1.	Language	87	Very Good
2.	Material	91	Very Good
3.	Media	88	Very Good
4.	Learning Tools	97	Very Good
5.	Evaluation	89	Very Good
	Mean	90	Very Good

Based on the e-worksheet readability testing stage, an 81% score was obtained, qualifying as very strong. Ten students were involved in the readability testing and were selected randomly. Based on the teachers' evaluation of the e-worksheet implementation, a practicality level of 91.25% was achieved, considered very effective. The fourth stage is dissemination. At this stage, there is validation testing to see the effectiveness of implementing PBL-based e-worksheet with a STEAM approach on critical thinking skills, which can be observed by analyzing the critical thinking of students in the control and experimental classes. A series of statistical procedures was applied, including normality tests, homogeneity tests, Wilcoxon tests, Mann-Whitney tests, and N-gain calculations.

Calculation of normality test data

Based on the normality test results indicating that the pretest and posttest scores were not normally distributed, the Shapiro-Wilk test was conducted. The results of the normality test analysis are presented in Table 3 below:

Table 3. Results of the Normality Test for the Control Class and the Experimental Class

Shapiro-Wilk				
CTS	Class	Statistic	df	Significance
	Pretest Control	0.926	34	0.024
	Posttest Control	0.944	34	0.084
	Pretest Experiment	0.952	34	0.136
	Posttest Experiment	0.932	34	0.035

Based on the results of the normality test, the control class's pretest data showed a significance value (0.024) < α (0.05), indicating that the data were not normally distributed, while the control class's posttest data showed a significance value (0.084) > α (0.05), indicating that the data were normally distributed. Meanwhile, for the experimental class, the pretest sig. value (0.136) > α (0.05), indicating that the data is normally distributed, and the posttest sig. value (0.035) < α (0.05), indicating that the data is not normally distributed.

Calculation of Homogeneity Test Data

The next analysis was a homogeneity test, which aimed to determine whether the variances of the data between the experimental and control groups were homogeneous. A summary of the test results is presented in Table 4 below :

Table 4. Results of the Homogeneity Test for the Control Class Pretest and the Experimental Class Pretest

Levene Statistic			df1	df2	Sig.
CTS	Based on Mean	.123	1	66	.727
	Based on Median	.011	1	66	.916
	Based on Median and with adjusted df	.011	1	60.4	.916
	Based on trimmed mean	.110	1	66	.742

Based on the SPSS output for the homogeneity test, the significance value for the mean is 0.727 > 0.05; therefore, the pretest data for the control and experimental classes have homogeneous variances. Then, the results of the homogeneity test for the control class posttest and the experimental class posttest. Based on the SPSS output for the homogeneity test, the significance value for the mean is 0.056 > 0.05; therefore, it is concluded that the posttest data for the control class and the experimental class have homogeneous variances.

Table 5. Results of the Homogeneity Test for the Control Class Posttest and the Experimental Class Posttest

		Levene Statistic	df1	df2	Sig.
CTS	Based on Mean	3.798	1	66	0.056
	Based on Median	4.454	1	66	0.039
	Based on Median and with adjusted df	4.454	1	63.1	0.039
	Based on Trimmed mean	3.967	1	66	0.051

Calculation of Wilcoxon Test Data

The Wilcoxon test was used to analyze the significance of the difference between the means of two paired samples. In this study, the test utilized pretest and posttest data from each group, including both the control class and the experimental class. A summary of the statistical analysis results using the Wilcoxon test is presented in detail in Table 6 below :

Table 6. Results of the Control Group Calculations in the Wilcoxon Test

	Statistic Test
	Posttest control – Pretest control
Z	-5,097b
Asymp. Sig. (2-tailed)	0.000 ($p<0.05$)

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks

Based on the results of the Wilcoxon test analysis, Asymp. Sig. (2-tailed) was 0.000 < 0.05; therefore, H_0 was rejected and H_1 was accepted, meaning there is an effect on the critical thinking skills of students taught using conventional instruction. The results for the experimental class are shown in Table 7 below:

Table 7. Results of the Experimental Class Calculations in the Wilcoxon Test

	Statistic Test
	Posttest Experiment-Pretest Experiment
Z	-5,102b
Asymp. Sig. (2-tailed)	0.000 ($p<0.05$)

a. Wilcoxon Signed Ranks Test
b. Based on negative ranks

Based on the results of the Wilcoxon test (Asymp. Sig. (2-tailed)), where 0.000 < 0.05, H_0 is rejected and H_1 is accepted, meaning there is an effect on the critical thinking skills of students in the experimental class before and after learning using PBL-based electronic learning materials with a STEAM approach. Thus, it can be concluded that the control class had no effect, as the students' pretest and posttest results were obtained from learning without the use of electronic worksheets, whereas the experimental class's pretest and posttest results were obtained using PBL-based electronic worksheets with a STEAM approach.

Mann-Whitney test data analysis

The results of the Mann-Whitney U test on the posttest scores of the two groups showed an Asymp. Sig. value of 0.000. Since this significance value is less than 0.05 (0.000 < 0.05), H_0 is rejected, and Ha is accepted. These findings confirm a significant difference in critical thinking skills between students in the control and experimental classes within the biotechnology curriculum. This difference was influenced by the use of PBL-based electronic worksheets with a STEAM approach in the experimental class, which was not implemented in the control class.

Table 8. Results of the Mann-Whitney Posttest Analysis: Control Group and Experimental Group Posttest

Statistic Test	
	Learning outcomes
Mann-Whitney U	0.000
Wilcoxon W	595.000
Z	-7.134
Asymptotic Significance (2-tailed)	0.000

Calculation of N-Gain Test Data

The N-gain analysis results show that the control class obtained a score of 0.33, which is classified as low. In contrast, the experimental class achieved an N-gain score of 0.78, which is classified as high. These findings indicate that implementing a PBL-based e-worksheet using a STEAM approach effectively improves students' critical thinking skills in biotechnology.

Table 9. Results of the analysis of the effectiveness of the control class and the experimental class

Class	Pretest	Posttes	N-Gain Score	Criteria
X2 Control	35.36	57.50	0.33	Low
X5 Experiment	37.50	86.83	0.78	High

The experimental class used a PBL learning model with a STEAM approach; in accordance with the model's sequence, the activity began with problem orientation guiding students toward the problem presented in the e-worksheet with the theme of waste in Palembang. The activity started with a problem presentation that required students to systematically identify and formulate the problem within the e-worksheet. This approach is designed to capture students' attention so that their critical thinking skills can be honed through the problem-identification process presented in the learning materials. At this stage, the STEAM aspect specifically the science component emerges through the presentation of problems in the digital learning materials. The science aspect arises from the presentation of factual information regarding waste in Palembang, consistent with the research by [11], which states that the science component in STEAM comprises elements that explain matters factually, conceptually, procedurally, and metacognitively.

During the problem orientation stage, the critical thinking indicator of interpretation emerges, where students interpret information from the problem context and understand the issue to be resolved. Interpretation involves understanding and making sense of information, whether in text, images, symbols, or observed events [12]. Interpretation is defined as the ability to understand and make sense of diverse experiences, situations, and data. This ability encompasses a deep understanding of events, decisions, conventions, and belief systems, as well as an accurate grasp of specific rules, procedures, and criteria [13]. In this context, students are asked to interpret and investigate the waste problem in Palembang (in the electronic worksheet).

During this interpretation phase, students must be able to categorize information, interpret, and express the meaning of the problem at hand [14]. Classroom observations indicated that most students were able to identify the causes and impacts of waste problems and formulate appropriate problem statements and discussion questions. This finding suggests that contextual problems in students' daily environments effectively supported the development of interpretation skills. Consistent with [15], interpretation skills help students understand and define problems. Using real-life contexts enhances conceptual understanding [16], enabling students to analyze phenomena, explain their reasoning, and formulate problems effectively [17].

Second, organizing students for learning. At this stage, students were organized into six groups of 6–7 members and assigned to prepare the materials required for eco-enzyme production, including molasses, fruit or vegetable scraps, water, essential oils, plastic containers, scales, spoons, and label paper. This activity reflects the PBL syntax of organizing learning tasks related to the problem [18].

The stage also integrated the science, engineering, and mathematics components of STEAM. Students designed the eco-enzyme production process by determining the appropriate ratios of molasses, water, and organic waste, selecting suitable fermentation containers, ensuring proper sealing to allow gas release, and planning safe and effective production procedures. These activities required students to apply scientific concepts and engineering design while using mathematical reasoning to determine ingredient proportions.

Classroom observations indicated that students actively discussed alternative production methods, compared material compositions, and justified their design decisions. These activities promoted the analysis indicator of critical thinking, as students identified the causes of organic waste problems in Palembang, examined relationships among variables, and evaluated the relevance of evidence before deciding on the most appropriate production procedure. This finding is consistent with the definition of analysis as the ability to identify relationships, decompose problems into components, and assess evidence critically [12].

The findings are consistent with previous studies showing that PBL enhances scientific literacy by improving students' ability to formulate scientific questions and draw evidence-based conclusions [19]. Furthermore, integrating PBL with STEAM has been shown to strengthen collaboration, problem-solving, creativity, and critical thinking by connecting scientific concepts with engineering and mathematical reasoning [20], [21]. These empirical classroom observations support the improvement in students' analytical thinking skills throughout the learning process.

Third, guiding the investigation. At this stage, students investigated the utilization of organic waste into eco-enzymes by collecting information from various sources and conducting experiments to determine appropriate production procedures. Guided by the teacher, each group analyzed the collected information and used the experimental results to formulate solutions to the environmental problem, consistent with the PBL syntax of guiding students through investigation and inquiry [18].

The investigation integrated all STEAM components. The science component enabled students to understand the fermentation process of organic waste through direct observation, while the technology component supported information retrieval using smartphones and internet-based learning materials, as well as digital and laboratory tools such as scales and measuring equipment. In the engineering component, students designed fermentation containers and planned production procedures to ensure the safe, effective production of eco-enzyme. The art component encouraged students to improve product quality by incorporating natural aromatherapy ingredients, such as pandan leaves, citrus peel, and cinnamon, making the final product more attractive. Meanwhile, the mathematics component required students to calculate the correct ratio of molasses, water, and organic waste to achieve optimal fermentation.

Classroom observations showed that students actively compared information from different sources, discussed alternative procedures, interpreted experimental findings, and justified their decisions based on evidence. These activities strengthened the inference indicator of critical thinking, as students formulated logical conclusions from the data collected during the investigation. According to [12], inference refers to the ability to draw reasonable conclusions based on evidence and analytical reasoning. The improvement observed in this stage indicates that integrating STEAM into PBL provides students with meaningful opportunities to investigate authentic problems and construct evidence-based solutions.

These findings are consistent with previous studies reporting that PBL enhances scientific literacy by engaging students in authentic investigations and evidence-based reasoning [22], while STEAM integration promotes problem-solving, creativity, and higher-order thinking through interdisciplinary learning experiences [20], [23], [24]. Compared with the conventional class, where learning focused primarily on conceptual explanation, students in the experimental class demonstrated greater involvement in designing investigations, interpreting evidence, and drawing scientifically justified conclusions.

Fourth, developing and presenting the final project. At this stage, each group presented the results of their investigation by explaining the eco-enzyme production procedure and displaying a poster designed to educate the community about the importance of managing organic waste through eco-enzyme production. Students actively communicated their ideas, justified the procedures they had developed, and responded to questions from their peers during class discussions.

This stage integrated the technology, engineering, and art components of STEAM. Students used digital resources to support the preparation of presentation materials, applied engineering principles when explaining the production process, and demonstrated creativity through poster design and product presentation. Classroom observations indicated that students were able to organize information clearly, explain the rationale behind their production procedures, and communicate their findings confidently.

These activities strengthened the explanation indicator of critical thinking, which refers to the ability to communicate reasoning, justify decisions, and describe procedures systematically [12]. The improvement observed during presentations suggests that integrating STEAM into the PBL model provided students with meaningful opportunities to construct and communicate evidence-based solutions. This finding supports previous studies reporting that STEAM-integrated PBL enhances scientific literacy, creativity, and students' ability to communicate scientific ideas effectively [20], [21].

Fifth, analyzing and evaluating the problem-solving process. At the end of the learning activities, students completed a self-reflection through an electronic worksheet to evaluate the problem-solving strategies they had applied during the eco-enzyme project. Guided by the teacher, students reviewed the results of their investigation, identified strengths and weaknesses in their work, and proposed improvements for future learning, in accordance with the final PBL stage of analyzing and evaluating the problem-solving process [18].

Classroom observations and students' reflection responses showed that most students were able to identify the main environmental problem, evaluate the effectiveness of eco-enzyme production as a waste management solution, and recognize aspects of their investigation that required improvement. Students also reported that the contextual presentation of problems in the electronic worksheet increased their engagement and helped them understand biotechnology concepts more effectively.

These activities strengthened the evaluation and self-regulation indicators of critical thinking. Students evaluated the appropriateness of their proposed solutions using logical reasoning and evidence, reflecting the evaluation skill defined as the ability to assess arguments and make justified decisions [12]. Through self-reflection, students also monitored their own learning, recognized misconceptions, and identified strategies for improvement, demonstrating the self-regulation component of critical thinking [12]. The collaborative discussions and reflective activities encouraged students to become more independent and critical learners. These findings support previous studies showing that STEAM-integrated learning enhances students' ability to evaluate evidence, reflect on their learning process, and develop innovative solutions to real-world problems [25], [26], [27].

The implementation of the PBL model during classroom learning reached 100%, indicating that all planned learning stages were successfully carried out. This high level of implementation was reflected in students' active participation throughout the learning process, including identifying problems, conducting investigations, presenting findings, and reflecting on their learning. These activities contributed to the improvement of students' critical thinking skills observed during the intervention.

The findings support previous studies showing that PBL facilitates critical thinking by engaging students in authentic problem-solving and evidence-based inquiry [28]. Furthermore, integrating STEAM into PBL provides richer learning experiences than conventional instruction by encouraging students to apply interdisciplinary knowledge to real-world environmental issues [29]. Although the learning materials were implemented effectively, classroom observations indicated that several activities required considerable time, particularly during investigations and presentations. Therefore, more efficient time management and organization of learning activities are recommended to maintain learning quality while ensuring that all planned activities can be completed effectively.

Conclusion

The application of PBL-based e-worksheet with a STEAM approach in the classroom can improve students' critical thinking skills. The use of a PBL-based e-worksheet with a STEAM approach is more effective than conventional learning, as evidenced by N-gain effectiveness scores of 0.33 (low criteria) for the control class and 0.78 (high criteria) for the experimental class. However, this study is limited to a single school context and focuses only on critical thinking skills, without examining other competencies such as collaboration and creativity. Therefore, future research is recommended to expand the scope of implementation, include additional learning variables, and provide more detailed guidance for classroom application to strengthen the role of STEAM-based digital learning innovation in biology education.

Author's Contribution

R.M. Bonet: as the first researcher, she was responsible for the article. A.S.W. Sumah & W. Saputri: as supervisors, assisted in the creation of this article.

Acknowledgements

The author would like to thank State Senior High School 11 Palembang for providing a place for data collection in this research.

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