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Critical thinking transformation in the digital era: The effectiveness of e-module based on read-STEM in elementary school

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Article info

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Abstract

Critical thinking is an essential 21st-century skill students need to face global challenges. It involves the ability to analyse information deeply, present arguments objectively, and make evidence-based decisions. However, the level of critical thinking skills of elementary students in Indonesia remains relatively low. To address this issue, the development of suitable learning media is needed. This study aims to develop and test the effectiveness of an e-module based on Read-STEM in improving elementary students' critical thinking skills. The research used the Borg and Gall development model, involving 4th-grade students from several elementary schools in Jember. Instruments were validation sheets and critical thinking skill tests. The validation results showed a validity score of 95.1%, categorised as "very valid." The effectiveness test indicated an average N-Gain of 0.61, placing it in the "medium" improvement category. These results indicate that the Read-STEM-based e-module is a valid and effective learning medium. Furthermore, these findings have broader implications for other educational contexts, such as science or social studies, which require complex problem analysis and evidence-based reasoning. This research contributes to the existing body of knowledge on digital learning tools by providing a specific, practical framework that combines the strengths of the STEM approach with critical reading strategies, demonstrating its potential for developing higher-order thinking skills beyond the elementary level.

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1. Introduction

21st-century learning requires students to have essential skills known as the 4C, namely creativity, collaboration, critical thinking, and communication. Among the four skills, critical thinking skills are the primary foundation in forming students who can understand problems in depth, make rational decisions, and solve complex problems based on data and logic (Hermita., et al, 2019). Critical thinking includes understanding essential meanings, analysing information, drawing objective conclusions, evaluating arguments, expressing opinions based on facts, and reflecting on one's thinking process (Facione and Gittens, 2016).

Despite its high urgency, various studies show that the critical thinking skills of students in Indonesia are still relatively low. According to the OECD (2023), the 2022 PISA results consistently show that Indonesian students perform poorly in science, mathematics, and reading literacy. Compared to the previous cycle in 2018, Indonesia's mean scores declined across all three domains: mathematics dropped by 13 points (from 379 to 366), reading by 11 points (from 371 to 360), and science by 4 points (from 396 to 392), which corresponds to a decrease of approximately 3.4%, 3.0%, and 1.0%, respectively. The assessment measures students' ability to solve complex problems, think critically, and communicate effectively. These findings indicate that many students still struggle to develop critical thinking skills, such as evaluating arguments based on evidence, drawing logical conclusions, and connecting scientific concepts to real-life situations (Sahyar et al., 2019; Wahdaniyah et al., 2023). This condition is exacerbated by the limited learning media that support the development of critical thinking in a structured manner (Anisa, Ipungkarti, and Saffanah, 2021; Rahmawati and Rosy, 2021; Landina and Agustiana, 2022).

Improving students' critical thinking skills can be done by providing opportunities for students to be actively involved in solving complex problems (Suratno and Kurniati, 2017). The STEM (Science, Technology, Engineering, and Mathematics) approach can strengthen critical thinking skills. This approach emphasises the relationship between scientific fields and learning based on solving real problems (Yuniar et al., 2020; Aguayo et al., 2023). Problem-solving skills offer students hands-on experiences that enhance their ability to construct, comprehend, and apply the concepts they have learned (Syahyadi et al., 2024). The STEM approach encourages the development of students' hard and soft skills through active learning that emphasises communication, collaboration, problem-solving, and creativity (Wardani and Ardhyantama, 2021). As a scientific approach, STEM hones critical thinking skills in dealing with real problems. Various studies have shown that STEM-based learning can improve students' critical thinking and analytical skills (Wahyunita and Subroto, 2021; Kustiana, Suratno, and Wahyuni, 2020).

Integration with critical reading skills was considered strategic to strengthen the influence of the STEM approach in learning. Reading skills enable students to understand texts, assess information's relevance, and form opinions based on valid evidence (Abbasi-Sosfadi et al., 2025). Reading is the process of understanding and interpreting texts that help students obtain new information and identify thought patterns, assess the relevance of information, and construct logical arguments (Rahma, Deyanti, and Fitriyah, 2024). Through good reading skills, students can: 1) analyse important information from various reading sources; 2) develop a deeper understanding to support critical thinking; 3) form critical reading habits, such as finding biased sentences in texts and making objective evaluations. This integration theoretically enhances students' critical thinking skills based on established indicators. For example, students are trained to interpret and analyse through contextual reading by identifying key meanings and recognising logical relationships among various statements. Moreover, literacy in the context of science (scientific literacy) has been shown to significantly contribute to students' ability to evaluate data and make inferences to draw objective conclusions (Sanjiartha et al., 2024). This approach enables students to explore phenomena, analyse data, and draw evidence-based conclusions, which are core critical thinking components.

However, it is still rare to find the development of teaching materials that explicitly integrate the STEM approach and reading skills into one complete unit. As a solution to this need, the e-module based on read-STEM was developed as a learning innovation that combines the strengths of the STEM approach with critical reading strategies. This e-module stimulated high-level thinking skills through contextual reading, problem solving, and cross-disciplinary exploration (Doang, Gunayasa, and Setiawan, 2022). This digital format module also offers high flexibility and interactivity, in line with the characteristics of modern learning (Safitri and Sari, 2023). Previous research has shown that developing e-modules oriented toward reasoning and problem-solving effectively enhances students' critical and creative thinking skills (Suarsana, 2013; Akmala, 2025). A study by Mutia et al. (2025) demonstrated that interactive, project-based e-modules can foster independent learning, support the development of students' cognitive abilities, and provide a more meaningful and reflective learning experience, with a t-test significance value of 0.003.

The use of e-modules with a Read-STEM approach has been shown to improve students' understanding by presenting material in a structured and interactive manner, incorporating visual elements, simulations, and features that facilitate the comprehension of complex concepts. These e-modules also offer a personalised and flexible learning experience while enhancing explanatory skills through global issues embedded in the readings. This allows students to articulate and justify their reasoning using facts, concepts, methods, and contexts that form the basis of persuasive and easily understood arguments (Agnafia, 2019). Irmawati et al (2021) stated that STEM-based e-modules effectively enhance students' analytical skills through project-based learning, making the learning process more meaningful. Furthermore, multimedia helps visualise content and concretise abstract concepts, thereby improving students' understanding and cognitive skills (Rohana et al., 2021; Rahmawati et al, 2025).

Despite these advantages, implementing Read-STEM-based e-modules in classrooms, particularly in elementary schools, faces several challenges. Technical issues such as limited access to digital devices and unstable internet connections often hinder their use. Moreover, teachers' readiness to integrate technology and STEM-oriented approaches remains crucial. Ramdani et al (2024) emphasised that effective e-module implementation requires adequate teacher outreach and training. Another key challenge is ensuring the e-module content aligns with curriculum standards and meets students' learning needs (Fitriyah, 2023). Based on these problems, this study aims to develop and test the validity and effectiveness of the e-module based on read-STEM in improving the critical thinking skills of elementary school students. It is hoped that the research results can contribute to developing learning media relevant to the needs of 21st-century education.

2. Method

This study uses a Research and Development (R&D) approach, which is defined as a form of research that aims to produce a particular product and assess its effectiveness. This study focuses only on the preliminary research stage, which aims to gather fundamental insights and initial data to evaluate the feasibility and potential impact of the developed product. Therefore, no control class was used in this study, as the focus was limited to the early development and testing of the product. The R&D process involves evaluating an e-module based on read-STEM, designed to improve students' critical thinking skills. The model used in this study was the Borg and Gall (1983) model.

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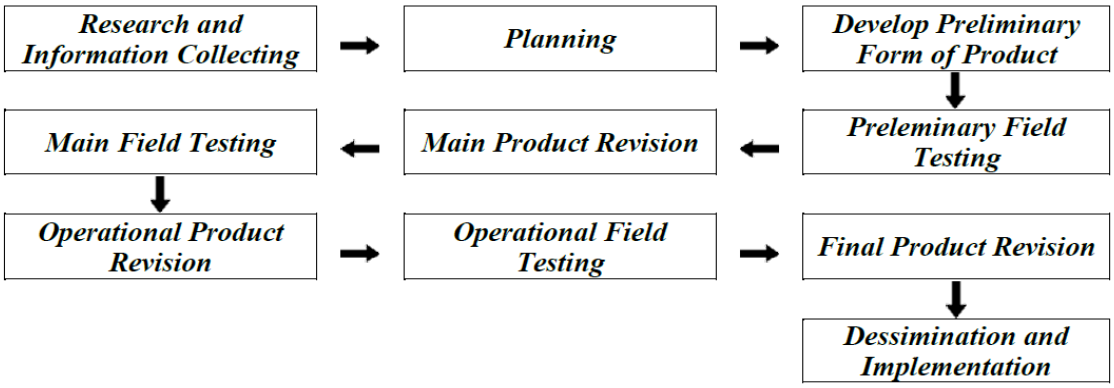

Source: (Borg dan Gall, 1983: 775-786)

The research was conducted during the even semester of the 2024/2025 academic year at four public elementary schools in Jember Regency, East Java. The research subjects were fourth-grade students selected through purposive sampling, in which participants are intentionally chosen based on specific characteristics or criteria relevant to the objectives or focus of the research (Hariyati, 2020). Sample selection considered variations in school characteristics, including accreditation status, geographic location (urban and suburban), and school readiness regarding curriculum, facilities, and students who had studied photosynthesis material. This approach aimed to ensure that the sample represented a broader population of elementary students in the context of digital media implementation. The total sample size for the preliminary field-testing phase consisted of 15 students from SDN Jember Lor 03. The main field-testing phase involved 29 students from SDN Jember Lor 03, while the operational field-testing phase included 53 students from two schools: SDN Kebonsari 03 and SDN Sukorejo 02. The dissemination and implementation phase involved 27 students from SDN Wirolegi 03.

The data collection instruments included:

a. The Critical Thinking Skills Test, a pre-test and post-test based on six indicators from Facione & Gittens (2016), was used to measure students' critical thinking skills. Experts have validated previous tests through a limited pilot study with 15 students in the preliminary field-testing phase. All items correlated above r ($\alpha = 0.05$), indicating validity. The reliability test yielded a Cronbach's Alpha of 0.815, indicating the instrument's reliability.
b. Two questionnaires were used: a validation questionnaire and a student response questionnaire. The validation questionnaire assessed the feasibility of the media and instruments, involving expert validators in subject matter, language, and media, as well as in the test and response instruments. A student response questionnaire is used to provide input and evaluate the e-module after implementation in class.

Data obtained from the assessment during the validation process was analysed to determine the extent of the validity of the product that had been developed. The product validity formula uses the Valpro formula (Akbar, 2016: 82). Indicators of product design validation result criteria are listed in Table 1.

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Table 1. Product design validation result criteria indicators

Percentage	Categories
81.00%– 100 %	Very valid
61.00%– 80.00%	Quite valid
41.00%– 60.00%	Less valid
21.00% – 40.00%	Not valid
0% – 20.00%	Very invalid

Source: Akbar (2016: 82)

The product development can be tested if it falls into the feasible category with a minimum score of 61. If the score is less than 61, the developed product must be revised before the product usage trial is resumed.

$$< N - gain > = \frac{Sf - Si}{100 - Si}$$

Description:

<g> = Mean N-gain score

Sf = Post-test score

Si = Pre-test score

Table 2. Criteria for effectiveness test results

Score N-Gain	Criteria
N-Gain > 0.70	High
0.30 ≤ N-Gain ≤ 0.70	Medium
0 < N-Gain < 0.30	Low

Source: Hake (1998)

3. Results

3.1 Research and information collection

The first research stage was data collection (research and information gathering). This stage aimed to collect information through curriculum analysis, needs, and literature studies.

3.2 Planning

The next stage was the planning stage, which involved formulating objectives and planning activities in the research on developing e-modules based on read-STEM. The goal formulation stage was intended to prepare the objectives to be achieved by creating a product as an e-module. E-modules were based on the following critical thinking skills indicators.

Table 3. Indicators and descriptions of critical thinking skills

No	Indicators	Descriptions
1.	Interpretation	The ability to capture and convey essential meanings from various aspects, including life experiences, situations faced, data obtained, events that occur, research conducted, existing habits, beliefs held, applicable rules, procedures carried out, and established criteria.
2.	Analysis	The ability to recognise or identify between the intended and actual logical relationships between various statements, questions, concepts, descriptions, or other forms of representation designed to convey beliefs, judgments, experiences, reasons, information, or opinions.

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No	Indicators	Descriptions
3.	Inference	The ability to recognise or identify and obtain the knowledge needed to conclude, make speculations and hypotheses, consider related information, and analyse the possible impacts that can arise from various sources of knowledge, including data, statements, questions, concepts, and explanations.
4.	Evaluation	The ability to assess the reliability of various statements or symbols that describe a person's responses, experiences, situations, evaluations, beliefs, or views, as well as the ability to assess the logical strength of inferential relationships (both real and intended) between statements, descriptions, questions, or other forms of representation.
5.	Explanation	The ability to express and justify reasoning by reviewing facts, concepts, methods, criteria, and contexts that form the basis of thinking, and presenting these reasons in the form of persuasive and easily understood arguments. The ability to consciously examine one's own thinking activities, the elements involved in those activities, and the results achieved, especially by applying analytical and evaluation skills to self-assessment, with the aim of questioning, confirming, validating, or improving both our thinking processes and the results of our thinking.
6.	Self-regulation	The ability to capture and convey essential meanings from various aspects, including life experiences, situations faced, data obtained, events that occur, research conducted, existing habits, beliefs held, applicable rules, procedures carried out, and established criteria.

Source: Facione and Gittens, (2016)

3.3 Develop a preliminary form of product

The initial stage of designing an e-module was to create the initial appearance and adjust it to the e-module components designed using the Canva application. Furthermore, the module appearance will be changed into an e-module using development support software, namely Heyzine Flipbook. The e-module components are divided into three e-module parts: introduction, content, and conclusion. The next stage was to assess the e-module based on read-STEM by the validator using a validation instrument. The validation results of the e-module development based on read-STEM can be seen in Table 4.

Table 4. Validator value results

Assessment Aspects	Validator Score			Average Valpro	Category
	V1	V2	V3		
Material Aspect	24	25	25	98.6%	Very valid
Languange Aspect	24	21	24	92%	Very valid
Media Aspect	25	21	25	94.6%	Very valid
Average Valpro Product				**95.11%**	**Very valid**

Developing the e-module that three validators have validated requires several revisions. The revisions include the alignment of feature icons, the addition of barcode instructions with the sentence "Scan the barcode next to get more information," the preparation of learning objectives (TP) using the ABCD formula, and the replacement of the word "answer" with "*jawaban*." Additional activities are also inserted into material 1 to increase interactivity. This update aims to make the e-module more informative and interesting. After the revision, product development continues to the next stage.

3.4 Preliminary field testing and revision

The revised e-module was then subjected to limited testing to identify errors in the product during the actual implementation of the model so that it could be refined again. The limited test sample was 15 students from class IVB SDN Jember Lor 03. The results of the product's effectiveness on critical thinking skills at the limited test stage are obtained as follows.

Table 5. Results of the effectiveness test at the preliminary field testing

Indicators	Sample	Pre-test	Post-test	N-Gain	Category
Interpretation	15	63.3	88.3	0.68	Medium
Analysis		36.6	73.3	0.57	Medium
Inference		36.6	68.3	0.5	Medium
Evaluation		53.3	85	0.67	Medium
Explanation		51.6	81.6	0.62	Medium
Self-regulation		60	86.6	0.66	Medium
Total		**50.2**	**80.5**	**0.60**	**Medium**

Based on student questionnaires, most students report that the visual presentation of the e-module is engaging and makes it easier for them to understand the photosynthesis material. Some also state that the instructions in the student worksheet are too dense and confusing and, therefore, need to be simplified to make them more accessible to elementary school students. Based on the limited test results, a revision is made to streamline the LKPD to make it easier for students to understand the activities.

3.5 Main field tasting and revision

The revised read-STEM-based e-module was then tested in a large class IVA SDN Jember Lor 3 group. The results of the product's effectiveness on critical thinking skills at the main field test stage are as follows.

Table 6. Results of the effectiveness test at the main field tasting

Indicator	Sample	Pre-test	Post-test	N-Gain	Category
Interpretation	29	83.6	94.8	0.68	Medium
Analysis		58.6	82.7	0.58	Medium
Inference		42.2	71.5	0.50	Medium
Evaluation		57.7	86.2	0.67	Medium
Explanation		49.1	81	0.62	Medium
Self-regulation		56	85.3	0.66	Medium
Total		**57.9**	**83.6**	**0.61**	**Medium**

Student feedback indicates that embedding videos instead of barcodes significantly helps them understand the concept of light and dark reactions. Students express that the videos made the material more engaging and easier to digest than simply reading text or viewing images. Furthermore, they feel more engaged because the material feels more real. Based on the field test results, a revision is made by replacing the barcode with a video in the further information section

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explaining the dark and light reactions. In addition, illustrations depicting high and low temperatures have been updated to provide a clearer understanding. This update aims to increase the interactivity and effectiveness of learning.

Table 7. Results of the effectiveness test at the operational field testing

School Names	Indicators	Sampel	*Pre-test*	*Post-test*	N-Gain	Categories
Kebonsari 03	Interpretation	28	*82.1*	*94.6*	0.7	Medium
	Analysis		*51.7*	*80.3*	0.59	Medium
	Inference		*33.9*	*67.8*	0.51	Medium
	Evaluation		*55.3*	*85.7*	0.68	Medium
	Explanation		*51.7*	*83*	0.64	Medium
	Self-regulation		*0.67*	*87.5*	0.67	Medium
	Total		**56.1**	**83.1**	**0.61**	**Medium**
Sukorejo 02	Interpretation	25	81	95	0.73	High
	Analysis		47	78	0.58	Medium
	Inference		31	67	0.52	Medium
	Evaluation		46	83	0.68	Medium
	Explanation		56	85	0.65	Medium
	Self-regulation		66	89	0.67	Medium
	Total		**54.5**	**82.6**	**0.61**	**Medium**

3.6 Operational field testing and revision

At this stage, data was collected by distributing e-modules based on read-STEM to be taught to students without researcher assistance. Feasibility test 1 occurred at SDN Kebonsari 03 with 28 student samples, and feasibility test 2 at SDN Sukorejo 02 with 25 student samples. The data obtained were then analysed and reported as a whole. The results of the product's effectiveness on critical thinking skills at the operational field test stage are as follows.

Based on questionnaire responses and small group discussions, students find the e-module to be a fun learning experience because it allows them to learn independently with the help of interactive visual features. However, some students at SDN Sukorejo 02 report having difficulty understanding specific scientific terms without direct guidance, highlighting the importance of teachers' role in providing initial guidance during the use of the e-module. At this stage, the final revision was completed to perfect the e-module according to the feasibility test results. Hopefully, this revision will eliminate the deficiencies in the teaching material and make it suitable. The draft e-module that has been tested is now ready to be used as teaching material in learning about photosynthesis.

3.7 Dissemination and implementation

The last research and development stage is the product dissemination stage at SDN Wirolegi 03. This dissemination aims to ensure that information, innovation, or research results can be accessed, understood, and utilised by relevant parties, so that they can increase knowledge, encourage decision-making, and create a positive impact. The results of the product's effectiveness on critical thinking skills at the dissemination and implementation stage are as follows.

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Table 8. Results of the effectiveness test at the dissemination and implementation

Indicators	Sample	*Pre-test*	*Post-test*	N-Gain	Categories
Interpretation	27	*62.9*	*89.8*	0.72	High
Analysis		*53.7*	*80.5*	0.58	Medium
Inference		*29.6*	*65.7*	0.51	Medium
Evaluation		*58.3*	*87*	0.68	Medium
Explanation		*50.9*	*82.4*	0.64	Medium
Self-regulation		*65.7*	*88.8*	0.67	Medium
Total		**53.5**	**82.4**	**0.62**	**Medium**

During the dissemination phase, student responses are collected through a questionnaire not intended to improve effectiveness but as initial input to assess the e-module's widespread acceptance and feasibility for further use. The results show that most students find the e-module engaging and easy to use, and it helps them understand the photosynthesis material more easily. They also appreciate the illustrations, videos, and contextual activities encouraging learning engagement. However, some students criticise the length of the reading material. They suggest that the e-module be supplemented with more interactive videos and game-based exercises to enhance learning diversity and reduce boredom.

4. Discussion

The read-STEM-based e-module is a product developed in this study that three validators have validated. According to Akbar (2016), a development product is considered valid if it reaches a score of 61% or is "quite valid". The validation results from the e-module material aspect obtained a score of 98.6%, from the language aspect in the "very valid" category. Above all, the read-STEM-based e-module can be implemented in science learning activities because the e-module has been declared very valid in every aspect of the assessment. The validation results for the material aspect obtained a score of 98.6%, which is included in the "very valid" category. The qualification in terms of material can be achieved due to several things, namely: (1) clarity of instructions for use; (2) suitability of the systematics, content of the material, and depth of the material used in the e-module; (3) ease of understanding; (4) clarity of the formulation of evaluation questions, and the level of difficulty of the questions is appropriate; (5) and the accuracy of the references used. The validity of the learning material covers all aspects related to the subject matter, this includes the integration of learning theories that are presented adequately to be used as a basis for developing the model, the scope of theories that support the learning model comprehensively, the relevance of the character concept as the basis for the learning model, and the suitability of the instructional impact and accompanying impacts to be achieved (Wulandari, et al., 2023).

Dewi and Lestari (2020) argue that e-modules provide a comprehensive understanding if the material is presented thoroughly and meets the objectives. The material in the e-module was designed to help students understand the lesson, so learning objectives can be more easily achieved if delivered systematically. Ensuring content validity is crucial for developing effective e-modules because it ensures that the e-module is in line with the expected learning outcomes, improves understanding, and fosters an adaptive learning environment (Vainshtein, et al., 2021).

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One of the main features supporting students' critical thinking development in this study was integrating Read-STEM activities. This approach combines critical reading with hands-on STEM projects, engaging students in contextual learning. Activities in the e-module encouraged students to design simple tools (e.g., oxygen generators or basic hydroponics systems), which helped strengthen their understanding of scientific and engineering principles while promoting analysis, evaluation, and creative thinking (Lestari, 2020; Ramadhan, 2023). The design also includes contextual reading materials with embedded problems, supporting students' ability to identify key information and formulate logical solutions (Fisher, 2011; Abrar, 2022). The emphasis on engineering aspects in the e-module also trained students to make collaborative decisions, evaluate designs, and foster analytical thinking in science learning (Lottero-Perdue, 2015; Wahono, 2018; Utomo., et al., 2020).

The results of the language aspect validation scored 92% which is included in the "very valid" category. The qualification of being very valid in terms of language contains several things, namely: (1) the sentences used do not have double meanings; (2) conformity with language rules; (3) use of language appropriate to the level of thinking of students; (4) clarity of work instructions; and (5) a communicative language style. This is also proven by research conducted by Belawati (Fadillah and Jamilah, 2016), which states that clarity in preparing teaching materials and systematics of the material will be easier for students to understand when absorbing information. In line with this opinion, Fatin and Yunianti (2018); Kosasih (2021) stated that reading texts can be considered quality if they are in accordance with the reader's education level and do not make it difficult for readers to understand the contents of the reading. This shows that the language used in e-modules must be able to convey information so that students can understand the contents of the material without experiencing confusion. The selection of appropriate vocabulary, clear sentence structure, and suitability to students' level of understanding are essential factors in compiling e-modules. E-modules have STEM-based activities encouraging students to learn actively and hone their skills (Sari., et al., 2022).

The results of the media aspect validation obtained a score of 94.6% which is included in the "very valid" category. The very valid qualifications in terms of media include several things, namely: (1) illustrations and displays in the e-module were attractive and could help to understand the material; (2) the clarity of the font used made it easier for readers to understand the material; (3) not using too many combinations of fonts; (4) the appearance of the e-module could create easy and enjoyable learning; and (5) the design of the e-module was in accordance with the learning material. This aligns with Pramana et al. (2020) who stated that the sense of sight can receive appropriate and easy-to-read text to convey the message effectively to students. Dewi and Lestari (2020) argue that displaying images and animations in modules accessed via computers can create a pleasant learning atmosphere for students. The existence of this multimedia can visualise the material and concretise abstract things so that students' understanding and skills can increase (Hasan et al., 2021). The results of the e-module effectiveness test on critical thinking tests obtained an average N-gain score of 0.61 in the "medium" category (Hake, 1998). At the field test stage, an N-gain score of 0.61 was obtained in the "medium" category. These results indicate that e-modules can improve students' critical thinking skills. Furthermore, data on the effectiveness of e-modules on essential thinking skills were collected at the feasibility test stage, obtaining an N-gain score of 0.61, which is

included in the "medium" category. At the dissemination stage, an N-gain score of 0.62 was obtained in the "medium" category. As such, it can be seen that there is an increase at each stage. This can occur due to two factors: internal factors, including experience and motivation, and external factors, including different teacher teaching styles and differences in learning time (Suciono, 2021).

The effectiveness test results indicate a notable improvement in students' critical thinking, particularly in problem-solving. The interpretation indicator achieved the highest average N-gain score of 0.7 among the six critical thinking indicators. This suggests that students could not only identify problems—such as from visual representations of wilted plants—but also construct logical explanations based on scientific concepts in a structured manner. These findings reflect the effectiveness of a contextual learning approach that encourages students to connect real-world phenomena with scientific knowledge (Agnafia, 2019). Visual illustrations, in particular, played a vital role in helping students understand and respond to problems more effectively (Kosasih, 2021).

On the other hand, many students still have difficulty with the inference indicator, indicated by the average N-gain score on the inference indicator being 0.5, where this average is still below other indicators. The inference indicator refers to students' ability to recognise statements, important reasons, or elements needed to reach logical conclusions (Facione and Gittens, 2016). In this case, students tend only to repeat statements in questions or provide answers without explaining the cause-and-effect relationship, such as stating that "the leaves can still photosynthesise" without explaining the decrease in efficiency. Students provide more descriptive answers without linking them to logical reasoning, even though concluding is essential in interpreting what has happened or been observed (Koasih, 2014). This is in line with research by Sarip et al. (2022), which states that the cause of low inference skills is that students cannot identify and solve problems until they find a conclusion. Research conducted by Irmawati et al. (2021) stated that the use of e-modules in learning can improve students' understanding in analysis, as it presents material in a structured and interactive manner, equipped with visual elements, simulations, and read-STEM features that make it easier to understand complex concepts. E-modules that present material systematically, complete with examples, case studies, and reflective questions, can encourage students to compare, assess, and determine the advantages or disadvantages of a concept. In addition, e-modules provide a personal and flexible learning experience, while developing explanatory skills to express and justify reasoning through facts, ideas, methods, and contexts that form the basis of persuasive and easy-to-understand arguments (Agnafia, 2019; Sari and Sutihat, 2022).

Furthermore, when examining the development between testing stages, there was a decline in N-Gain scores for several specific indicators, particularly in the operational and dissemination stages, such as the evaluation and inference indicators in different schools. This decline was likely due to the reduced role of teachers or direct assistance during implementation. At this stage, e-modules were provided to students without direct intervention or assistance from researchers, making it difficult to understand scientific terms or the logical reasoning required in critical questions (Ramdani et al., 2024).

Furthermore, score variations can also be influenced by differences in student background, the availability of supporting facilities, and individual learning styles. As reported at SDN Sukorejo 02, students experienced difficulties understanding scientific terms without teacher guidance. This aligns with the findings of Fitriyah et al. (2023), who stated that the effectiveness of digital media is

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highly dependent on the appropriateness of the school context and the readiness of the infrastructure. This indicates that although e-modules are interactive, their successful implementation is highly dependent on teacher support and the readiness of the learning environment (Ermawan and PS, 2024).

Thus, to maximise improvement in all critical thinking indicators, particularly inference, e-module development needs to consider adding scaffolding, such as step-by-step thinking prompts, examples of data-based conclusion drawing, and structured reflection activities. Teacher training is also crucial to guide students in understanding the inferential thinking process more systematically (Abbasi-Sosfadi et al., 2025; Hartini et al., 2025).

While the e-module demonstrated positive effects across various indicators and school contexts, several contextual challenges were observed during implementation. It is essential to consider these challenges in understanding the broader applicability of the module. This study also has several limitations that need to be acknowledged. First, the sample size, although involving multiple schools, remained relatively small and localised within a single regency, which might limit the generalizability of the findings. Second, the duration of exposure to the e-module in each testing phase was relatively short (one instructional cycle), which might not be sufficient to observe long-term development in critical thinking skills. A more extended intervention period could provide deeper insights into sustained impact. Third, the effectiveness of the e-module might also be influenced by variations in teachers' digital literacy and pedagogical readiness to implement Read-STEM effectively, as some students reported difficulties in understanding scientific concepts without teacher support.

In comparison to other studies, similar trends have been observed. For instance, Putri et al. (2023) also developed a STEM-based module to improve critical thinking and scientific literacy, but emphasised the importance of teacher facilitation during implementation. Likewise, research by Wahdaniyah et al. (2023) on PBL-STEM integration stressed that teacher preparedness significantly affects the success of student-centred digital learning approaches. These findings are aligned with our observations, reinforcing that even though the Read-STEM e-module shows promise, its success depends on contextual factors such as teacher support, student readiness, and sufficient implementation time.

Thus, while the Read-STEM-based e-module presents a strategic alternative to foster critical thinking, further research with larger and more diverse samples, extended learning durations, and consideration of teacher-mediated instruction is recommended to validate and optimise its effectiveness.

5. Conclusion and Implications

This study demonstrates that the Read-STEM-based e-module is a valid and practical innovation for enhancing elementary students' critical thinking skills. Validation results in material, language, and media aspects yielded an average score of 95.1%, indicating a "very valid" rating. The module's structured and communicative design aligns well with students' cognitive characteristics. Its effectiveness is shown by a consistent increase in critical thinking skills across various school contexts, with an average N-Gain of 0.61 ("medium" category), offering meaningful and challenging learning experiences.

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Educators are advised to implement this e-module with clear guidance on its interactive features while fostering a classroom culture of inquiry and discussion. The model can be adapted to other subjects, such as social studies or language arts, by integrating context-specific, problem-based scenarios while maintaining critical reading and analysis components, such as analysing historical documents in social studies. Policymakers are encouraged to support this initiative by ensuring adequate digital infrastructure and teacher training. The e-module holds potential for broader implementation, particularly in under-resourced areas, to improve education quality. Future research should explore its long-term impact on critical thinking development and adaptability across educational levels and disciplines to strengthen its pedagogical relevance.

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