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Development of a STEM-based worksheet on biotechnology to enhance creative thinking of biology students

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ABSTRACT

This study aims to develop STEM-based student worksheet on environmental biotechnology material and analyze their validity, practicality, and effectiveness in improving students' creative thinking skills. This study uses the 4D model development method, which includes the define, design, develop, and disseminate stages, with 40 students from the Biology Study Program at Surabaya State University class of 2025 as the research subjects. The research instruments included expert validation sheets, student response questionnaires, activity observation sheets, and pretest and post-test tests of creative thinking skills. The data were analyzed using validity and practicality percentages and N-Gain scores to measure effectiveness. The results showed that the STEM-based student worksheet were highly valid with a validity percentage above 85% and highly practical based on student responses. The readability level was appropriate for students. The effectiveness of the student worksheet was demonstrated by an increase in the average creative thinking ability score from 68.75 on the pretest to 95.00 on the post-test with N-Gain values in the high to very high category. These findings indicate that the integration of the STEM approach through experimental activities and the use of technology is effective in training student creativity. This study recommends the use of STEM-based student worksheet as innovative teaching materials to support biotechnology learning in higher education.

INTRODUCTION

Global developments marked by rapid technological advances and the complexity of 21st-century issues require students to possess a set of essential skills known as the 4Cs, namely critical thinking, communication, collaboration, and creativity. These skills are considered core competencies in 21st-century learning because they play an important role in preparing students to face the challenges of the modern world and future professional demands (Thornhill miller et al., 2025). In line with this, creative thinking is an essential skill for students in the 21st century to face complex global challenges that demand innovative solutions in higher education (Karunarathne & Calma, 2024). Creativity supports effective problem solving in both academic and industrial contexts, which are increasingly dependent on technology-based innovation (Nazzal & Kaufman, 2020). Previous research also emphasizes that creativity development is one of the main indicators of successful science learning in higher education, particularly in responding to the demands of innovation and rapid technological developments (Corr & Mour, 2025).

According to official OECD data, the average creative thinking score of Indonesian students in PISA 2022 was only 19 points out of 60, far below the OECD average of 33 points, and only 31% of students achieved a basic level of creative thinking skills. This shows the low level of creative thinking skills among Indonesian students and is an important concern in strengthening pedagogy that encourages original ideas and problem-solving (OECD, 2024).

A study by Retno et al. (2025), found that students' creative thinking skills in Indonesia remain relatively low, particularly in terms of originality, as most students tend to produce general ideas rather than innovative solutions. This condition becomes even more concerning when viewed in light of the PISA 2022 framework, which emphasizes the ability to generate creative ideas (GCI) as a key component of creative thinking. As shown by Kraus et al. (2026), this aspect accounts for the largest proportion of assessment items, indicating its central role in evaluating students' creativity. Therefore, students' limited ability to generate original ideas reflects not only a general weakness but also a gap in one of the most essential dimensions of creative thinking. The predominance of procedural learning in Indonesian schools is a major obstacle to mastering the indicators of originality and flexibility in creative thinking (Putri et al., 2024).

Pratama et al. (2025), demonstrate that although research on creative thinking in Indonesia is increasing, strengthening pedagogical approaches through Project-Based Learning (PjBL) and STEM integration is key to addressing the low levels of creative thinking skills that continue to pose a challenge in Indonesian schools. This is further supported by Winaryati et al. (2025), who found that STEM-integrated PjBL can foster creativity and other 21st-century skills through meaningful learning activities across different learning stages. However, their findings also suggest that the development of these skills remains uneven, underscoring the importance of more consistent, well-designed implementation in classroom practice.

Creativity plays an important role in creating new solutions that can drive research and technological advances, particularly in technology development and environmental problem-solving (Animasaun et al., 2023). Biology learning that relies on traditional teaching methods tends to lead students to focus on memorizing scientific concepts, such as in biotechnology, rather than applying them in challenging real-life situations (Aguiar & Calabrese, 2025). This condition shows that current biotechnology learning practices are not yet fully capable of meeting the needs of developing students' creative thinking skills (Ramadhani & Hardianti, 2025).

The importance of using innovative technology-based educational tools to improve 21st-century skills among students (Minatani et al., 2025). Conventional student worksheets tend to be linear and limited to presenting tasks and step-by-step guidelines that focus more on understanding basic theory without providing sufficient space for exploring original ideas or solving complex problems (Nadhiroh & Latifah, 2020). Traditional student worksheets often fail to provide opportunities for students to develop higher-order thinking skills, such as creativity, analysis, and evaluation, which are essential in 21st-century education (Kahar et al., 2021). Although conventional student worksheets serve to organize learning tasks, their limitations in stimulating student creativity are a major concern in curriculum development in higher education (Widodo et al., 2025).

The STEM approach integrates science, technology, engineering, and mathematics into a learning process designed to help students connect theoretical concepts with their application in real-world contexts through problem-solving and experiment-based activities (Kwon & Lee, 2025). This integration encourages students to view knowledge not as separate disciplines, but as interconnected fields that can be applied collaboratively to address complex, real-life problems. In the current development of higher education, the STEM approach is increasingly recognized as an effective pedagogical framework for developing 21st-century skills, particularly creativity and problem-solving abilities, through contextual and experience-based learning that emphasizes active student involvement, inquiry, critical thinking, collaboration, and meaningful engagement in authentic learning experiences (Nur & Mahmud, 2024). In line with this paradigm, the application of STEM-based student worksheets is an important strategy because it bridges theory and practice through experiments that are relevant to the real world, while encouraging students to integrate interdisciplinary knowledge in solving biotechnology problems (Wahdaniyah & Agustini, 2023). STEM-based learning not only focuses on mastering concepts but also provides students with opportunities to engage in direct exploration, address practical challenges, and design technology-based solutions creatively and innovatively (Fior et al., 2025). This is supported by research by Anwar et al. (2022), which shows that students who use a STEM-based curriculum achieve significant improvements in science learning outcomes compared to those in conventional learning.

This study proposes a novel approach to developing a STEM-based student worksheet that integrates Arduino Uno and pH-4502C sensors for biotechnology learning. This student worksheet is designed to enhance students' creative thinking skills by providing opportunities to tackle practical challenges and develop technology-based solutions. Through this STEM-based student worksheet, students not only understand biotechnology concepts but also apply them in practical experiments relevant to real-world problems (Astawan et al., 2023). This technology-based approach is expected to stimulate students to think creatively in designing experiments, solving challenges, and exploring various alternative solutions (Kwon & Lee, 2025). This study aims to develop a STEM-based student worksheet and analyze its validity, practicality, and effectiveness in improving the creative thinking skills of Biology students in biotechnology learning.

METHODS

Research Design

This study employed a research and development (R&D) design using the 4D development model, which consists of four stages: define, design, develop, and disseminate. The 4D model was selected because it provides a systematic and structured framework for developing, validating, and evaluating instructional materials to ensure their feasibility, practicality, and effectiveness in learning contexts (Huda et al., 2020). Through these stages, the development process can be carried out in a more organized manner, from identifying learning needs to producing a final product ready for implementation. The product developed in this study was a STEM-based student worksheet designed to enhance students' creative thinking skills in biotechnology learning. To examine the effectiveness of the developed worksheet, this study used a pretest–posttest design to measure changes in students' creative thinking abilities before and after its implementation in the learning process.

Population and Samples

Table 1.
Demographic Data Regarding the Population and Sample

No.	Variable	Category	Frequency	Percentage
1.	Gender	Men	7.00	17.5%
		Women	33.00	82.5%
	Number		**40.00**	**100%**
2.	Age	18 Years Old	24.00	60%
		19 Years Old	14.00	35%
		20 Years Old	2.00	5%
	Number		**40.00**	**100%**

The study population is students in the active Biology D Study Program at Surabaya State University (UNESA), class of 2025. The sample used in the study consists of 40 students with a background in heterogeneous education and diverse academic abilities. A purposive sample was selected to obtain representative data on the effective use of STEM-based student worksheets (Alfiza et al., 2024). Of the 40 samples used in the study, the majority were female (82.5%), while 17.5% were male. In terms of age, the majority of the sample was 18 years old (60%), followed by 19 years old (35%), and only 5% were 20 years old. The demographic characteristics of the population can be presented in Table 1.

Instrument

Several instruments were used to evaluate the validity, practicality, and effectiveness of the developed STEM-based student worksheet. The validity instrument used in this study employed a four-point Likert scale adapted from Riduwan & Sunarto (2019), as shown in Table 2. This scale was designed to assess the validity of the developed STEM-based student worksheet using expert judgments. A score of 1 indicates that the assessed component is considered invalid, while a score of 4 represents a very valid category. The use of a four-point Likert scale allows validators to provide clear and decisive assessments without a neutral option, thereby strengthening the interpretation of the validation results.

Table 2.
Likert Scale Criteria

Score	Information
1	Invalid
2	Less Valid
3	Valid
4	Very Valid

(Source: Riduwan & Sunarto, 2019)

Validation data were analyzed using a percentage-based approach to determine the validity of the developed STEM-based student worksheet. In this process, Table 2 served as the scoring guide for each assessment item, with validators rating it on a four-point Likert scale. The validity score was calculated by dividing the total score obtained from the validators by the maximum possible score and then multiplying the result by 100. Furthermore, Table 3 was used to interpret the final percentage score into validity categories adapted from Riduwan & Sunarto (2019). Table 2 functions at the item-assessment stage, whereas Table 3 functions at the overall validity interpretation stage. These criteria were used to determine the worksheet validity category, as presented in Table 3.

Table 3.
Criteria for Interpreting the Validity of Student Worksheet

Score (%)	Information
25–39.9	Invalid
40–54.9	Less Valid
55–69.9	Quite Valid
70–84.9	Valid
85–100	Very Valid

(Source: Riduwan & Sunarto, 2019)

The student response sheet and the activity observation sheet in this study employed the Guttman scale adapted from Sugiyono (2015). This scale was used to obtain clear and firm responses regarding the practicality and implementation of the STEM-based student worksheet during the learning process. Each item was answered with either "Yes" or "No," where a score of 1 indicated agreement or appropriate implementation, and a score of 0 indicated disagreement or non-implementation. The use of the Guttman scale allows for straightforward interpretation of student responses and observed activities, ensuring objectivity in assessing the practicality of the developed worksheet.

Table 4.
Practicality Criteria for Student Worksheet

Score (%)	Information
0–48	Very Impractical
49–61	Not Practical
62–74	Quite Practical
75–87	Practical
88–100	Very Practical

(Source: Riduwan & Sunarto, 2019)

The practicality of the STEM-based student worksheet was analyzed using two indicators, namely user responses and readability level. The practicality results obtained from student response questionnaires and activity observations were interpreted using the practicality criteria adapted from Riduwan & Sunarto (2019), as presented in Table 4. This interpretation was used to classify the worksheet into categories ranging from very impractical to very practical.

In addition, the worksheet's practicality was evaluated based on its readability using the Fry Readability Graph. A readability analysis was conducted to ensure the language and sentence structure of the worksheet were appropriate for undergraduate biology students. The readability level was determined by calculating the number of remaining sentences based on the total number of words, as part of the Fry graph analysis procedure. The number of remaining sentences was determined by comparing the number of words in the 100-word sample with the number of words in the last sentence, as part of the Fry graph analysis procedure.

Student learning outcome data were used to determine the effectiveness of the STEM-based student worksheet by analyzing students' pretest and posttest scores. The effectiveness was measured using the normalized gain (N-Gain) score, adapted from Leedy & Ormrod (2015), which reflects the magnitude of improvement in students' creative thinking skills after the implementation of the developed worksheet. The N-Gain score was calculated by comparing the difference between the posttest and pretest scores with the difference between the maximum possible score and the pretest score.

The resulting N-Gain values were then interpreted using the criteria presented in Table 6 to classify the level of improvement in students' creative thinking skills, ranging from very low to very high. This interpretation provided a clear basis for assessing the effectiveness of the STEM-based student worksheet in enhancing students' creative thinking.

Table 5.
N-Gain Criteria

Score N-Gain	Information
0.81–1.00	Very High
0.61–0.80	High
0.41–0.60	Fairly High
0.21–0.40	Not High
0.00–0.20	Very Low

(Source: Mendoza & Sotomayor, 2023)

The instruments used in this study comprised several measurement tools designed to evaluate the validity, practicality, and effectiveness of the STEM-based student worksheet. The validity of the worksheet was assessed using a Likert scale to evaluate the appropriateness of the content, the clarity of the language, and its alignment with the biotechnology learning objectives. The scoring was based on expert judgments from material, media, and language validators, enabling the worksheet to be comprehensively evaluated for quality and suitability for learning.

The practicality of the worksheet was measured through students' responses using the Guttman scale, intended to identify the level of student acceptance and the worksheet's usability during the learning process. In addition, an observation sheet was used to record students' activities during classroom instruction and to assess the extent to which each activity on the worksheet was carried out as intended.

The effectiveness of the worksheet in improving students' creative thinking skills was determined using a pretest–posttest design. The tests were administered before and after the implementation of the worksheet to measure changes in students' creative thinking performance. The resulting scores were then analyzed using the N-Gain formula to determine the extent of improvement after students participated in STEM-based learning (Gustati et al., 2025).

Procedure

The research procedure followed the 4D development model, which consists of four main stages: define, design, develop, and disseminate. These stages are systematically interconnected to form a structured development cycle, enabling the product to be developed through a clear, sequential process. Each stage has a specific function, beginning with identifying needs and continuing through planning, development, and final dissemination of the product. The overall process provides a systematic framework to ensure that the developed product is relevant, feasible, and ready for implementation, as illustrated in Figure 1 (Ansori et al., 2024).

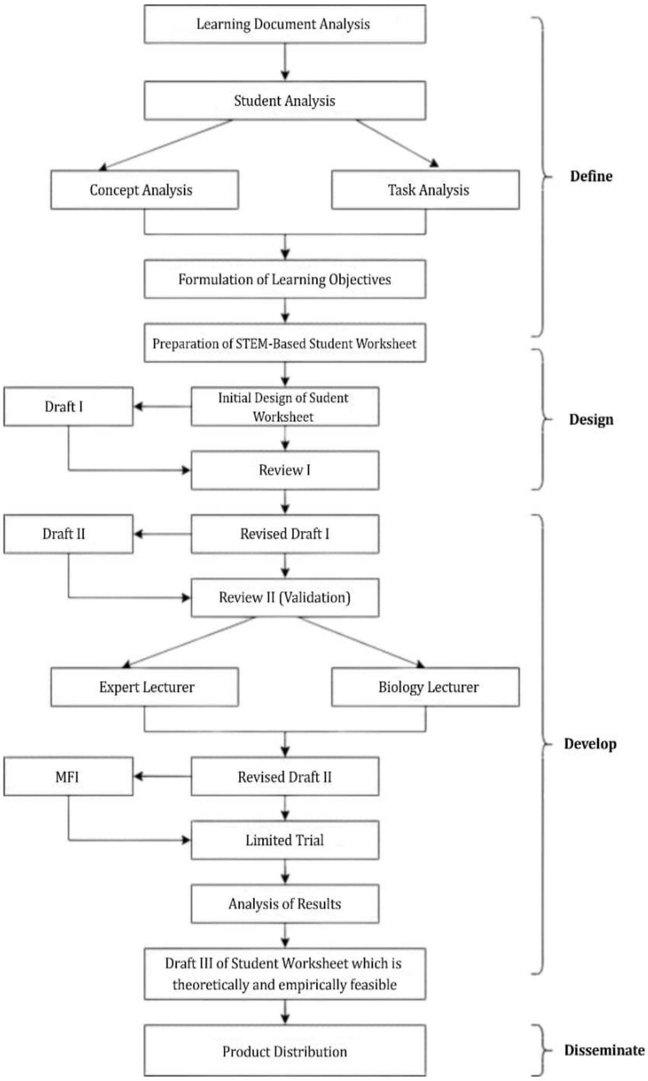


Figure 1. Procedure Study, Adapted: Ansori et al. (2024)

Stage First: Define is complete, with an in-depth analysis of several components that serve as the basis for the Worksheet development for Students. Analysis covering studies to document learning, such as Achievements Course Learning and Plans Semester Learning, to ensure the student worksheet aligns with objectives and expected competencies. In addition, an analysis was carried out of students' characteristics, learning assignments, and the concepts of biotechnology to be taught, using this knowledge to meet students' needs at an appropriate level of understanding.

Design stage: compile the beginning of a STEM-based student worksheet that integrates components important to STEM, such as Science, Technology, Engineering, and Mathematics. Design this to cover the part introduction, core activities, and sheet reflection. For motivating students to think creatively. Activities designed for learning covering experiments, practical work, pH measurement of leachate, and eco-enzymes using a pH-4502C sensor based on an Arduino Uno, aiming to increase students' skills and practicality while delving into biotechnology concepts directly.

Stage, student worksheet products that have been designed will go through the development process further, including validation by experts, material, media experts, and experts in language. Validation aims to ensure that the student worksheet has high-quality content, presentation, and language. In addition, the trial was conducted with a small group of students to gather feedback on the clarity of instructions, the level of difficulty, and the Power Pull student worksheet in support of the activity study. The results of the trial will be used to improve and refine the product.

The stage, student worksheet that has been perfected, will be disseminated to 40 students. To get the bait, come back with your thoughts on the usefulness, understandability, and effectiveness of the student worksheet in increasing the ability to think creatively. Trial data was then analyzed to evaluate the impact of the student worksheet on improving skills and creative thinking in students, who are the main objective of the study. This is expected to make a positive contribution to STEM-based development learning in tall environmental education.

Data Analysis Techniques

Data analysis in this study is conducted through several steps to assess the validity, practicality, and effectiveness of the STEM-based worksheet for students. Measuring the validity of the student worksheet used a Likert scale to evaluate the content, presentation, language, and suitability for objective learning. This Likert scale is used to assess the validity of the student worksheet based on expert evaluations of materials, media, and language. Percentage validity is calculated using the appropriate formula and then categorized according to the known level of student worksheet feasibility. Validation results. This provides a description of the extent to which the student worksheet is feasible for learning biotechnology (Tanujaya et al., 2022).

Assess the practicality of student worksheet use by measuring students' responses with the Guttman scale. This scale is used to evaluate students' reception of the student worksheet, as well as whether the worksheet is easy to understand and used during the learning activity (Septiani et al., 2025). In addition, the readability of the analysis is assessed using Fry's chart for known-level student worksheet difficulties based on the number of sentences and the number of existing syllables in the student worksheet (Inggriyani et al., 2022).

The effectiveness of the student worksheet was measured using a pretest and posttest administered before and after its use. The pretest and posttest were designed to measure improvements in students' creative thinking skills after participating in STEM-based learning activities using a student worksheet. The pretest and posttest data were analyzed using the N-Gain formula, which allows researchers to measure the extent of improvement in students' creative thinking skills after learning. The N-Gain results were then categorized to evaluate the effectiveness of the learning received by students (Gustati et al., 2025).

All data collected through instruments will be analyzed quantitatively to yield results that can serve as a basis for revising and improving the student worksheet, as well as to ensure that the student worksheet developed increases the ability to think creatively effectively.

RESULTS AND DISCUSSION

This study produced a STEM-based student worksheet on biotechnology material designed to improve students' creative thinking skills. The student worksheet was implemented in two meetings. The first meeting consisted of a pretest and learning activities in which students completed discussion questions, identified variables, and formulated problems and hypotheses. The second meeting focused on practicum activities, during which students measured the pH of leachate and eco-enzyme samples, collected experimental data, constructed graphs, analyzed the results, completed data analysis questions, filled in innovation tables, drew conclusions, and carried out reflection activities.

Efforts to improve creative thinking skills can be supported through the application of various strategies, media, and learning models, because varied learning approaches have been shown to enrich students' creative thinking skills in the context of modern education compared to conventional learning (Li & Yu, 2025). In this study, the STEM-based student worksheet was developed in a structured manner, integrating several learning components. The worksheet begins with a discussion activity in which students read and analyze a case related to organic waste problems, observe initial data on leachate and eco-enzymes, answer the provided guiding questions, and relate their findings to environmental conditions and the application of environmental biotechnology in daily life.

Furthermore, the worksheet includes practicum activities that engage students in assembling and using an Arduino Uno-based pH measuring device integrated with a pH-4502C sensor. Through this activity, students are introduced to the required tools and materials, guided to assemble the device, and directed to measure the pH of leachate and eco-enzyme samples. To support the implementation of this practicum, a tutorial video on assembling the Arduino Uno-based pH-measuring device can be accessed at the following link: https://youtu.be/_7WRazDhcS4**.** The obtained data are then recorded, processed, and analyzed as part of biotechnology learning.

This activity reflects the integrated application of STEM components. The science aspect is represented through the analysis of organic waste issues and environmental biotechnology concepts. The technology aspect is reflected in the use of Arduino Uno and the pH-4502C sensor as measurement tools. The engineering aspect appears in the process of assembling and operating the device, while the mathematics aspect is demonstrated through the processing and interpretation of numerical data in the form of tables, comparisons, and graphs.

In addition, the worksheet provides a data-processing section that directs students to identify variables, formulate research problems, develop hypotheses, and complete observation tables based on practicum findings. This is followed by a data-analysis section in which students construct graphs from the results, identify differences in acidity levels, explain the possible causes of these differences, and evaluate the suitability of the results for application as liquid organic fertilizer. These activities were designed to train students to organize findings systematically and interpret evidence scientifically.

Another important component of the developed worksheet is the innovation design section, which provides space for students to formulate solution ideas based on the pH measurement results of leachate and eco-enzyme using the Arduino Uno-based sensor system. In this section, students are encouraged to connect real environmental problems to the data they obtained and to propose innovative applications of biotechnology in environmental contexts. The worksheet concludes with a summarizing and reflecting section, in which students write conclusions from the discussion and practicum activities, describe their understanding and learning experiences, identify difficulties encountered, and explain the benefits of using a technology-assisted worksheet in biotechnology learning.

The distinctive feature of this product lies in the integration of STEM-based learning with Arduino Uno and a pH-4502C sensor in environmental biotechnology practicum activities. This integration not only supports students' conceptual understanding but also provides opportunities for hands-on investigation, data-based analysis, and the development of innovative ideas. Therefore, the developed worksheet does not merely function as a conventional learning aid but also serves as an innovative instructional product that emphasizes contextual problem-solving and the development of creative thinking skills in higher education. The complete worksheet can be accessed through the following link: https://bit.ly/4ts1O5U.

The features of this student worksheet align with indicators of creative thinking in STEM-based learning. The main indicators of creative thinking are fluency, flexibility, originality, and elaboration, which measure the ability to generate many ideas, various types of ideas, unique ideas, and develop ideas in detail (Ameeque, 2026). Student activities in the student worksheet are detailed in Table 6.

Table 6.
Activity Students at STEM-Based Student Worksheet on Biotechnology

Indicator	Aspect STEM	Activity Student
Fluency	Science & Mathematics	Create ≥3 questions critical based on phenomenon; identify as much as Possible factor reason increasing amount rubbish organic; propose utilization ideas waste become product biotechnology (eco enzyme) or (fertilizer organic liquid); make chart pH comparison and explain pattern base chart as step beginning interpretation.
Flexibility	Science, Mathematics & Technology	Determine variables free, bound, and controlled; compose formulation problem in form question research; make hypothesis H0 and Ha based on possibility pH changes; explain pH difference of various possibility causes (fermentation, activity microorganisms, types of material organic, process time, temperature); identify obstacle during activities and compiling a number of alternative solutions that can applied.
Originality	Technology & Engineering	Designing innovation new sensor- based (pH/Arduino) for monitoring waste organic; determine problem real in the environment. Then connect it with pH data; select component technology (pH sensor, Arduino) is appropriate design myself; describe mechanism work tool in a way original according to personal ideas; determine benefits and location implementation innovation with approach creative.

Indicator	Aspect STEM	Activity Student
Elaboration	Science, Engineering & Technology	Assembling pH–4502C sensor circuit with details (connecting 5V–GND–A0 cable on Arduino); perform the calibration process until voltage reach mark stable; doing pH measurements at the 3rd, 6th and 9th minutes as well take notes all data in detailed; explain results pH difference and assess suitability with standard eligibility fertilizer organic liquid; writing reflection learning in the form of matter new things that are obtained, difficulties that are experienced, and steps details for overcome it.

The quality of a student worksheet is determined by the criteria for effective teaching materials, relevant to current learning needs. Teaching materials designed and compiled in a comprehensive, planned manner can increase students' interest and motivation to learn, thereby enhancing the effectiveness of the teaching and learning process (Choppin et al., 2020). In educational literature, a quality student worksheet must be independent and directly accessible to students without relying on other sources, cover all necessary material, and be systematically designed in accordance with specific learning objectives. In addition, effective modules must be adaptable to developments in science and technology and easy for students to use as flexible teaching materials responsive to their learning needs (Hattie & Abad, 2025). Based on these principles, the validity of this student worksheet was tested through several main aspects, namely presentation feasibility, content feasibility, linguistic feasibility, and suitability with STEM to ensure that the developed student worksheets are not only complete and informative but also easy to understand and relevant to the STEM context used in biotechnology learning. The following bar chart shows the validity results of the STEM-based student worksheet developed to improve students' creative thinking skills. The following is Figure 3, which shows the validity results of the student worksheet shown in the chart.

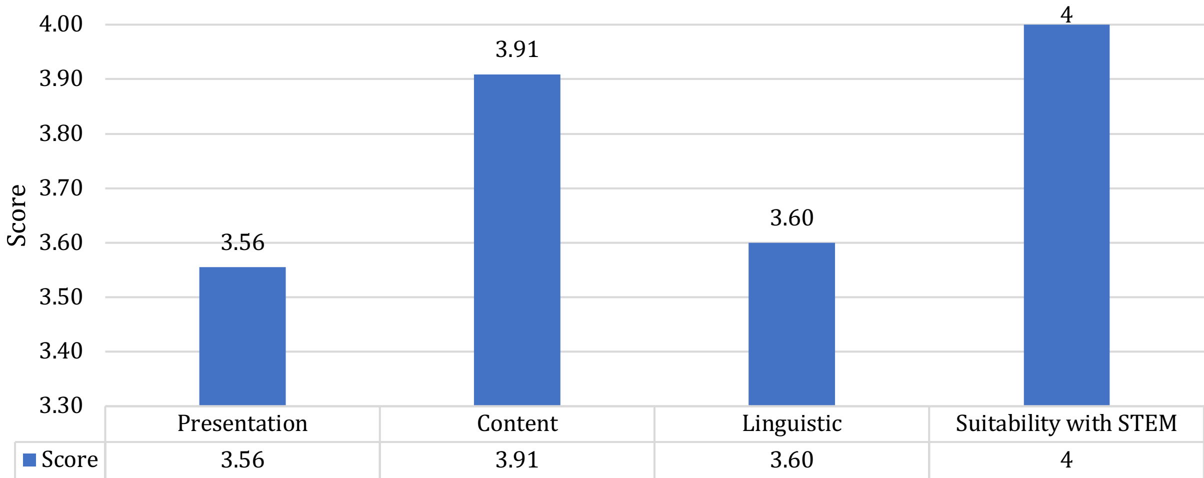


Figure 2. Bar Chart Validity of STEM-Based Student Worksheet on Biotechnology

Based on Figure 2, the bar chart, the presentation aspect received the lowest score among the other aspects, namely 3.56. This shows that although the student worksheet presentation is quite good, the material needs improvement to be more engaging and easier for students to understand. According to the multimedia learning theory proposed by Mayer (2021), presenting material in a combination of text, images, and videos can improve students' understanding and capture their attention, so improvements in presentation can contribute to a more effective learning experience. The content aspect scored 3.91, indicating that the material presented in the student worksheet was very much in line with the learning objectives and expected competency standards. This shows that the material is not only complete but also relevant to the principles of STEM (Science, Technology, Engineering, and Mathematics). The integration of biotechnology concepts with relevant technology makes this student worksheet effective in equipping students with the skills needed to understand the material in depth. This aligns with constructivist theory, which holds that knowledge is built through experience and active understanding (Tohari & Rahman, 2024). The linguistic aspect scored 3.60, indicating that the language used is clear and easy for students to understand. However, there is still room to simplify the language so the instructions are easier to follow. Cognitive load theory reminds us that the use of overly complex language can burden students' cognition, so improving the readability and simplicity of the language in this Student Worksheet is very important so that students can focus on the core material without being distracted by difficulties in understanding the text (Mutlu-bayraktar et al., 2019).

The suitability aspect of STEM received a score of 4.0, indicating that this Student Worksheet is highly relevant to STEM concepts. This aligns with research by Ates & Aktamis (2024), which emphasizes that STEM-based learning can improve critical and creative thinking skills and provide a more integrated experience in science, technology, engineering, and mathematics. Thus, this STEM-based student worksheet not only supports the development of students' technical skills but also enhances their creative thinking abilities through the application of relevant technology and practical experiments.

The difference in scores across validity aspects indicates that the quality of the student worksheet is not homogeneous but shows strengths and areas for development. Lower scores on the presentation aspect indicate that although the material structure is appropriate, optimization of visual elements and presentation flow is still needed to support multimedia-based learning. This reinforces Mayer (2024), view that the effectiveness of learning is not only determined by the accuracy of the content, but also by how information is presented and processed by the working memory of learners.

Meanwhile, the high scores in the content and STEM suitability aspects indicate that the integration of biotechnology with Arduino and pH sensors has successfully represented authentic interdisciplinary learning. This confirms that the validity of the student worksheet lies not only in its suitability to the curriculum but also in its relevance to 21st-century competency requirements, particularly creative thinking and technology-based problem-solving.

The compatibility of students' thinking levels with readability is a very important aspect in developing teaching materials (Purnomo & Puspitawati, 2025). Readability tests were conducted on each sub-material of the student worksheet developed to ensure clarity and content suitability. The selected samples were intended to represent the entire material in the student worksheet. A summary of the readability analysis results of the student worksheet is presented in Table 7.

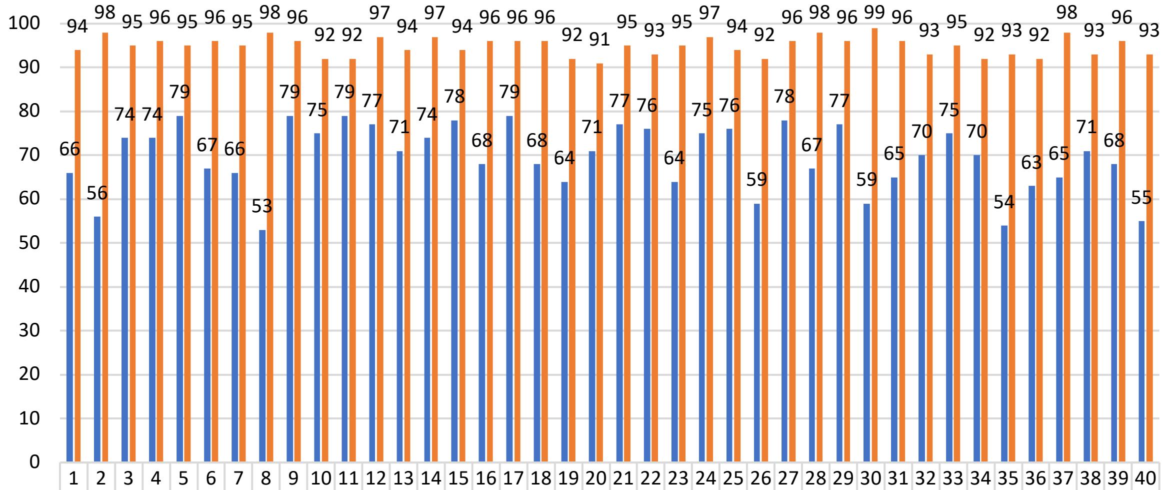
Table 7.
Recapitulation of STEM-Based Student Worksheet on Biotechnology Readability Results

Sample	Page	Number of Syllables x 0.6	Level
1	1	166.20	13
2	3	168.00	13
3	6	164.40	13

Based on the results in Table 7, the three samples analyzed were at a readability level appropriate for college-level readers. These findings indicate that the student worksheets developed are practical and effective in terms of readability. These results align with the research by Rets et al. (2022), which found that teaching materials in higher education should be designed with an appropriate level of linguistic complexity to support conceptual understanding and reduce students' cognitive load. In addition, appropriate readability contributes to the effectiveness of learning and student engagement in text-based activities in higher education.

Student response was the second indicator used to assess the practicality of the STEM-based student worksheet developed on biotechnology material. Based on a limited trial involving 40 students, the average overall response rate reached 96.01%. The study's results showed that the STEM-based student worksheet fell into the “very practical” category. These findings indicate that student worksheets are highly effective for developing students' creative thinking skills, especially in the context of biotechnology learning. Data from observing student activities during the learning process using STEM-based student worksheets indicate that these worksheets are appropriate and effective for learning. This is evidenced by students' active involvement and the achievement of learning objectives. This finding is consistent with the study by Guo et al. (2020), which emphasizes that the effectiveness and overall quality of teaching materials can be assessed through the learning outcomes achieved by students after participating in a series of structured learning activities. In this context, students’ performance serves as an important indicator of how well the instructional materials support the learning process and facilitate the achievement of the intended objectives. Therefore, improvements in student learning outcomes may reflect that the teaching materials are not only appropriately designed but also capable of providing balanced and meaningful learning experiences for students.

Figure 3 presents a comparison of students’ creative thinking test scores before (pretest) and after (posttest) the implementation of the STEM-based student worksheet on biotechnology material. The graph illustrates the change in each student’s creative thinking performance after using the developed worksheet during the learning process. Overall, it provides a visual representation of improvements in students’ creative thinking skills after participating in the STEM-based learning activities designed for this study.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Pre Test	66	56	74	74	79	67	66	53	79	75	79	77	71	74	78	68	79	68	64	71
Post Test	94	98	95	96	95	96	95	98	96	92	92	97	94	97	94	96	96	96	92	91

	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Pre Test	77	76	64	75	76	59	78	67	77	59	65	70	75	70	54	63	65	71	68	55
Post Test	95	93	95	97	94	92	96	98	96	99	96	93	95	92	93	92	98	93	96	93

Figure 3. Test Score Analysis: Ability Creative Thinking Student

Based on the results of the students' creative thinking ability test, the average pretest score before using the STEM-based student worksheet on environmental biotechnology material was 68.75, which is in the moderate category. After using the student worksheet, the average posttest score increased significantly to 95.00, placing it in the excellent category. These findings indicate that a STEM-based student worksheet on environmental biotechnology material is effective in training students' creative thinking skills.

This effectiveness can also be seen in the percentage of students who achieved on the creative thinking skills test. Before using the student worksheet, some students had not fully achieved the set achievement criteria because their creative thinking skills were still at a moderate level. However, after implementing the STEM-based student worksheet, all students achieved excellent learning outcomes, resulting in an achievement percentage of 100%. This shows that all students who participated in STEM-based learning using a worksheet successfully achieved the set standard for creative thinking. The implementation of STEM-based student worksheets effectively improved students' creative thinking skills. This aligns with the study by Zhang et al. (2026), which shows that integrated STEM learning significantly improves students' creative thinking skills. Figure 4 presents the results of the creative thinking skills test, which includes indicators of fluent, flexible, original, and detailed thinking.

The test results show a significant improvement after the implementation of the STEM-based student worksheet. Before using a STEM-based student worksheet, the average score for students' creative thinking skills was 0.71, which is considered high. After implementing the STEM-based student worksheet, the average score increased to 0.96, which is considered very high. In detail, fluent thinking skills increased from 0.65 to 0.93, flexible thinking skills increased from 0.74 to 1.00, original thinking skills increased from 0.79 to 1.00, and detailed thinking skills increased from 0.67 to 0.90. These findings indicate that STEM-based student worksheets not only improve students' raw scores but also enhance the quality of creative thinking in all measured indicators. The improvement in students' creative thinking abilities in this study aligns with findings from various studies showing that STEM-based learning can foster creativity through learning activities that integrate science, technology, engineering, and mathematics in meaningful, relevant contexts. A meta-analysis by Kwon & Lee (2025) found that implementing project-based STEM learning had a significant positive effect on students' creativity, with a substantial effect size, thereby reinforcing the relevance of using STEM-based student worksheets in higher education. Additionally, research by Sarıoğlan & Özkaya (2023) shows that integrated STEM learning significantly increases students' creativity and metacognitive awareness, which is consistent with the increase in pretest and posttest scores for students' creative thinking abilities in this study.

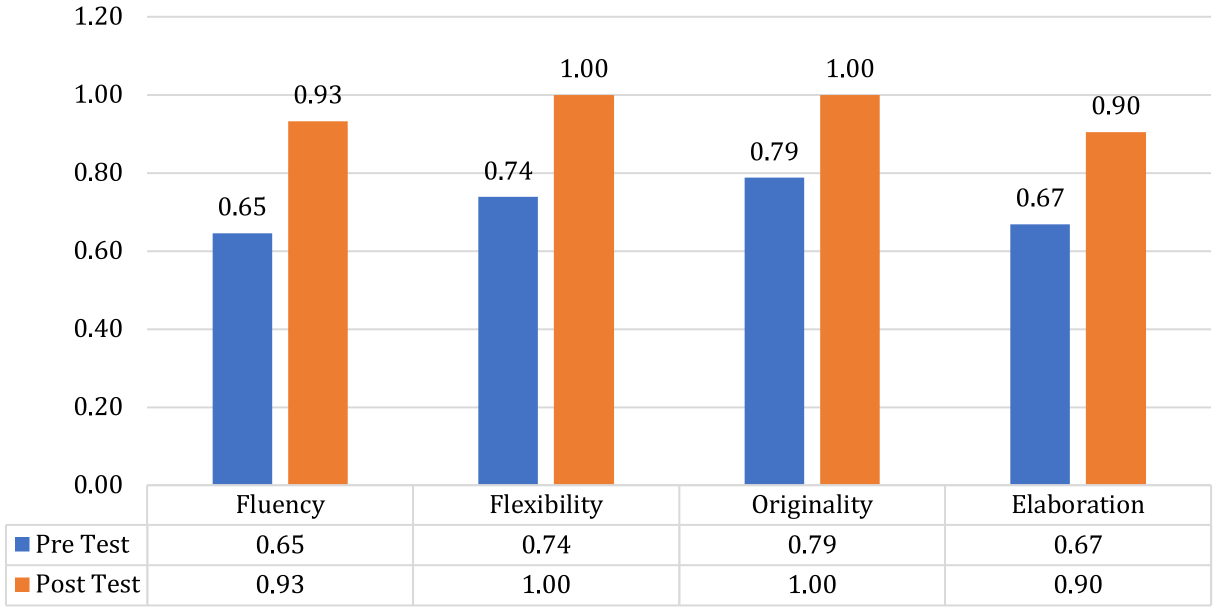


Figure 4. Capabilities Creative Thinking before and after using the STEM-Based Student Worksheet

These findings are also consistent with the research by Sonthong et al. (2023), which shows that STEM-based learning can stimulate creativity through stages of problem identification, information gathering, solution design, and reflection on results. Pedagogically, this indicates that STEM-based student worksheets serve not only as teaching materials to convey biotechnology concepts but also as a means to facilitate complex, innovative higher-order thinking processes needed in the 21st-century workplace.

Efforts to develop students' creative thinking skills also require the support of diverse learning strategies and media. Research shows that indicators of creative thinking, such as fluency, flexibility, and originality, interact significantly in predicting creativity-related activities and achievements, suggesting the need for a learning approach that can develop these various dimensions of thinking simultaneously (Runco & Abdulla, 2024). Additionally, Li & Yu (2025) found that implementing collaborative learning in higher education significantly improves students’ creative thinking and problem-solving skills by providing opportunities to exchange ideas and respond to diverse perspectives during the learning process. These findings reinforce that the practicality and quality of STEM-based student worksheet design correlate with increased learning interaction, motivation, and learning effectiveness. Thus, the developed student worksheets are not only technically feasible but also pedagogically effective in fostering students' creative thinking skills.

CONCLUSION

This study concludes that STEM-based student worksheets on biotechnology developed through the 4D model are of excellent quality and effective in improving students' creative thinking skills. The student worksheets are highly valid and practical, with an appropriate level of readability and positive student responses. The results of the effectiveness analysis show a significant increase in students' creative thinking skills after implementing a STEM-based student worksheet, reflected in higher scores from high to very high across all creative thinking indicators. The integration of the STEM approach through experimental activities, contextual problem solving, and the use of technology makes student worksheets not only teaching materials but also learning tools that support the development of students' creative thinking skills in higher education.

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