frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 15 July 2025
DOI 10.3389/feduc.2025.1635133

OPEN ACCESS

EDITED BY
Konstantinos T. Kotsis,
University of Ioannina, Greece

REVIEWED BY
Riskan Qadar,
Universitas Mulawarman Fakultas Keguruan dan Ilmu Pendidikan, Indonesia
Georgios Stylos,
University of Ioannina, Greece

*CORRESPONDENCE
Jesi Alexander Alim
✉ jesi.alexander@lecturer.unri.ac.id

RECEIVED 26 May 2025
ACCEPTED 30 June 2025
PUBLISHED 15 July 2025

CITATION
Alim JA, Hermita N, Putra ZH and Oktaviani C (2025) Development of a STEM-based e-module using the MIKiR model on energy sources material to enhance students' critical thinking skills. *Front. Educ.* 10:1635133. doi: 10.3389/feduc.2025.1635133

Development of a STEM-based e-module using the MIKiR model on energy sources material to enhance students' critical thinking skills

Jesi Alexander Alim*, Neni Hermita, Zetra Hainul Putra and Cici Oktaviani

Department of Elementary Education, Faculty of Teacher Training and Education, Universitas Riau, Pekanbaru, Riau, Indonesia

Introduction: Elementary students' critical thinking skills remain below average, partly due to the lack of interactive teaching materials. This research aims to develop STEM-integrated MIKiR-based e-modules on the topic of energy sources for fourth-grade students that are valid, practical, and effective.

Methods: The study uses the Plomp development model consisting of Preliminary Research, Prototyping, and Assessment phases. Participants included 2 expert lecturers, 2 teachers, and 69 fourth-grade students. Data were collected through questionnaires, interviews, and tests, and analyzed using descriptive quantitative methods.

Results: Media expert validation scored 97.03%, and language experts 90%, indicating high validity. The practicality score was 96.33%. A *t*-test result of 0.001 < 0.005 shows a significant effect after implementation.

Discussion: The STEM-based MIKiR e-modules effectively improve students' critical thinking skills and can be used as innovative and interactive teaching materials.

KEYWORDS

critical thinking, digital era, elementary students, e-module, STEM

1 Introduction

The development of information and communication technology continues to increase with various human needs, including in the field of education. With the onset of the 5.0 era, technology has become an integral part of human life itself (Al Faruqi, 2019; Salgues, 2018; Serpa and Ferreira, 2018). The advancement of technology requires teachers and lecturers to innovate in teaching by using materials that combine computer programs consisting of text, graphics, sound, images, and even animations (Alim et al., 2020b; Hamidi et al., 2011; Kulsum et al., 2019; Wijaya et al., 2021). Education is becoming increasingly important to ensure that learners have the ability to learn, innovate, use technology and information media, work, and survive using life skills (Alim et al., 2020a; Oktaviani et al., 2024; Wijaya et al., 2021).

Despite these technological advances, student achievement in core subjects remains a concern. According to the 2015 Trends in International Mathematics and Science Study (TIMSS) coordinated by The International Evaluation of Education Achievement (IEA), which examines the mathematics abilities of children aged 9–13, Indonesia ranked 44th out of 49 participating countries with an average score of 397 out of 500 (Setiawan et al.,

2022). Meanwhile, in the 2018 Program for International Student Assessment (PISA) study, Indonesia's mathematical literacy and science performance ranked 72nd out of 79 participating countries, with scores of 379 and 396, respectively (Dewi and Ekawati, 2022). In the 2022 PISA science category, Indonesia was ranked 15th (OECD, 2023). This category saw an increase of 6 points from PISA 2018, but it still shows a low rating and needs further improvement efforts.

The findings above indicate the low mathematics and science abilities of Indonesian students. This is caused by several factors, such as students (1) lacking focus and having a tendency to get bored easily during lessons, (2) having low memory retention, (3) lacking confidence to ask questions, (4) having poor critical thinking skills due to poor systematic management, (5) paying insufficient attention to teachers during the delivery of lesson materials, (6) having limited teaching materials in textbooks or text-based learning instead of hands-on learning, (7) experiencing non-contextual learning or failing to connect knowledge with everyday life, (8) having low use of teacher worksheets during the learning process, and (9) using simple worksheets that focus on cognitive problem-solving (Kusumaningpuri et al., 2022; Sukmana, 2018). This leads to students having difficulty solving real-life problems, such as answering questions about the mechanisms of energy changes in a lamp and the energy sources needed to produce electrical energy.

Addressing these issues requires foundational support through curriculum reform. As one of the essential pillars of education, the curriculum has undergone adjustments, including the introduction of the Independent Curriculum in early 2021. It focuses on developing learning outcomes related to learning motivation and demands educators to innovate in designing learning materials to stimulate students' abilities and skills. There needs to be a renewal in learning. Teachers can manifest their creativity and innovation by developing strategies, media, approaches, and materials. Teachers play a crucial role here in providing meaningful learning to students. Teachers are expected to deliver meaningful instruction so that students' abilities can improve in learning (Astuti et al., 2020; Gultom et al., 2020; Metekohy et al., 2022). Many efforts can be made by teachers, one of which is applying media in learning (Iwung and Nugraha, 2022; Mfreke et al., 2020; Ningsih and Sari, 2021; Sibuea et al., 2023).

One effective learning medium is the e-module, which helps students discover concepts that can make learning more meaningful through activities they experience individually or collectively (Eliyasni et al., 2021; Rahmatsyah and Dwiningsih, 2021; Wulandari et al., 2023; Wulandari et al., 2022). This ensures that students acquire knowledge and skills and discover personal learning concepts through recalling facts and events (Firdaus et al., 2022; Firdaus and Wilujeng, 2018). The modules currently used by teachers generally consist of summaries and discussions derived from the curriculum without detailed explanations, thus failing to stimulate students' critical thinking skills and abilities. Therefore, this research develops STEM-based MIKiR e-modules.

The STEM (Science, Technology, Engineering, and Mathematics) approach can make learning more meaningful, guiding students to become more creative and gain hands-on experience (Oktapiani and Hamdu, 2020; Safira et al., 2024). The MIKiR method (Experience, Interaction, Communication, and Reflection) is developed to enable students to act creatively, collaborate in teams, apply critical thinking, and achieve set learning objectives (Widyawati et al., 2024). The integration of MIKiR within STEM-based modules is expected to enhance students' participation and enhance critical thinking skills (Alim et al., 2023; Asmaryadi, 2023; Oktaviah et al., 2023).

Supporting this approach, Yang et al. (2024), it is hoped that through this e-module, students' interest and participation in learning can increase, alongside stimulating their skills, knowledge, and attitudes to think critically in the problem-solving process. Research by Widyawati et al. (2024) revealed that implementing STEM in learning can enhance students' critical thinking skills and motivation. Additionally, research by Safira et al. (2024) showed that STEM implementation can be a potential avenue for educators to improve the quality of education. Overall, this research aims to develop a valid, practical, and effective STEM-based e-module using the MIKiR Model on Energy Sources Material to Enhance Students' Critical Thinking Skills for fourth-grade elementary students.

2 Theoritical background

2.1 STEM education

The STEM (Science, Technology, Engineering, and Mathematics) approach is highly relevant for fostering critical thinking skills, as it places students in learning situations that encourage them to actively analyze, evaluate, and solve problems logically (Yaki, 2022). In STEM-based learning, students are not merely passive recipients of information; rather, they are trained to explore concepts through hands-on activities grounded in real-world problems (Astawan et al., 2023; Morris, 2025). For instance, when studying the topic of "Energy Sources," students are invited to compare various types of energy, assess their advantages and disadvantages, and design simple solutions for utilizing alternative energy sources. This process naturally cultivates critical thinking, as students are required to understand, reason, and make decisions based on evidence and observation.

Moreover, the interdisciplinary nature of STEM helps students develop the habit of connecting concepts across science, technology, engineering, and mathematics in addressing problems (Abdurrahman et al., 2023; Goos et al., 2023; Nugraha et al., 2024). This approach integrates analytical skills through scientific experiments, mathematical logic through calculations and estimations, systematic thinking in engineering and design, and the effective use of technology. These elements collectively form a crucial foundation for critical thinking. According to research by Sukmana (2023), STEM education significantly enhances students' critical thinking skills by providing opportunities to observe, ask questions, test hypotheses, and draw conclusions based on data and logical reasoning. Hence, the relevance of the STEM approach lies in its ability to offer a learning experience that is challenging, meaningful, and reflective qualities essential for cultivating critical thinking from an early age (Elsayary, 2025; Prayogi et al., 2024).

Another study conducted by Hermita et al. (2023a) developed a STEM-based city map application for elementary school students. The findings revealed that the use of the STEM-integrated city map

application led to a significant improvement in students' critical thinking skills. The STEM approach aligns closely with the direction and objectives of both the 2013 Curriculum and the Independent Curriculum, which emphasize the development of higher-order thinking skills (HOTS), particularly critical thinking and problem-solving. In the context of the "Energy Sources" topic, STEM enables students to grasp concepts not only theoretically but also through practical applications such as designing simple tools that utilize alternative energy or conducting observations of energy use in their surroundings. Such learning experiences foster active and reflective student engagement, consistent with the principles of differentiated and contextual learning promoted in the Merdeka Curriculum.

STEM learning combines various disciplines to understand several concepts through an engineering process. This is appropriate for the 2013 curriculum, which is implemented through an integrative and scientific thematic approach. Learning integrates several student-centered subjects to enable the development of various skills. Although STEM learning is very suitable for the 2013 curriculum because its implementation is based on educating students in a real-life context (Nurlenasari et al., 2019), several problems have been described in the educational practice in elementary schools. These include the absence of engineering in the basic curriculum, though problem-solving process activities and innovations exist in science and mathematics learning, alongside the different interpretations of the meaning of technology at the basic level. Other problems are weak skills and confidence of educators in teaching science and mathematics and the teacher's poor science and mathematics studying content during lectures, despite their significance in supporting STEM learning (Blackley and Howell, 2015). Consequently, optimal preparation is needed before teaching by developing project-based STEM learning designs.

Three approaches can be used and adapted for STEM learning in Elementary Schools, namely silo, embedded, and integrated approaches (Roberts and Cantu, 2012). The silo approach refers to isolated instruction within each STEM subject (Dugger, 2010). The embedded approach can be broadly defined as an educational method in which domain knowledge is acquired through an emphasis on real-world situations and problem-solving techniques in social, cultural, and functional contexts (Chen, 2001). Meanwhile, the integrated approach to STEM education envisions removing the barriers between each STEM content area and teaching them as single subjects (Breiner et al., 2012) (Figure 1).

As shown in Figure 2, integration in STEM Education can be implemented through content and context integration. Content integration means preparing a structured STEM education or flexible curriculum that covers more than one discipline. Conversely, context integration refers to focusing on one discipline and teaching meaningfully by selecting relevant contexts from other disciplines without compromising the unique characteristics, depth, and rigor of the main discipline (Cunningham, 2017; Kertil and Gurel, 2016). In the basic Indonesian curriculum, two integration models and three learning approaches are considered STEM learning models.

Recent studies show that STEM education provides various benefits for students. Sungur Gul et al. (2023) found that STEM education can enhance students' skills to meet the demands of the 21st century. Through STEM, students can engage in problem-solving activities that connect prior knowledge and skills with new learning experiences. Parno Supriana et al. (2021) reported that student engagement in STEM learning can facilitate critical thinking in education. Astawan et al. (2023) revealed that using a STEM-based scientific learning model can help students enhance their critical and creative thinking skills. Aâyun et al. (2020) also revealed that through media such as digital books, it is possible to enhance students' creativity and critical thinking abilities in a collaborative environment. Preca et al. (2023) stated that STEM activities can help students acquire important 21st-century skills essential for future success.

Rather than rigidly separating science, technology, engineering, and mathematics, the STEM approach provides an integrated and interactive learning experience (Cunningham, 2017; Hermita et al., 2023b; Kurniati et al., 2021). Project-based activities, experiments, and problem-solving tasks accustom students to think systematically, collaborate effectively, and make decisions grounded in data and logic (Goos et al., 2023; Ridlo et al., 2020). This directly contributes to enhanced reasoning skills, creativity, and scientific communication. Therefore, STEM not only supports the achievement of national curriculum learning outcomes but also serves as a logical and relevant foundation to be integrated with the MIKiR (Experiencing, Interaction, Communication, Reflection) approach, as both emphasize active, exploratory, and meaningful learning processes.

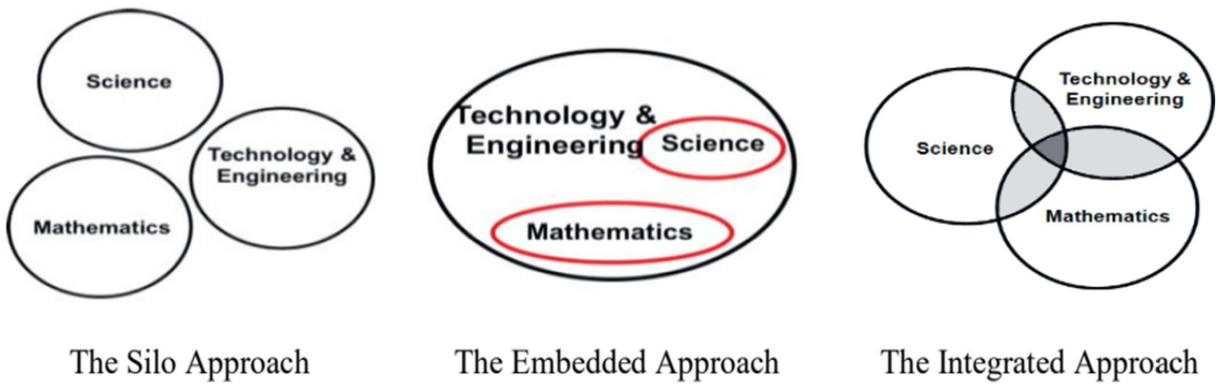

FIGURE 1
Types of STEM education.

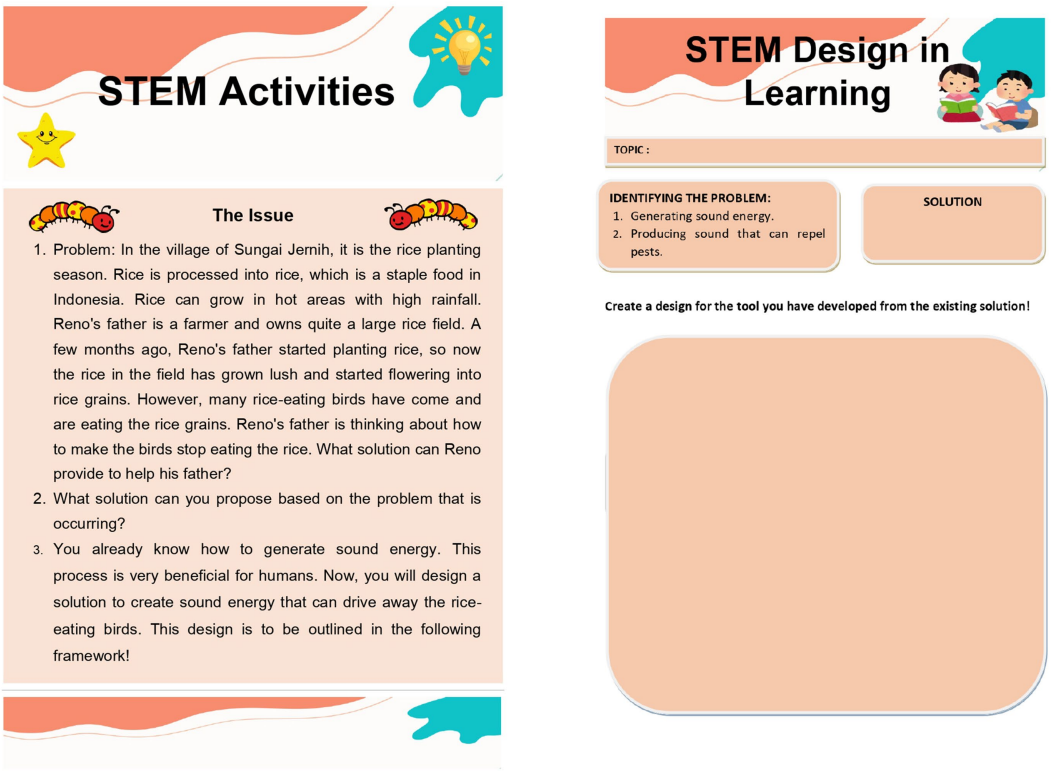

FIGURE 2
STEM activities carried out by students using the e-module.

2.2 MIKiR-based STEM e-module

In 2018, the Tonato Foundation initiated a learning method called MIKiR (Yulisra et al., 2022; Anisah, 2020), which stands for experience, interaction, communication, and reflection. This approach is an example of an active learning model that can develop students' potential and creativity. Concerning the MIKiR method, experience means performing teaching and learning activities. Interaction is a process of exchanging thoughts and ideas between two or more people. Communication is a process of conveying thoughts and ideas from one person to another, while reflection involves repeating learning and drawing conclusions. The use of the MIKiR approach can provide new experiences, such as interesting and fun learning, which will increase students' involvement and promote collaboration. Meanwhile, the students' worksheet measures the extent to which students understand the material taught.

The MIKiR approach an acronym for experiencing, interacting, communicating, and reflecting is an active learning model designed to fully engage students in the learning process (Fatmawati et al., 2021; Martuti, 2023). Each component plays a complementary role in fostering meaningful learning. The *experiencing* phase offers students the opportunity to engage directly in exploratory activities, such as experiments or observations of phenomena, thereby establishing a strong foundation of understanding through firsthand experience. The *interacting* phase encourages collaboration and dialogue among peers and with teachers, reinforcing comprehension through the exchange of ideas. *Communicating* trains students to articulate their thoughts, findings, and questions both orally and in writing. Finally, the *reflecting* phase provides a space for students to critically evaluate their learning process and outcomes, recognize errors, and identify areas for improvement. Together, these four elements promote not only active student engagement but also the development of deep, meaningful learning experiences aligned with 21st-century competencies (Alpusari et al., 2019; Putra et al., 2025).

When combined with the STEM approach, MIKiR offers an ideal pedagogical framework for developing thematic e-modules, particularly on the topic of "Energy Sources" in elementary education. For instance, students may engage in hands-on learning by conducting simple experiments on alternative energy, such as creating windmills from recycled materials. They then collaborate in groups to analyze the efficiency of their models, discuss the challenges encountered, and formulate solutions together. In the communication phase, students present their project outcomes and explain the reasoning behind their designs. Finally, during the reflection phase, they evaluate the effectiveness of their prototypes and relate their learning to environmental issues and real-life energy needs. This integration brings STEM learning to life making it more engaging, practical, and personally meaningful for students.

Furthermore, the MIKiR approach has been shown to support the development of critical thinking skills. The *reflection* component encourages students to evaluate their arguments and thought processes an essential step in critical thinking (Hasnunidah et al., 2020; Indrašienė et al., 2023; Rüütmann, 2019). *Interaction* through discussion familiarizes students with listening actively and constructing logical arguments. *Communication* reinforces the ability to articulate ideas in a coherent and structured manner, while

experiencing provides concrete foundations that foster deeper analysis. Thus, MIKiR not only promotes active learning but also serves as a strategic vehicle for cultivating higher-order thinking skills in a purposeful and measurable way (Alpusari et al., 2019, 2020; Putra et al., 2025).

The integration of the STEM and MIKiR approaches in digital e-module development offers an innovative and contextualized learning model for elementary education. These modules go beyond delivering thematic content such as "Energy Sources" by facilitating experiential learning, collaboration, and reflection. This creates an interactive learning environment that is closely aligned with students' real-life experiences and the principles of the Independent Curriculum (Indonesian Independent Curriculum). As such, the combination of STEM and MIKiR provides a robust logical and pedagogical foundation for designing e-modules that not only achieve learning outcomes but also foster students' critical thinking skills.

Study Alpusari et al. (2020) indicates that integrating the MIKiR model in learning can enhance students' critical thinking abilities. Zulaikhah et al. (2022) informs that through MIKiR-based learning, learning becomes active as students are directly engaged in the learning process. The MIKiR method can create more active learning, this method is also very simple and simple, so it's easy to compile a lesson scenario so that it will not be difficult for teachers to prepare (Ruzaini, 2021). Asmaryadi (2023) reveals that developing STEM learning modules with MIKiR can make learning more interactive. The next Mangangantung et al. (2021) found Through the MIKiR model, it can assist in conceptualizing the material to be taught. Therefore, through the development of STEM modules based on MIKiR, it is expected to make learning more interactive, engage students more actively in learning, thus enhancing students' critical thinking abilities.

3 Method

3.1 Research type

This study is a development research using the Plomp development model. Therefore, this research falls under the category of developmental research design, and the formulated product is the STEAM e-module based on MIKiR. The activities are based on the Plomp model (2013) design with 3 phases: Preliminary Research Analysis, Development or Prototyping, and Assessment. This study employed a Research and Development (R&D) approach using the Plomp development model, which consists of three main phases: preliminary research, development or prototyping, and assessment. In the preliminary research phase, the researcher conducted a literature review on STEM-based learning, the MIKiR approach, and the topic of energy sources within the context of the Independent Curriculum. Additionally, a needs analysis was carried out through interviews with Grade 4 teachers, classroom observations, and a review of the curriculum and student characteristics. This information served as the foundation for designing the content of the e-module. The development phase focused on the creation of a prototype e-module based on the STEM-MIKiR framework, which integrated exploratory and reflective learning activities around the theme of energy sources. The prototype underwent limited testing through expert review, involving subject matter experts, media experts, and educational practitioners to gather feedback on content quality, instructional design, and component integration. The assessment phase involved product effectiveness testing through experimentation, aimed at evaluating the impact of the e-module on students' critical thinking skills.

3.2 Location and research subjects

This research was conducted at SDN 192 Pekanbaru during the academic year 2021/2022 involving fourth-grade students. The development phase took place at the Elementary School Teacher Education Study Program, Faculty of Education, Universitas Riau, and SDN 191 Pekanbaru. This study developed STEAM-based MIKiR e-modules for use with the topic "Transforming Energy" for fourth-grade students. The sampling technique employed in this study was purposive sampling, aimed at selecting elementary schools that have fully implemented the Independent Curriculum and meet a minimum threshold of technological readiness. For the effectiveness trial, students were divided into two groups: an experimental group that used the STEM-MIKiR e-module and a control group that used a conventional module. A total of 60 students participated in the research (Table 1).

3.2.1 Data collection instruments and data analysis techniques

The data collection instruments in this study include validation questionnaires, practicality questionnaires, test questions, and interviews. Data analysis techniques consist of descriptive statistics. Furthermore, to assess the effectiveness of using the e-module in enhancing students' critical thinking, effectiveness tests were conducted using experimental and control groups of fourth-grade students. Details of the data collection can be seen in Table 2.

Data analysis in this study includes product validation tests, practicality tests, and product effectiveness tests. Product validation was determined based on the average score obtained from the validators using the assessment categorization below. The data obtained were analyzed using IBM SPSS Statistics 20. Normality was tested using the Kolmogorov–Smirnov Test, while homogeneity of variance was assessed using Levene's Test. To examine the effectiveness of the e-module on students' critical thinking skills, an independent samples *t*-test was conducted with a significance level of 0.05. The

TABLE 1 Research subjects.

No.	Phases	Respondents	Total respondents
1	Validation	Expert lecturers	2 Expert lecturers
2	*One by One*	Students	3 Students
3	Small group test	Teachers	2 Teachers
		Students	6 Students
4	Large group test	Students	60 Students
Total			73 Respondents

TABLE 2 Data collection instruments.

No.	Data collection tool	Respondents
1	Validation Questionnaire	Media experts
		Subject matter experts
2	Practicality Questionnaire	Teachers
		Students
3	Pretest-posttest Questions	Students
4	Interviews Students	Students

results of these analyses were used to test the research hypothesis and to determine the magnitude of the effect of the STEM MIKiR-based e-module on improving the critical thinking skills of elementary school students (Table 3).

The guidelines for calculating the percentage score of the validation questionnaire are as follows:

$$percentage = \frac{\text{Score Obtained}}{\text{Score maximum}} x\,100\%$$

Criteria for decision-making for the MIKiR-Based STEM E-Modul validation are presented in Table 4.

Data on the effectiveness of the e-module were obtained through the analysis of students' critical thinking and mathematical reasoning test results. The reasoning test consisted of validated essay questions aligned with the instructional content, and student responses were assessed using a standardized scoring rubric. This study employed a Randomized Posttest-Only Control Group Design, a true experimental design in which participants were randomly assigned to either an experimental group or a control group, and only posttest measurements were taken after the intervention. This design was selected because it eliminates the potential for pretest sensitization, which can influence student responses and affect the authenticity of the learning outcomes. By administering only the posttest, the study aimed to capture the pure effect of the intervention.

Randomization was conducted after identifying students who met the inclusion criteria those from elementary schools that had fully implemented the Independent Curriculum and possessed at least the minimum technological readiness. The eligible students were randomly assigned to the experimental or control group using a simple random assignment technique, ensuring that each student had an equal chance of being placed in either group. To ensure group equivalence, initial checks were conducted to compare baseline characteristics of the participants. In addition, tests of normality and homogeneity were performed before hypothesis testing to confirm that the two groups had comparable distributions and variances. This helped ensure that any observed differences in posttest scores could be attributed to the treatment rather than pre-existing group differences. Statistical analysis was carried out using IBM SPSS Statistics 20, with a significance level set at 5% ($\alpha = 0.05$). The analysis aimed to determine whether there was a statistically significant difference in the average critical thinking skills scores between the experimental and control groups (Siregar and Sari, 2020).

TABLE 3 Validation assessment categorization.

Category	Score
Strongly agree	4
Agree	3
Neutral	2
Disagree	1

Source: Arkunto's modification (2014).

TABLE 4 Percentage validation score and category of the teaching materials.

Interval (%)	Category
25–44%	Very invalid
45– 64%	Invalid
65–84%	Valid
85–100%	Very valid

Source: Riduan's modification (Rahayu and Azizah, 2012).

4 Result

4.1 Preliminary phase

Based on interviews with fourth-grade teachers from SDN 192 Pekanbaru and related data, the teaching process begins with delivering the material, followed by providing sample questions and exercises to students. Teachers deliver the material according to the Lesson Plan (RPP) using the educational books provided by the school. This was performed to determine the essential concepts related to the energy source topic that required an explanation namely by identifying and arranging the main concepts systematically. The main concept in the materials was identifying energy sources, conversion mechanisms, and alternative energy producers (wind, water, solar, geothermal, organic fuels, and nuclear).

The stages of the MIKiR-based STEM design will be conducted with learning and understanding of issues related to energy sources. This will be followed by planning for the presented problem. After creating a learning design, students will be directed to prepare tools and materials to create a product. Next, students will construct the planned design. After that, students will develop alternative energy source solutions, and upon completion, they will present the results of their discussions.

The curriculum analysis aims to formulate learning outcomes for the "energy transformation" topic in fourth-grade primary school, determine adequacy in achieving learning objectives, and develop the material effectively. The Student e-module discusses sound and light energy sources by aligning learning objectives within the 2013 curriculum through a combination of learning outcomes from the School as Driver Curriculum.

4.2 Prototyping phase

This evaluation aimed to obtain expert feedback on prototype 2 before its use to produce prototype 3. This stage involved validating the product design using developed teaching materials. A revised product was formulated and validated based on input from the

validator. The validation consisted of two validators with different areas of expertise, namely media experts and linguists. Questionnaires were used as the instrument to validate the MIKiR-based STEM e-module. The results of the expert validation are presented to assess the feasibility of the developed teaching materials, which can be seen in Table 5.

The feasibility assessment of the learning media was conducted by two expert validators, evaluating four main aspects: content, learning, layout, and language. Each aspect was assessed based on specific indicators, and the average percentage score for each was calculated. The results showed that all aspects received scores above 85%, ranging from 93.75 to 100%. According to the assessment criteria, a score range of 85–100% falls within the "very valid" category. Therefore, with an overall average score of 97.03%, the developed media is considered to be very valid and appropriate for use in the learning process.

4.3 Assesment phase

Subsequently, after the media has been assessed by validators and deemed suitable, the next step is to conduct media trials with students. The initial trial is conducted individually to observe how students use the media. If any difficulties in using the media are encountered, adjustments can be made before conducting larger-scale field trials. The individual evaluation stage is also known as One-to-One Evaluation. At this stage, 3 students with low, medium, and high skills were selected and evaluated using a MIKiR-based STEM e-module test for Grade IV class.

Based on the one-by-one trial that has been conducted, it was found that the design in Learning. The individual evaluation indicated that the MIKiR-based STEM e-module was easily understood by students with low, medium, and high skills. Students understood the experiments, answered questions satisfactorily, and appropriately performed activities for discovering alternative sound and light energy sources in the worksheets. The next stage, following the one-by-one media trial, which yielded results indicating that students from the low, moderate, and high score categories can easily use the developed e-module, involves conducting small group trials. Students who were participants in the small group trial were selected from the consideration of students with 2 low, 2 medium, and 2 high scores. A MIKiR-based STEM e-module was tested on a small group of 6 students.

The small group evaluation was divided into two meetings. At the first meeting, students conducted experiments on e-module alongside STEM designs. At the second meeting, they created tools according to their designs. Students were divided into two groups, with each consisting of 3 members with low, medium, and high skills. They were very enthusiastic about the experiments Subsequently, students with low skills experienced little difficulty in the group learning process. They were assisted by those with medium and high skills in answering questions and finding solutions to existing problems regarding the questions on the student worksheets, based on the students' learning outcomes after two sessions, it was found that students, whether from the low, moderate, or high score categories, were all highly interested in using the e-module for learning. The activities carried out by students are as follows.

TABLE 5 Data validation from experts.

No.	Assessment aspect	Average (%)	Category
1	Content	93.75	Very valid
2	Learning	96.87	Very valid
3	Layout	97.5	Very valid
4	Language	100	Very valid
	Average Validation	97.03	Very valid

The use of the STEM-based e-module significantly improved students' understanding and made them more actively engaged in the learning process when studying the topic of energy sources in science. Meanwhile, individual and small group tests were conducted during the test phase. The individual tests were performed to determine the readability of the developed teaching materials, while practical tests were implemented on students and teachers while evaluating the MIKiR-based STEM e-module. Practicality tests were conducted to measure the practicality of the materials using small group tests, which involved 6 students, who were asked to fill out a questionnaire. The results of the practicality test are shown in Table 6.

Based on the results of the practicality test involving 6 students using a 1–4 point Likert scale, the MIKiR-based STEM e-module was found to be very practical. Each aspect instruction, objective, language, graphics, and benefit was assessed through 3 to 5 aspect s and received scores above 90%, with an overall average of 96.33%, placing it in the "very practical" category. These results suggest that the e-module is easy to use, suitable for students' characteristics, and effectively supports the learning process. Therefore, it can be concluded that the e-module meets the practicality criteria based on student responses.

The effectiveness of the MIKiR-based STEM e-module is seen in the results of students' critical thinking tests. Critical thinking was exhibited by students' ability to provide opinions through different answers or strategies. Students learn informal and formal problems, and their variety of answers and opinions indicates an increase in this skill compared to the previous learning model. The effectiveness of the e-module was tested at the State Elementary School of 191 Pekanbaru on Grade IV students in the 2021/2022 academic year. The learning process was performed offline with a limited face-to-face system in order to comply with government regulations and health protocols. The sample consisted of 2 classes, with IV A as the experimental class and IV D as the control. The experimental class will use the MIKiR-based STEM e-module, while the control class only use the thematic student book. A total of 60 students were involved in this research, and the material discussed was alternative energy sources. The material was taught to the experimental and control classes in 4 meetings. Subsequently, the science. The average increase in critical thinking is shown in Table 7.

According to Table 4, the improvement of students' critical thinking with the MIKiR-based STEM e-module was higher than the learning model commonly used by teachers. The prerequisite analysis performed was a normality test, using the Mann–Whitney and Shapiro–Wilk methods. The following table shows the results of the normality test for improving critical thinking outcomes (Table 8).

Values with significance > α indicated normally distributed data. The results of data processing with *Kolmogorov-Smirnov*[a] showed a

TABLE 6 Results of the practicality test on the MIKiR-based STEM e-module by students.

No.	Assessment aspect	Average (%)	Practical category
1	Instruction	100	Very practical
2	Objective	94.16	Very practical
3	Language	95.83	Very practical
4	Graphics	91.66	Very practical
5	Benefit	100	Very practical
Average		96.33	Very practical

significance of 0.227 > 0.05 for the experimental class and 0.324 > 0.05 for the control class. Furthermore, the analysis using *Shapiro–Wilk* showed that the data for both classes were normally distributed (Table 9).

The criterion for homogeneous variance was sig > α. The data processing showed that the significance value obtained was 0.070 > 0.05 for IVB and 0.033 > 0.05 for IVD. Therefore, the variance for the increasing students' mathematical critical thinking aspects was homogeneously distributed. The results of the normality and homogeneity test are shown in Table 10.

Following the normality and the homogeneity tests of variance, the hypotheses were evaluated using *t*-tests through SPSS 19. The results of the *t*-tests for Mathematical Critical Thinking are shown in Table 11.

An independent samples *t*-test was conducted to compare the learning outcomes between the experimental and control classes at Elementary School of 37. The experimental class (Class IV A) had a mean score of 51.80 with a standard deviation of 9.67 and a standard error of 10.76, while the control class (Class IV D) had a mean score of 46.30 with a standard deviation of 4.01 and a standard error of 0.73. The significance value obtained from the *t*-test was 0.001, which is lower than the predetermined alpha level of 0.05. The effect size test using Cohen's d yielded a value of 0.72, which falls into the "large" category. This indicates that the use of the MIKiR-based STEM e-module has a strong influence on students' thinking skills. This result indicates a statistically significant difference between the two groups. Therefore, it can be concluded that the implementation of the MIKiR-based STEM e-module had a significant positive effect on students' learning outcomes compared to conventional teaching methods. This means that the increase in students' Critical Thinking in each class taught using the MIKiR-based STEM e-module for science and Mathematics learning was better than in groups where the worksheet was not used. This proves its effectiveness in increasing students' critical thinking. Figure 2 also highlights the gratification of the effectiveness test for science and mathematics learning to increase students' critical thinking in each sample class. An increase in Mathematical Critical Thinking is displayed in Figure 2.

Figure 3 presents a comparison of the average pretest, posttest, and normalized gain (N-Gain) scores between the experimental class (Class IV A) and the control class (Class IV D), each consisting of 30 students. The experimental class, which utilized a STEM-based e-module integrated with the MIKiR learning model, showed a substantial improvement in learning outcomes. The average pretest score increased from 30 to 90 on the posttest, resulting in an N-Gain score of 0.78, which falls into the high category. In comparison, the control class, which received conventional instruction, also started with an average pretest score of 30, but only improved to 75 on the posttest, with an N-Gain score of 0.63, categorized as moderate. These findings indicate that the use of the MIKiR-based STEM e-module had a more significant impact on enhancing students' understanding and learning outcomes compared to traditional teaching methods.

5 Discussion

The MIKiR-based STEM e-module developed in this study was found to be valid, practical, and effective in enhancing elementary students' critical thinking skills on the topic of Energy Sources. The validity of the e-module was supported by expert evaluations, which yielded an average score in the "very valid" category, particularly in terms of content quality, the integration of STEM and MIKiR components, and alignment with the characteristics of elementary learners. This validity can be theoretically explained through its grounding in a constructivist approach, wherein students actively construct knowledge through exploratory and collaborative activities, as emphasized by the MIKiR model and STEM-based learning principles. Additionally, the structured module design which includes reflection stages at the end of each activity strengthens students' evaluative abilities, a core dimension of critical thinking.

MIKiR is a learning stage where students undergo experiencing, interaction, communication, and reflection (Alpusari et al., 2019, 2020). In the research, students will first experience issues related to various energy sources through in-depth learning activities. This aims to stimulate strong initial interest and understanding of the subject matter. After grasping the fundamentals of energy issues, students will interact with the material through discussions, simulations, or experiments. The goal is to deepen their understanding and foster exchange of ideas among peers. During the Communication phase, students engage in discussions and presentations to articulate their understanding of proposed energy solutions. In the final stage, students will reflect on their learning. This reflection helps students internalize the concepts learned and apply them in real-life contexts. The focus on developing MIKIR-based STEM e-modules as a response to the evolving needs of 21st-century education is a commendable effort. As we navigate the complexities of modern education, it's evident that traditional teaching methods may fall short in fully engaging and preparing students for the challenges they will face in the future (Lopez-Fernandez et al., 2021). Therefore, it is crucial to innovate in learning (Puranik, 2020; Senthilkumar and Kannappa, 2017), whether in terms of teaching methods or the media used. This research rightly recognizes that digital media can be a transformative tool in this context (Bakhri et al., 2023; Mashuri et al., 2022; Qumillaila Lestari et al., 2022). The acknowledgment of digital media digital as a potential facilitator of interactive and engaging learning aligns with the changing landscape of education (Dhivya et al., 2023; Haleem et al., 2022). Today's students are digital natives, growing up in an era where technology is an integral part of their daily lives. Therefore, leveraging digital media in education not only captures their attention but also speaks their language.

It is very necessary for teachers' abilities to create interesting learning in accordance with the 21st century (Artama et al., 2023;

TABLE 7 Average student critical thinking skill.

School	Class	Group type	N	Pretest average	Posttest average	Gain average
Elementary School of 37	IV A	Experimental class	30	53	84	0.78
	IV D	Control class	30	30	75	0.63

N-Gain = (Posttest Score-Pretest Score)/(Maximum Score-Pretest Score).

TABLE 8 Result of normality test of the experimental and control classes.

School	Kolmogorov-Smirnov[a]	Shapiro–Wilk	Comparison with α	Description
Control Class	0.227	0.535	0.05	Normally distributed
Experimental Class	0.324	0.620	0.05	Normally distributed

TABLE 9 Result of analysis of homogeneity of variance of the mathematical critical thinking data with the Levene statistic.

Class	Significance value	Comparison with α	Description
IV A	0.070	0.070 > 0.05	Homogeneous
IV D	0.033	0.070 > 0.05	Homogeneous

TABLE 10 Conclusion of the normality and homogeneity tests of the data variance on the improved mathematical critical thinking.

Class	Normality test	Homogeneity test	Hypothesis test
Experimental	Normally distributed	Homogeneous	*T*-test
Control	Normally distributed		

Inggriyani, 2017; Kim et al., 2019). The research findings revealing the significant potential of the MIKIR-based STEM e-module in enhancing critical thinking skills are promising. Critical thinking is increasingly regarded as a cornerstone skill in the 21st century (Mardhatillah and Anas, 2023; Sari and Wardhani, 2020). With critical thinking it can empowers individuals to analyze information critically, make informed decisions, and adapt to an ever-changing world (Mardhatillah and Anas, 2023). By developing tools that foster critical thinking, educators are contributing to the holistic development of students. The inclusion of validation and practicality testing by educational experts is a crucial step in ensuring the effectiveness of the e-module. Education standards and quality are paramount, and any digital tool introduced into the classroom must align with these standards.

This process acts as a quality assurance mechanism, guaranteeing that the e-module is not only pedagogically sound but also user-friendly. Furthermore, involving experts in the validation process provides a layer of credibility to the research. It substantiates the claim that the developed media is suitable for student use. This, in turn, gives educators confidence in adopting the technology in their teaching. However, it's important to note that while expert validation is a significant step, it represents only one facet of the journey toward effective educational technology. It's equally vital to engage with teachers and students in the development and testing phases. Their feedback and experiences can offer valuable insights into usability, accessibility, and real-world classroom dynamics. In addition to this, a holistic approach to evaluating the impact of the e-module should encompass not only its effects on critical thinking skills but also its broader implications. These might include changes in teaching methodologies, shifts in student engagement, and alterations in the overall learning environment. A comprehensive assessment would provide a more nuanced understanding of the e-module's influence on education.

The research results indicate that MIKIR-based STEM e-modules are effective in enhancing students' critical thinking skills. This holds true for students with various skill levels, ranging from low to high. Critical thinking skills encompass students' ability to analyze information, evaluate arguments, and make evidence-based decisions. The e-module provides a supportive environment to nurture these abilities. This finding aligns with previous research (Iwung and Nugraha, 2022) this research aims to make a webtoon-based e-module on work and energy topics which tested for feasibility, effectiveness and implementation to improve students' critical thinking skills. Based on the research findings, it is concluded that the e-module can enhance students' critical thinking abilities. Furthermore, a study conducted by Uma'iyah et al. (2023), which developed a mobile learning-based e-module, yielded results indicating that through this e-module, it is also possible to enhance students' critical thinking abilities. Thus, it can be concluded that innovation in modules can enhance students' critical thinking abilities (Suastrawan et al., 2021).

In addition to improving critical thinking skills, this e-module also successfully enhances students' interest and participation in learning (Oktarina and Dewi, 2023; Sujanem and Putu Suwindra, 2023). This suggests that interactive digital media can offer a more engaging learning experience for students, subsequently improving their learning outcomes. The research outcomes have significant implications in the field of education, particularly in the context of STEM (Science, Technology, Engineering, and Mathematics) education (Adha et al., 2023; Kurniati et al., 2021). MIKIR-based STEM e-modules can be integrated into the curriculum to enhance students' critical thinking skills. Furthermore, this research provides a foundation for further

TABLE 11 Results of the *T*-tests for the increase in the mathematical critical thinking of students in elementary school of 37 Pekanbaru.

School	Class	Group type	Mean	Std. Error Mean	Std. deviation	Sig. (2-tailed)	Cohen's d
Elementary School of 37	IV A	Experimental class	51.80	10.76	9.67	0.001	0.72
	IV D	Control class	46.30	0.73	4.01		

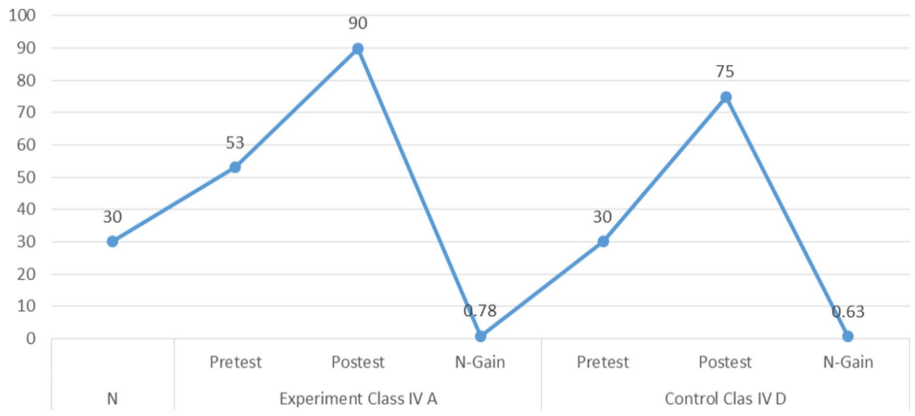

FIGURE 3
Pretest and posttest for experiment class and control class.

studies in the development of digital media for more effective and interactive learning.

6 Conclusion

This study confirms that the STEM-based MIKiR e-module developed for elementary science education is valid, practical, and effective in supporting the development of students' critical thinking skills. The validation results from experts yielded an average score of 97.03%, placing the module in the "very valid" category. Practicality testing involving six students resulted in an average score of 96.33%, classified as "very practical." In terms of effectiveness, the experimental class achieved a normalized gain score of 0.78, which falls into the high category, indicating a significant improvement in learning outcomes compared to the control group. The integration of the MIKiR model (Experiencing, Interaction, Communication, Reflection) within a digital STEM framework represents a innovative contribution to instructional design. This approach not only promotes active, student-centered learning but also aligns with the goals of 21st-century education. The e-module shows strong potential for use in classroom settings, especially in enhancing students' higher-order thinking skills.

Future studies are encouraged to examine the application of this e-module across different subjects and educational levels, as well as to assess its long-term impact on students' cognitive and affective outcomes. Teachers and instructional designers are advised to consider integrating the module into the existing curriculum as a tool to foster critical thinking and inquiry-based learning. Additional research could also focus on improving the module's accessibility, ensuring that it can be effectively utilized in diverse educational contexts and reach a broader range of learners.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by SDN 192 Pekanbaru. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

JA: Conceptualization, Validation, Project administration, Data curation, Formal analysis, Writing – review & editing, Writing – original draft. NH: Data curation, Conceptualization, Formal analysis, Writing – review & editing, Funding acquisition. ZP: Validation, Methodology, Supervision, Writing – review & editing, Project

administration. CO: Methodology, Software, Writing – review & editing, Visualization.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Aâyun, Q., Rusilowati, A., and Lisdiana, L. (2020). Improving students' critical thinking skills through the stem digital book. *J. Innov. Sci. Educ.* 9, 237–243. doi: 10.15294/Jise.V8i3.35260

Abdurrahman, A., Maulina, H., Nurulsari, N., Sukamto, I., Umam, A. N., and Mulyana, K. M. (2023). Impacts of integrating engineering design process into stem makerspace on renewable energy unit to Foster students' system thinking skills. *Heliyon* 9:E15100. doi: 10.1016/J.Heliyon.2023.E15100

Adha, T. Z., Asrizal, A., and Rahim, F. R. (2023). Development of E-module integrated stem approach to improve students' critical and creative thinking skills. *Phys. Learn. Educ.* 1, 62–70. doi: 10.24036/Ple.V1i2.27

Al Faruqi, U. (2019). Future service in industry 5.0. *Jurnal Sistem Cerdas* 2, 67–79. doi: 10.37396/jsc.v2i1.21

Alim, J. A., Fauzan, A., Arwana, I. M., and Musdi, E. (2020a). Model of geometry realistic learning development with interactive multimedia assistance in elementary school. *J. Phys. Conf. Ser.* 1471:012053. doi: 10.1088/1742-6596/1471/1/012053

Alim, J. A., Fauzan, A., Made Arnawa, I., Sari, I. K., and Hermita, N. (2020b). Development of learning flow on two-Dimentional Figure based realistic mathematics education. *Univ. J. Educ. Res.* 8, 3579–3584. doi: 10.13189/Ujer.2020.080834

Alim, J. A., Oktaviani, C., Hermita, N., and Putra, Z. H. (2023). Enchanting math Audiblebook: insights from teachers, university students, and young learners. *Pythagoras Jurnal Pendidikan Matematika* 18, 112–123. doi: 10.21831/Pythagoras.V18i2.65593

Alpusari, M., Mulyani, E. A., Hermita, N., and Putra, E. D. (2020). Improving fourth grade students' critical thinking skills with Mikir approach. *J. Teach. Learn. Elem. Educ.* 3:192. doi: 10.33578/Jtlee.V3i2.7850

Alpusari, M., Mulyani, E. A., Putra, Z. H., Widyanthi, A., and Hermita, N. (2019). Identifying students' scientific communication skills on Vertebrata organs. *J. Phys. Conf. Ser.* 1351:012070. doi: 10.1088/1742-6596/1351/1/012070

Anisah, L. U. (2020). Implementasi Pendekatan Pembelajaran MIKiR dalam Meningkatkan Kegiatan Belajar diKelas IV MI Ma'arif Brangsong Kecamatan Brangsong Kabupaten Kendal. Pendidikan guru madrasah ibtidaiyah fakultas tarbiyah dan ilmu keguruan institut agama islam negeri (iain). (Skripsi Sarjana, Institut Agama Islam Negeri Salatiga). (The implementation of the MIKiR learning approach in improving learning activities in Grade IV at MI Ma'arif Brangsong, Brangsong Sub-district, Kendal Regency (Undergraduate thesis, State Institute for Islamic Studies (IAIN) Salatiga). Fakultas Tarbiyah Dan Ilmu Keguruan, Pendidikan Guru Madrasah Ibtidaiyah.

Artama, K. K. J., Budasi, I. G., and Ratminingsih, N. M. (2023). Promoting the 21st century skills using project-based learning. *Lang. Circ.* 17, 325–332. doi: 10.15294/Lc.V17i2.39096

Asmaryadi, A. I. (2023). Developing science-based modules with MIKiR and literacy learning in the grade V. *PPSDP Int. J. Educ.* 2, 15–26. doi: 10.59175/Pijed.V2i2.104

Astawan, I. G., Suarjana, I. M., Werang, B. R., Asaloei, S. I., Sianturi, M., and Elele, E. C. (2023). Stem-based scientific learning and its impact on students' critical and creative thinking skills: an empirical study. *Jurnal Pendidikan Ipa Indonesia* 12, 482–492. doi: 10.15294/Jpii.V12i3.46882

Astuti, F. N., Suranto, S., and Masykuri, M. (2020). The appropriateness of developing the media: experts' validation and students' response of learning media based on augmented reality technology for natural science lesson. *J. Phys. Conf. Ser.* 1567:042023. doi: 10.1088/1742-6596/1567/4/042023

Bakhri, S., Tsuroya, N. H., and Pratama, Y. (2023). Development of learning media with Quickappninja android-based (guess image & amp; find words) to increase elementary school teachers' digital literacy. *Jurnal Penelitian Pendidikan Ipa* 9, 4879–4884. doi: 10.29303/Jppipa.V9i7.3574

Blackley, S., and Howell, J. (2015). A stem narrative: 15 years in the making. *Aust. J. Teach. Educ.* 40:8. doi: 10.14221/ajte.2015v40n7.8

Breiner, J. M., Harkness, S. S., Johnson, C. C., and Koehler, C. M. (2012). What is stem? A discussion about conceptions of stem in education and partnerships. *Sch. Sci. Math.* 112, 3–11. doi: 10.1111/j.1949-8594.2011.00109.x

Chen, M. (2001). A potential limitation of embedded-teaching for formal learning. Proceedings of the Twenty-Third Annual Conference of the Cognitive Science Society, eScolarship University of California. 194–199.

Cunningham, C. M. (2017). Engineering in elementary stem education: Curriculum design, instruction, learning, and assessment. Amsterdam: Teachers College Press.

Dewi, D. L., and Ekawati, R. (2022). Students' numeracy skills in solving the fourth level of minimum competency assessment question development on ratio and proportion. *Mathedunesa* 11, 278–286. doi: 10.26740/Mathedunesa.V11n1.P278-286

Dhivya, D. S., Hariharasudan, A., and Nawaz, N. (2023). Unleashing potential: multimedia learning and education 4.0 in learning professional English communication. Cogent. *Soc. Sci.* 9:2248751. doi: 10.1080/23311886.2023.2248751

Dugger, W. E. (2010). Evolution of stem in the United States. The 6th Biennial International Conference on Technology Education Research'nda Sunulmuş Bildiri, Gold Coast, Queensland, Australia: Griffith Institute for Educational Research.

Eliyasni, R., Habibi, M., Rahmatina, and Azima, N. F. (2021). E-module flipbook model for designing E-learning materials in higher education. Proceedings of the 2nd Progress in Social Science, Humanities And Education Research Symposium. Atlantis Press. doi: 10.2991/Assehr.K.210618.004

Elsayary, A. (2025). Enhancing teachers' design thinking mindsets through reflective practice: cultivating innovation in an upskilling Steam training program. *EURASIA J. Math. Sci. Technol. Educ.* 21:Em2600. doi: 10.29333/Ejmste/16048

Fatmawati, K., Siregar, N., Mukminin, A., Anwary, A., Ikhtiati, and Azim, P. (2021). Online learning based on the Mikir approach during the Covid 19 pandemic at Mis Muhajirin Jambi City. *J. Phys. Conf. Ser.* 1842:012015. doi: 10.1088/1742-6596/1842/1/012015

Firdaus, F. M., Afianti, D., Cahya, R., and Septianingtias, A. (2022). The use of macromedia flash application in improving the mathematical understanding of elementary school students. *Jurnal Prima Edukasia* 10, 114–122. doi: 10.21831/Jpe.V10i2.47427

Firdaus, M., and Wilujeng, I. (2018). Development of guided inquiry learning modules to improve critical thinking skills and student learning outcomes. *Jurnal Inovasi Pendidikan Ipa* 4, 26–40. doi: 10.21831/Jipi.V4i1.5574

Goos, M., Carreira, S., and Namukasa, I. K. (2023). Mathematics and interdisciplinary stem education: recent developments and future directions. *ZDM Math. Educ.* 55, 1199–1217. doi: 10.1007/S11858-023-01533-Z

Gultom, S., Hutauruk, A. F., and Ginting, A. M. (2020). Teaching skills of teacher in increasing student learning interest. *Bp. Int. Res. Critic. Inst.* 3, 1564–1569. doi: 10.33258/Birci.V3i3.1086

Haleem, A., Javaid, M., Qadri, M. A., and Suman, R. (2022). Understanding the role of digital technologies in education: a review. *Sustain. Oper. Comput.* 3, 275–285. doi: 10.1016/J.Susoc.2022.05.004

Hamidi, F., Kharamideh, Z. M., and Ghorbandordinejad, F. (2011). Comparison of the training effects of interactive multimedia (Cds) and non-interactive media (films) on increasing learning speed, accuracy and memorization in biological science course. *Procedia Comput. Sci.* 3, 144–148. doi: 10.1016/j.procs.2010.12.025

Hasnunidah, N., Susilo, H., Irawati, M., and Suwono, H. (2020). The contribution of argumentation and critical thinking skills on students' concept understanding in different learning models. *J. Univ. Teach. Learn. Pract.* 17, 1–13. doi: 10.53761/1.17.1.6

Hermita, N., Alim, J. A., Putra, Z. H., Nasien, D., and Wijoyo, H. (2023a). Developing stem autonomous Learning City map application to improve critical thinking skills of primary school teacher education students. *Int. Sci. Electron. J.* 64, 675–690. doi: 10.32744/pse.2023.4.41

Hermita, N., Alim, J. A., Putra, Z. H., Putra, R. A., Anggoro, S., and Aryani, N. (2023b). The effect of stem autonomous Learning City map application on students' critical thinking skills. *Int. J. Interact. Mob. Technol.* 17, 87–101. doi: 10.3991/ijim.v17i03.34587

Indrašienė, V., Jegelevičienė, V., Merfeldaitė, O., Penkauskienė, D., Pivorienė, J., Railienė, A., et al. (2023). Critical reflection in students' critical thinking teaching and learning experiences. *Sustainability* 15:13500. doi: 10.3390/Su151813500

Inggriyani, F. (2017). Soft skills for 21st century teacher. International Coferences: Character Building Through Pricesly International Education. FKIP Unpas. 143–147.

Iwung, K., and Nugraha, A. (2022). Development of Webtoon-based physics E-modules in work and energy topics on students' critical thinking skills. *J. Teach. Learn. Phys.* 7, 62–71. doi: 10.15575/Jotalp.V7i1.14286

Kertil, M., and Gurel, C. (2016). Mathematical modeling: a bridge to stem education. *Int. J. Educ. Math. Sci. Technol.* 4, 44–55. doi: 10.18404/ijemst.95761

Kim, S., Raza, M., and Seidman, E. (2019). Improving 21st-century teaching skills: the key to effective 21st-century learners. *Res. Comp. Int. Educ.* 14, 99–117. doi: 10.1177/1745499919829214

Kulsum, S. I., Wijaya, T. T., Hidayat, W., and Kumala, J. (2019). Analysis on high school students' mathematical creative thinking skills on the topic of sets. *Jurnal Cendekia* 3, 431–436. doi: 10.31004/cendekia.v3i2.128

Kurniati, R. D., Andra, D., and Wayan Distrik, I. (2021). E-module development based on Pbl integrated stem assisted by social media to improve critical thinking skill: a preliminary study. *J. Phys. Conf. Ser.* 1796:012077. doi: 10.1088/1742-6596/1796/1/012077

Kusumaningpuri, A. R., Murtiyasa, B., Fuadi, D., and Hidayati, M. (2022). Analysis of mathematical difficulties in statistics topics among elementary school students. *Jurnal Basicedu* 6, 933–942. doi: 10.31004/Basicedu.V6i1.2058

Lopez-Fernandez, D., Gordillo, A., Alarcon, P. P., and Tovar, E. (2021). Comparing traditional teaching and game-based learning using teacher-authored games on computer science education. *IEEE Trans. Educ.* 64, 367–373. doi: 10.1109/Te.2021.3057849

Mangangantung, J. M., Wijaya, T. T., Putra, R. A., and Hermita, N. (2021). Pre-service elementary teachers' mental model on heat transfer concept as the effect of applying Cdoi model integrated Mikir approach. *Al-Ishlah Jurnal Pendidikan* 13, 1868–1876. doi: 10.35445/Alishlah.V13i3.823

Mardhatillah, S., and Anas, N. (2023). The influence of crossword puzzle science learning media toward students' critical thinking ability. *Prisma Sains* 11:791. doi: 10.33394/J-Ps.V11i3.8372

Martuti, U. (2023). Mikir learning with go "Adik Simba" for Indonesian language education. 2nd International Conference on Early Childhood Education in Multiperspective. Program Studi Pendidikan Islam Anak Usia Dini UINSAIZU.

Mashuri, S., Rosmayanti, and Jaiz, D. A. (2022). Implementation of the Classdojo platform as E-learning media at the Khalifah Islamic elementary school Palu. *Paedagogia* 11, 197–210. doi: 10.24239/Pdg.Vol11.Iss2.325

Metekohy, L. M., Daliman, M., Metekohy, B., and Ming, D. (2022). The impact of teaching and learning quality process to school and university education for sustainable future. *Jurnal Penelitian Pendidikan Indonesia* 8:143. doi: 10.29210/020221203

Mfreke, U. J., Ismail, S., and Isong, M. B. (2020). Teaching and learning with media technology. *Int. J. Innov. Eng. Res. Technol.* 7, 296–300.

Morris, D. L. (2025). Rethinking science education practices: shifting from investigation-centric to comprehensive inquiry-based instruction. *Educ. Sci.* 15:73. doi: 10.3390/Educsci15010073

Ningsih, P. E. A., and Sari, M. N. (2021). Are learning media effective in English online learning?: the students' and teachers' perceptions. *Tarbawi* 17, 173–183. doi: 10.32939/Tarbawi.V17i2.1012

Nugraha, M. G., Kidman, G., and Tan, H. (2024). Interdisciplinary stem education foundational concepts: implementation for knowledge creation. *EURASIA J. Math. Sci. Technol. Educ.* 20:Em2523. doi: 10.29333/Ejmste/15471

Nurlenasari, N., Lidinillah, D. A. M., Nugraha, A., and Hamdu, G. (2019). Assessing 21st century skills of fourth-grade student in stem learning. *J. Phys. Conf. Ser.* 1318:012058. doi: 10.1088/1742-6596/1318/1/012058

OECD. (2023). PISA 2022 results (volume II): Learning during–and from–disruption. Ii. Organisation for Economic Co-operation and Development. doi: 10.1787/A97db61c-En

Oktapiani, N., and Hamdu, G. (2020). Desain Pembelajaran Stem Berdasarkan Kemampuan 4c Di Sekolah Dasar. *Jurnal Ilmiah Pendidikan Dasar* 7:99. doi: 10.30659/Pendas.7.2.99-108

Oktarina, R., and Dewi, S. M. (2023). Project-based learning (Pjbl) model in E-module as an improvement of critical thinking in the department of cosmetology and beauty. *Indones. J. Comput. Sci.* 12. doi: 10.33022/Ijcs.V12i4.3264

Oktaviah, F. N., Dwiyanti, A., Suyadi, and Barumbun, M. (2023). Integrated stem-based teaching modules with the values of Pancasila student profiles in supporting the implementation of Kurikulum Merdeka in primary school. *Jurnal Ilmiah Sekolah Dasar* 7, 469–480. doi: 10.23887/Jisd.V7i3.57198

Oktaviani, C., Herwin, H., Adiwardana, M. R., Fianto, Z. A., and Dahlan, S. C. (2024). Harmonizing math and culture: exploring Ethnomathematics in Malay culture through children's storybooks. *J. Innov. Educ. Cult. Res.* 5, 229–237. doi: 10.46843/Jiecr.V5i2.1155

Parno Supriana, E., Widarti, A. N., and Ali, M. (2021). The effectiveness of stem approach on students' critical thinking ability in the topic of fluid statics. *J. Phys. Conf. Ser.* 1882:012150. doi: 10.1088/1742-6596/1882/1/012150

Prayogi, S., Bilad, M. R., Verawati, N. N. S. P., and Asy'ari, M. (2024). Inquiry vs. inquiry-creative: emphasizing critical thinking skills of prospective stem teachers in the context of stem learning in Indonesia. *Educ. Sci.* 14:593. doi: 10.3390/Educsci14060593

Preca, C. B., Baldacchino, L., Briguglio, M., and Mangion, M. (2023). Are stem students creative thinkers? *J. Intelligence* 11:106. doi: 10.3390/Jintelligence11060106

Puranik, S. (2020). Innovative teaching methods in higher education. *BSSS J. Educ.* 9, 67–75. doi: 10.51767/Je0907

Putra, D., Walid, A., Susanti, T., and Asari, A. (2025). Development of Mikir E-module through service-learning community based research. *Jurnal Penelitian Pendidikan Ipa* 11, 545–563. doi: 10.29303/Jppipa.V11i3.10448

Qumillaila Lestari, A. P., Kuboki, Y., and Hasim, F. (2022). Developing an E-flipbook on environmental education to promote digital literacy among elementary school students and teachers in rural areas in Indonesia. 2022 International Conference on ICT for Smart Society (ICISS), IEEE. 1–6. doi: 10.1109/Iciss55894.2022.9915108

Rahmatsyah, S. W., and Dwiningsih, K. (2021). Development of interactive E-module on the periodic system materials as an online learning media. *Jurnal Penelitian Pendidikan Ipa* 7, 255–261. doi: 10.29303/Jppipa.V7i2.582

Rahayu, D., and Azizah, U. (2012). Pengembangan Instrumen Penilaian Berbasis Komputer Dengan Kombinasi Permanan "Who Wants To Be a Cheimist" pada Materi Pokok Struktur Atom Untuk Kelas X SMA RSBI. (Development of a computer-based assessment instrument using the game "Who Wants to Be a Chemist" on the topic of atomic structure for Grade X RSBI). *Prosding Seminar Nasional Kimia Unesa*, 5, 41–50.

Ridlo, Z. R., Nuha, U., Terra, I. W. A., and Afafa, L. (2020). The implementation of project-based learning in stem activity (water filtration system) in improving creative thinking skill. *J. Phys. Conf. Ser.* 1563:012073. doi: 10.1088/1742-6596/1563/1/012073

Roberts, A., and Cantu, D. (2012). Applying Stem Instructional Strategies To Design And Technology Curriculum. Patt 26 Conference; Technology Education in the 21st Century; Stockholm; Sweden; 26–30 June; 2012, 073, 111–118.

Rüütmann, T. (2019). Development of Critical Thinking and Reflection. In: Auer, M., Tsiatsos, T. (eds) The Challenges of the Digital Transformation in Education. ICL 2018. Advances in Intelligent Systems and Computing, vol 917. Springer, Cham. 895–906. doi: 10.1007/978-3-030-11935-5_85

Ruzaini, R. (2021). An evaluation of Mikir learning in English subject. *Kaisa* 1, 1–11. doi: 10.56633/kaisa.v1i1.185

Safira, I., Dewanto, S., Solissa, E. M., and Yastanti, U. (2024). Asseessing the efficacy of Interdiciplinary Curiculum model in stem education: a review. *Indones. J. Eng. Educ. Technol.* 2, 237–245. doi: 10.61991/Ijeet.V2i2.44

Salgues, B. (2018). Society 5.0: Industry of the future, technologies, methods and tools. London: John Wiley & Sons.

Sari, D. M. M., and Wardhani, A. K. (2020). Critical thinking as learning and innovation skill in the 21st century. *J. Engl. Lang. Pedagog.* 3, 27–34. doi: 10.36597/Jelp.V3i2.8778

Senthilkumar, V., and Kannappa, D. R. (2017). Impact of innovative teaching and learning methodologies for higher educational institutions with reference to Trichirappalli District. *IOSR J. Bus. Manag.* 19, 88–92. doi: 10.9790/487x-1907028892

Serpa, S., and Ferreira, C. (2018). Society 5.0 And Social Development: Contributions To A Discussion.

Setiawan, A. A., Muhtadi, A., and Hukom, J. (2022). Blended learning and student mathematics ability in Indonesia: a Meta-analysis study. *Int. J. Instr.* 15, 905–916. doi: 10.29333/Iji.2022.15249a

Sibuea, R., Nasution, S., and Rambe, R. N. (2023). Teacher creativity in making learning media in min 3 Medan City. *Literasi Nusantara* 3, 95–107. doi: 10.56480/Jln.V3i3.866

Siregar, E. F. S., and Sari, S. P. (2020). Optimizing the Mikir approach as a solution for 21st century learning for teachers at Muhammadiyah elementary school, Medan City. *Dinamisia* 4, 550–556. doi: 10.31849/Dinamisia.V4i3.4376

Suastrawan, K. E., Suardana, I. N., and Sudiatmika, A. A. I. A. R. (2021). The effectiveness of science E-modules for class vii junior high schools based on Socioscientific issues to improve students' critical thinking skills. *J. Sci. Educ. Res.* 5, 1–9. doi: 10.21831/Jser.V5i2.42877

Sujanem, R., and Putu Suwindra, I. N. (2023). Problem-based interactive physics E-module in physics learning through blended Pbl to enhance students' critical thinking skills. *Jurnal Pendidikan Ipa Indonesia* 12, 135–145. doi: 10.15294/Jpii.V12i1.39971

Sukmana, R. W. (2018). Implementasi Pendekatan STEM (Science, Technology, Engineering and Mathematics) untuk Meningkatkan Keterampilan Berpikir Kritis Siswa di Sekolah Dasar. (Implementation of the STEM (Science, Technology, Engineering, and Mathematics) approach to improve elementary school students' critical thinking skills). *Primaria Educationem Journal*, 1.

Sukmana, R. (2023). Active learning using the stem approach improves critical thinking skills of elementary school students. International Conference On Elementary Education. Available online at: Https://Proceedings.Upi.Edu/Index.Php/Icee/Article/View/3169 (Accessed September 10, 2022).

Sungur Gul, K., Saylan Kirmizigul, A., Ates, H., and Garzon, J. (2023). Advantages and challenges of stem education in K-12: systematic review and research synthesis. *Int. J. Res. Educ. Sci.* 9, 283–307. doi: 10.46328/Ijres.3127

Uma'iyah, N., Wahyuni, S., and Nuha, U. (2023). Development of E-modules based on Mobile learning applications to improve students' critical thinking skills in science subject. *Jurnal Penelitian Pendidikan Sains* 12, 122–137. doi: 10.26740/Jpps.V12n2.P122-137

Widyawati, A., Kuswanto, H., and Suyanto, S. (2024). STEM learning model's impact on enhancing critical thinking skills and motivation: a literature review. *International Journal Of Religion* 5, 200–204. doi: 10.61707/Kc4x8954

Wijaya, T. T., Li, L., Hermita, N., Putra, Z. H., and Alim, J. A. (2021). Helping junior high school student to learn Fibonacci sequence with video-based learning. *Int. J. Interact. Mob. Technol.* 15:183. doi: 10.3991/ijim.v15i11.23097

Wulandari, D., Risdianto, E., and Setiawan, I. (2022). Development of E-module materials of quantities and units using Canva to increase students' interest in learning. *Jentik* 1, 25–34. doi: 10.58723/Jentik.V1i1.27

Wulandari, A. P., Salsabila, A. A., Cahyani, K., Nurazizah, T. S., and Ulfiah, Z. (2023). Pentingnya Media Pembelajaran Dalam Proses Belajar Mengajar. *J. Educ.* 5, 3928–3936. doi: 10.31004/Joe.V5i2.1074

Yaki, A. A. (2022). Fostering critical thinking skills using integrated stem approach among secondary school biology students. *Eur. J. STEM Educ.* 7, 1–10. doi: 10.20897/Ejsteme/12481

Yang, C., Zhang, J., Hu, Y., Yang, X., Chen, M., Shan, M., et al. (2024). The impact of virtual reality on practical skills for students in science and engineering education: a Meta-analysis. *Int. J. STEM Educ.* 11:28. doi: 10.1186/S40594-024-00487-2

Yulisra, E., Alim, J. A., Noviana, E., Hermita, N., Wijaya, T. T., Putra, Z. H., et al. (2022). The development of students worksheet stem based on Mikir. *Aksioma* 11, 38–47. doi: 10.24127/Ajpm.V11i1.4412

Zulaikhah, Z., Hidayati, A., and Fauziyah, R. (2022). The effectiveness of Mikir approach in mentoring program for lecturers during the Covid-19 pandemic. *Nadwa* 16, 33–50. doi: 10.21580/Nw.2022.16.1.13448