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Innovating STEM Education: The Role of a Digital Biotechnology Textbook in Fostering Critical Thinking and Problem-Solving in Industrial Agriculture-Based Schools

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ABSTRAK

Penelitian ini bertujuan untuk mengetahui pengaruh penerapan buku ajar berbasis STEM pada materi bioteknologi terhadap keterampilan berpikir kritis dan pemecahan masalah biologi bagi siswa SMA di Kawasan Pertanian Industrial. Kawasan tapal kuda yang meliputi Pasuruan, Probolinggo, Jember, dan sekitarnya didominasi dengan wilayah pertanian dan perkebunan yang menjadikan hal tersebut sebagai mata pencaharian utama masyarakat setempat. Kesenjangan ekonomi berdampak pada ketimpangan pendidikan sehingga menuntut siswa untuk memiliki keterampilan berpikir kritis dan pemecahan masalah yang baik. Buku ajar terintegrasi *Science, Technology, Engineering, and Mathematics* (STEM) dapat menjadi alternatif pembelajaran dalam meningkatkan kemampuan tersebut. Penelitian ini menggunakan metode quasi eksperimen yang melibatkan 74 siswa kelas XII MIPA SMAN 1 Dringu, Kabupaten Probolinggo. Data diperoleh melalui instrumen pretest dan postest yang divalidasi oleh ahli, selanjutnya dianalisis menggunakan uji T. Hasil penelitian menunjukkan bahwa kelas eksperimen mengalami peningkatan keterampilan berpikir kritis sebesar 17 dan peningkatan sebesar 12 pada tes keterampilan pemecahan masalah. Uji hipotesis menggunakan uji T menunjukkan signifikasi yaitu 0.008 dan 0.000. Dengan demikian dapat disimpulkan bahwa buku ajar berbasis STEM direkomendasikan menjadi alternatif pembelajaran bioteknologi khususnya terhadap keterampilan berpikir kritis dan keterampilan pemecahan masalah siswa SMA kelas XII di Kawasan pertanian industrial.

Keywords:
STEM
Digital Textbooks
Industrial Agriculture
Critical Thinking
Problem Solving

ABSTRACT

This study aims to analyze the effect of a STEM-based digital biotechnology textbook on the critical thinking and problem-solving skills of high school students in an industrial agriculture area. Using a quasi-experimental design with 74 students at SMAN 1 Dringu, Probolinggo, data were collected through validated pretests and posttests and analyzed using T-test. Results revealed significant improvements in both critical thinking (Sig. = 0.008) and problem-solving (Sig. = 0.000) skills in the experimental group. The findings suggest that STEM-based digital textbooks can serve as effective alternative learning

resources for enhancing higher-order thinking skills in biotechnology education.

INTRODUCTION

Indonesia is widely recognized as an agrarian country due to its abundant resources in the agricultural and plantation sectors. This recognition was reinforced when Indonesia received a Food Self-Sufficiency Award from the Food and Agriculture Organization (FAO) in 1985 (Febriyani et al., 2020). The plantation sector also provides significant commodity potential, particularly dominated by sugarcane plantations in the "Tapal Kuda" region of East Java Province, which includes Pasuruan, Probolinggo, Lumajang, Jember, Situbondo, Bondowoso, and Banyuwangi. As agriculture and plantation activities dominate, they serve as the primary livelihood for the majority of local communities. This condition directly influences per capita household expenditure, which in turn contributes to educational inequality in East Java. One of the influencing factors is the employment and academic background of the household head (Ferdiana et al., 2022).

Economic disparities often translate into educational inequality, where communities with limited resources tend to prioritize work over pursuing higher levels of education (Jamaluddin et al., 2022). According to the 2015 PISA assessment, Indonesia ranked 62nd out of 72 participating countries with an average score of 397, which further declined to 379 in 2018. The report highlighted that 71% of Indonesian students still struggled with problem-solving tasks, with 35% classified at competency level 1a and 17% below level 1 in scientific literacy (Wuryanto et al., 2022). Socio-economic conditions and the geographical location of schools contribute to the gap in reading competencies, as rural students consistently demonstrate lower reading performance compared to their urban peers. Ferdiana et al. (2022) further revealed that students' place of residence contributed 22.6% to educational inequality at the secondary level in East Java, with the Tapal Kuda region ranking highest with an inequality index of 0.5589. These conditions underscore the pressing need for students to develop creative, critical, and innovative thinking skills as essential competencies for facing 21st-century challenges (Fakhriyah, 2014).

The orientation of 21st-century learning emphasizes the mastery of strong problem-solving skills (Fitri et al., 2020), highlighting the importance of enhancing students' ability to solve complex problems in order to prepare younger generations to meet global challenges (Kurniawati et al., 2019). Students' critical thinking and problem-solving skills can be fostered through the application of Science, Technology, Engineering, and Mathematics (STEM)-integrated learning. STEM education integrates multiple disciplines in a collaborative way, allowing students to better grasp concepts and apply them to real-world challenges (Li et al., 2019). In particular, the integration of science in STEM-based learning provides students with opportunities to practice critical thinking and develop effective problem-solving strategies (Rusyati et al., 2019). One of the most effective ways to apply STEM principles is through instructional materials, such as textbooks. STEM-based digital textbooks can function not only as a communication medium between teachers and students but also as a tool to facilitate more interactive and meaningful learning processes (Wahono et al., 2020). Moreover, digital textbooks offer several advantages over traditional printed materials. Their flexibility allows students to access content anytime and anywhere, enabling self-paced learning that accommodates different learning styles and paces. The accessibility of multimedia features—such as videos, animations, and hyperlinks—enhances conceptual understanding and engagement. In addition, the interactive elements of digital

textbooks can increase students' motivation and foster a more student-centered learning environment, which aligns with the goals of STEM education.

Although several studies have investigated the relationship between critical thinking and problem-solving skills in students (Mardhiyah et al., 2021; Syafitri et al., 2021), research focusing on industrial agricultural areas remains limited. The socio-economic characteristics of these regions differ significantly from those of urban settings, necessitating a more contextualized learning approach. Considering the demographic, geographic, and methodological characteristics that shape STEM implementation (Kayan et al., 2022), this study seeks to provide empirical evidence on the effectiveness of a STEM-based biotechnology digital textbook in enhancing critical thinking and problem-solving skills of high school students in industrial agricultural areas.

Industrial agricultural areas are crucial to study because their communities often depend economically on agricultural production, while access to quality education and digital learning resources remains limited. Students in these areas may face challenges such as outdated learning materials, lack of laboratory facilities, and minimal integration of technology in classroom instruction. Therefore, exploring STEM-based digital textbooks in this context helps bridge the educational gap and aligns the curriculum with local socio-economic realities.

Over the past decade, previous research has mainly focused on the development of STEM-based learning models in urban or well-resourced school contexts (e.g., Margot & Kettler, 2019; Bybee, 2020; Suryani et al., 2022). However, few studies have examined how STEM-based instructional materials perform in rural or industrial-agricultural settings, where the availability of technological infrastructure and teacher readiness differ significantly. This study addresses that gap by situating STEM learning within the context of agricultural industry regions, providing new insights into how digital textbooks can enhance students' higher-order thinking skills under resource-constrained conditions.

METHOD

Researched Design

This study employed a quasi-experimental method with a nonequivalent control group design, consisting of an experimental group and a control group. Both groups were taught the same learning material but using different instructional approaches. The experimental group received treatment with a STEM-based digital biotechnology textbook, while the control group was taught using conventional methods.

Population and Sampling

The study was conducted at SMA Negeri 1 Dringu, Probolinggo Regency, during the even semester of the 2022/2023 academic year. The population consisted of all Grade XII MIPA (Mathematics and Natural Sciences) students. Because this research employed a quasi-experimental non-equivalent control group design, intact classes were used instead of randomly assigning individual students. A purposive sampling technique was applied to select two classes with relatively similar academic characteristics based on school records and teacher recommendations. One class (XII MIPA 3) was assigned as the experimental group, while another class (XII MIPA 4) served as the control group, with a total of 74 students participating in the study.

Instruments

Two sets of instruments were developed and validated for data collection. First, critical thinking skills test – consisting of five essay items designed to assess five core indicators which are interpretation, analysis, evaluation, inference, and explanation. Second,p roblem-solving skills test – consisting of four indicators which are identifying and understanding the problem, designing a solution plan, implementing the plan, and evaluating the results.

Prior to implementation, both instruments underwent expert validation by two biology education specialists and one psychometrics expert to ensure content validity. The validation process produced a Content Validity Index (CVI) of 0.89, indicating high validity. To determine reliability, the instruments were pilot-tested with 30 students from a comparable class outside the research sample. The reliability analysis using Cronbach's alpha showed coefficients of 0.86 for the critical thinking test and 0.84 for the problem-solving test, both indicating strong internal consistency. In addition to the tests, non-test data were collected through structured interviews with biology teachers at SMA Negeri 1 Dringu to triangulate findings and obtain deeper insights into instructional practices.

Data collection involved administering pretests and posttests to both the experimental and control groups. The pretest was conducted prior to the instructional intervention to measure students' baseline abilities, while the posttest was administered after the implementation of the STEM-based textbook to assess learning outcomes. To maintain procedural consistency, both groups were taught by the same biology teacher, using equivalent instructional durations and assessment schedules. The scoring of students' critical thinking and problem-solving skills was categorized into five levels ranging from very high to very low, as presented in Table 1 and Table 2.

Table 1. Critical Thinking Skills Scoring Categories

Interpretation (%)	Category
81.25 < X ≤ 100	Very High
71.5 < X ≤ 81.25	High
62.5 < X ≤ 71.5	Moderate
43.75 < X ≤ 62.5	Low
X ≤ 43.75	Very Low

Table 2. Problem-Solving Skills Scoring Categories

Score Range	Category
85 – 100	Very High
70 – 84	High
55 – 69	Moderate
40 – 54	Low
< 39	Very Low

Instruments

The collected data were analyzed using parametric statistical tests. Prior to hypothesis testing, assumptions of normality, homogeneity of variance, linearity, and homogeneity of regression slopes were verified. Subsequently, T-test was employed to compare posttest scores between the experimental and control groups while controlling for pretest scores. This method allowed for a more accurate estimation of the instructional intervention's effect on students' critical thinking and problem-solving skills.

RESULTS AND DISCUSSION

The research activities began with an initial observation of the school environment. Observations were also conducted in the trial classes. Both the control and experimental classes demonstrated a conducive learning atmosphere and were supported by adequate classroom

facilities. Students in both classes appeared enthusiastic about the lessons delivered. However, in the control class, students tended to be more passive during discussions because the textbook used was conventional and less engaging, which reduced students' reading interest. In contrast, the experimental class employed a STEM-based digital textbook designed with unique features that successfully captured students' interest, leading to more active and responsive participation during the learning process.

In the experimental class, students were introduced to basic and modern biotechnology, the role of biotechnology in daily life, and were provided with worksheets (LKPD) that required them to solve problems using biotechnology concepts. Students were also tasked with developing innovative ideas related to biotechnology based on their imagination. The implementation score of the learning process in both the control and experimental classes reached 100%, indicating that the entire learning sequence was carried out successfully.

Analysis of Critical Thinking Skills Test

Students' critical thinking skills were assessed through pretest and post-test scores. The test aimed to evaluate the effect of implementing a STEM-based textbook in biotechnology learning on students' critical thinking abilities.

Table 3. Frequency Distribution of Critical Thinking Skills Test Results

No	Critical Thinking Indicators	Control Class		Difference	Experimental Class	Difference
		Pretest	Posttest			Pretest
1	Interpretation	77	79	2		78
2	Analysis	63.5	65	1.5		68
3	Evaluation	65.5	66	0.5		70
4	Inference	67	70	3		70
5	Explanation	63	67	4		75

The critical thinking test consisted of five essay items covering interpretation, analysis, evaluation, inference, and explanation indicators. As shown in Table 3, the control class achieved the lowest improvement in the evaluation indicator (0.5), while the explanation indicator showed the highest increase (4 points). In the experimental class, the highest gains were observed in inference and explanation (both +7), while interpretation showed the lowest increase (+4).

The subsequent statistical analysis included normality, homogeneity, and hypothesis testing. The normality test using the Kolmogorov-Smirnov method showed a Sig. (2-tailed) value of 0.149 for the posttest, which was > 0.05, indicating that the posttest data of both groups were normally distributed. The homogeneity test of critical thinking skills revealed a significance value of 0.67 for the posttest, which was also > 0.05, confirming that the posttest data of both groups were homogeneous.

Table 4. Hypothesis Testing Results of Critical Thinking Skills

Class	N	Mean (Posttest)	Std. Deviation	Sig. (2-tailed)
Control	37	84.19	±5.34	0.008
Experimental	37	89.05	±9.12	

Table 4 indicated the hypothesis testing results of critical thinking sklills. The hypothesis testing using SPSS Statistics 22 revealed a Sig. (2-tailed) value of 0.008 for the posttest results. Since the significance level was < 0.05, it indicates that H_0 is rejected and H_1 is accepted. Thus, it

can be concluded that the STEM-based digital textbook in biotechnology has a significant effect on improving students' critical thinking skills in Grade XII.

Analysis of Problem-Solving Skills Test Results

Students' problem-solving skills were assessed using test items that included indicators of problem-solving ability. The purpose of this test was to determine the effect of applying the STEM-based textbook in biotechnology learning on students' biological problem-solving skills.

Table 5. Frequency Distribution of Problem-Solving Skills Test Results

No	Problem-Solving Indicators	Control Class	Difference	Experimental Class	Difference
		Pretest	Posttest		Pretest
1	Understanding the Problem	70	72	2	66
2	Developing a Solution Plan	67	70	3	75
3	Implementing the Solution	74	78	4	72
4	Reviewing Procedures and Outcomes	70	75	5	72
	Total Gain		14		

As presented in Table 5, the control class showed the highest improvement in the indicator reviewing procedures and outcomes (+5), while understanding the problem had the lowest improvement (+2). In the experimental class, the highest gain was observed in understanding the problem (+9), while the lowest gain was in developing a solution plan (+3).

Further analysis was conducted through normality, homogeneity, and hypothesis testing. The normality test using Kolmogorov-Smirnov revealed a Sig. (2-tailed) value of 0.058 for the posttest, which was > 0.05, indicating that the posttest data were normally distributed. The homogeneity test produced a significance value of 0.648 for the posttest, confirming that the data were homogeneous.

Table 6. Hypothesis Testing Results of Problem-Solving Skills

Class	N	Mean (Posttest)	Std. Deviation	Sig. (2-tailed)
Control	37	80.57	±8.93	0.000
Experimental	37	88.85	±8.21	

Based on the T-test analysis (Table 6), the Sig. (2-tailed) value of the posttest was 0.000. Since this value is < 0.05, it indicates that H_0 is rejected and H_1 is accepted. Therefore, it can be concluded that the STEM-based biotechnology textbook had a significant positive effect on students' problem-solving skills in Grade XII.

This study aimed to examine the effect of using STEM-based digital textbooks, particularly on biotechnology topics, compared to conventional textbooks commonly used by teachers in senior high schools within agricultural industrial areas, on students' critical thinking skills. Critical thinking is defined as self-regulated decision-making that involves intellectual processes such as interpretation, analysis, evaluation, and consideration of information presentation, with evidence as the basis for making decisions (Syafitri et al., 2021).

The STEM-based textbook on biotechnology is uniquely designed with various features to increase students' learning interest. The content is presented in audio-visual formats, providing students with a new reading experience that enhances learning quality and literacy engagement.

This aligns with Octafianellis et al. (2019), who noted that the STEM approach can foster innovative, logical, independent, and technology-responsive thinking. The textbook integrates the four STEM components: science, technology, engineering, and mathematics. The *science* component, according to Hasanah (2020), relates to students' scientific attitudes toward their surrounding natural environment. The *technology* component, as described by Ellis (2020), emphasizes the role of advanced instructional technologies as tools to enhance teaching and learning. The *engineering* component focuses on designing and applying solutions to particular conditions related to biotechnology (Simarro et al., 2021). Meanwhile, the *mathematics* component refers to activities involving calculation, analysis, assessment, and decision-making in problem-solving contexts (Just et al., 2022).

This STEM-based textbook is accessible both online and offline, allowing students to access it anytime and anywhere, thus improving learning quality while cultivating logical and critical thinking habits. Hizhar et al. (2020) similarly highlighted that STEM-integrated learning materials support students' observation, interpretation, analysis, and conclusion-making activities to foster critical thinking skills. In this study, the STEM-based textbook was chosen as it has the potential to enhance both critical thinking and problem-solving abilities. Developing learning materials in the form of digital e-modules is considered an alternative needed by both teachers and students, especially in the context of increasing demands for paperless learning resources that strengthen critical thinking and support sustainable education (Ekamilasari et al., 2021).

Based on the data analysis, the STEM-based digital textbook significantly influenced students' critical thinking and problem-solving skills. This finding is consistent with Iwuanyanwu et al. (2020), who emphasized that STEM-integrated textbooks can provide learning environments that promote critical thinking and problem-solving abilities. These results imply that integrating STEM-based digital resources in classroom instruction can enhance students' higher-order thinking skills and better prepare them to face real-world challenges. Therefore, teachers and curriculum designers should consider incorporating STEM-oriented materials to foster more interactive and inquiry-based learning experiences.

The Effect of STEM-Based Digital Textbooks on Biotechnology on Students' Critical Thinking Skills

The hypothesis testing conducted using T-test posttest value of 0.008. Since the significance level was less than 0.05, this result indicates that H_0 was rejected and H_1 was accepted. Therefore, it can be concluded that the STEM-based biotechnology digital textbook had a significant effect on enhancing the critical thinking skills of Grade XII students.

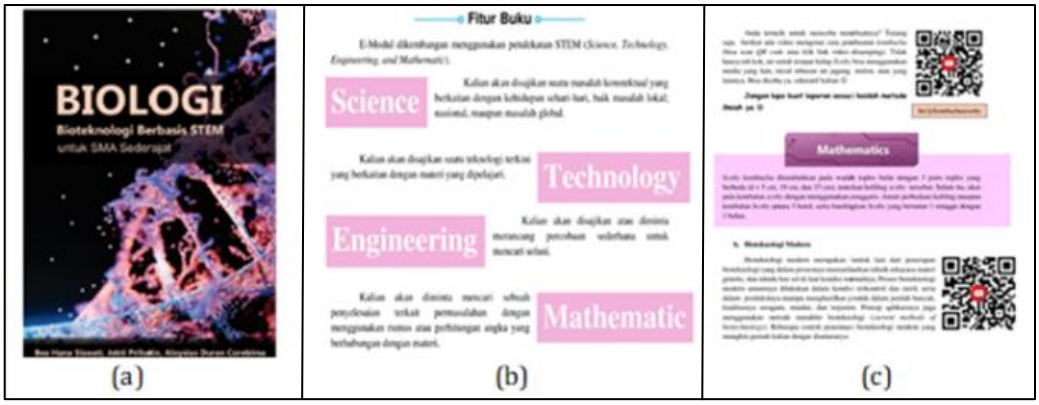

Figure 1. (a) Front cover of the textbook, (b) Features contained within the textbook, (c) Barcode feature included in the textbook.

The STEM-based textbook on biotechnology had a significant effect on students' critical thinking skills. This can be seen from the total pretest and posttest scores obtained by the students.

Critical thinking skills in the control class increased by 11 points, while the experimental class increased by 28 points after treatment. Thus, the difference in improvement between the two classes was 17 points. These results demonstrate that the STEM-based textbook positively influenced students' critical thinking skills. This finding is consistent with Yosep et al. (2021), who stated that the STEM approach has the potential to improve students' critical thinking abilities.

Critical thinking is a cognitive skill that enables students to think systematically in analyzing, processing, and evaluating an argument (Rogovaya et al., 2019). It is an essential skill for students to possess in facing various challenges of 21st-century learning. According to Al-Ghadouni (2021), critical thinking is one of the most important types of thinking that requires attention and development in learners. Critical thinking skills can be identified through several indicators, including interpretation, analysis, evaluation, inference, explanation, and self-regulation (Simatupang, 2020). In this study, these indicators were evident in students' ability to interpret biological concepts, analyze experimental results, and evaluate problem-solving strategies during classroom discussions, showing that critical thinking played a central role in improving their learning outcomes.

The STEM components—science, technology, engineering, and mathematics—are integrated into the features of the textbook to foster students' critical thinking skills. The science feature is implemented through student activities in worksheets (LKPD), where students analyze biotechnology products found in everyday life, distinguish between types of biotechnology products, and examine their production processes. These activities sharpen students' critical thinking by applying scientific principles. The integration of science in STEM enhances understanding and scientific inquiry skills, which directly affect critical thinking abilities (Tanti et al., 2020). The textbook also provides technology features, such as barcodes linked to instructional videos about modern biotechnology. The integration of technology and engineering features encourages students to think critically in creating new innovations (William et al., 2023). Meanwhile, the mathematics component is supported by problem examples embedded in the text, allowing students to practice mathematical principles. The mathematics component in STEM plays a crucial role in strengthening students' critical thinking skills (Harjo et al., 2019).

The Effect of Applying STEM-Based Digital Textbooks on Biotechnology on Students' Problem-Solving Skills

Hypothesis testing using T-test yielded a Sig. posttest value of 0.000. Since the significance value was less than 0.05, it indicates that H_0 was rejected and H_1 was accepted. Therefore, it can be concluded that the STEM-based textbook on biotechnology had a significant effect on students' biological problem-solving skills in Grade XII.

The effect of STEM-based textbooks on students' problem-solving skills was evident from the pretest and posttest results. Students in the control class showed an improvement of 14 points, while students in the experimental class improved by 26 points after the intervention, resulting in a difference of 12 points between the two classes. These findings confirm that STEM-based textbooks enhance students' problem-solving skills. This aligns with Zengin et al. (2022), who emphasized that STEM-based learning is an appropriate approach to designing educational practices that improve 21st-century problem-solving skills.

Problem-solving is the ability to systematically formulate steps in finding solutions to encountered problems (Malik et al., 2019). Students' problem-solving skills can be identified through several stages: understanding the problem, developing a solution plan, executing the solution, and reformulating the solution (Purnamasari et al., 2019).

STEM integrates components that collaboratively enhance students' problem-solving abilities. As Purwaningsih et al. (2020) highlighted, the integration of science, technology, engineering, and mathematics is essential for 21st-century learning. In this textbook, the science component is implemented through student activities in worksheets, where students analyze real-life problems using biotechnology principles. This approach allows students to actively construct understanding through analysis and conclusion-making (Suryaningtyas et al., 2020). The technology and engineering components are implemented through group discussions on

biotechnology-related problems in daily life, where students propose alternative solutions using biotechnology principles. Technology and engineering foster innovation and provide strategies to overcome learning challenges (Ellis et al., 2020). Finally, the mathematics component is integrated into discussions on fermentation processes and their changes. Students analyze possible failures and their causes, thereby exercising their problem-solving and analytical skills. The mathematics component supports systematic calculation and reasoning, which enhances students' problem-solving abilities (Ukobizaba et al., 2021). When combined, these features strengthen the development of both critical thinking and problem-solving skills (Li et al., 2019).

CONCLUSION

Based on the results of the study and the discussion, it can be concluded that the STEM-based digital textbook on biotechnology has a significant effect on high school students' critical thinking skills in the Industrial Agriculture Area (Sig. = 0.008). The STEM-based digital textbook also significantly influences students' biological problem-solving skills (Sig. = 0.000). However, this study has several limitations, including a relatively short research period, limited research instruments, and a sample restricted to one school, which may constrain the generalizability of the findings. Therefore, further research is recommended with a broader scope, longer duration, and more varied instruments to obtain more comprehensive results. Based on the findings, several suggestions and recommendations can be provided for relevant stakeholders. Teachers may consider using the STEM-based biotechnology textbook as an alternative learning resource for students. It is recommended that teachers foster literacy habits among students and incorporate STEM-based question variations in daily learning activities. The STEM-based biotechnology textbook can serve as a reference for enhancing future research outcomes. Researchers may also conduct further studies that incorporate activities designed to increase students' literacy interest.

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