e-ISSN : 3090-5354
Vol. 2, No.2, August 2026

Deep Learning-Based Digital Physics Comics for Fostering Critical Thinking in Alternative Energy Education

Nur Lailatul Ilmiah*, Muhammad Satriawan

State University of Surabaya, Surabaya, Indonesia

DOI : https://doi.org/10.26740/jdpe.2.2.55938

Sections Info

Article history:
Submitted: April 10, 2026
Final Revised: August 01, 2026
Accepted: August 10, 2026
Published: August 27, 2026

Keywords:
Alternative Energy;
Critical Thinking Skills;
Deep Learning;
Digital Physics Comics.

ABSTRACT

Objective: *This study aimed to develop a Deep Learning-based Digital Physics Comic on alternative energy to improve senior high school students' critical thinking skills.* ***Method:*** *This Research and Development (R&D) study adopted the ADDIE model, including analysis, design, development, implementation, and evaluation. The product was implemented with Grade X students at a senior high school in Sidoarjo, Indonesia, during the 2025/2026 academic year using a non-equivalent control group pretest–posttest design. Data were collected through expert validation sheets, learning implementation observations, critical thinking tests, and student response questionnaires. The media was evaluated for validity, practicality, and effectiveness.* ***Results:*** *The Digital Physics Comic achieved a validity score of 89.31% (very valid) and a learning implementation score of 91.67% (very practical). Student responses indicated high effectiveness (90.35%). The experimental class obtained a higher average N-Gain score (0.7332) than the control class (0.6209). The Mann–Whitney test showed a significant difference between the groups ($p = 0.007 < 0.05$), with the greatest improvement found in the inference indicator.* ***Novelty:*** *This study integrates a deep learning approach and Problem-Based Learning (PBL) into a digital physics comic on alternative energy. The media combines meaningful, mindful, and joyful learning through contextual stories, visual narratives, and problem-solving activities, offering an innovative approach to strengthening students' conceptual understanding and critical thinking skills in physics..*

INTRODUCTION

Critical thinking is one of the most essential competencies in 21st-century education because it enables students to analyze information, evaluate evidence, solve complex problems, and make reasoned decisions in rapidly changing scientific and technological environments (Khoiriyah & Suprapto, 2021). Among the various 21st-century skills, critical thinking is particularly important in physics learning because students are expected not only to understand scientific concepts but also to interpret physical phenomena, evaluate alternative explanations, and apply scientific reasoning to solve contextual problems. These competencies are fundamental for developing Higher Order Thinking Skills (HOTS), which have become a major objective of contemporary science education (Khoiriyah & Suprapto, 2021).

Despite its importance, empirical evidence consistently indicates that Indonesian high school students still demonstrate relatively low levels of critical thinking. The 2022 Program for International Student Assessment (PISA) reported that Indonesia achieved a science literacy score of only 396, substantially below the international average of 489, reflecting students' limited ability to analyze and reason scientifically. Previous studies further confirm this condition. Azrai et al. (2020) reported that among 167 senior high school students, 59% were classified as having low critical thinking skills, only 2%

reached the high category, and the average score was 45 (Azrai et al., 2020). Likewise, Nurhayati et al. (2022) found that 125 Grade XI students demonstrated low critical thinking performance, with interpretation skills reaching only 20%, while analysis and inference each achieved approximately 40% (Nurhayati et al., 2022). Similarly, Azis et al. (2025) reported that most Grade XII students from accredited senior high schools in Timika were categorized as having very low critical thinking skills. In contrast, Irmayanti et al. (2025) found that students from several senior high schools in Gowa obtained an average critical thinking score of only 7.47, indicating a low category (Azis et al., 2025; Irmayanti et al., 2025).

A preliminary study conducted at one SMA in Sidoarjo also revealed similar findings. Based on Ennis' five critical thinking indicators: elementary clarification, basic support, inference, advanced clarification, and strategy and tactics, most students were categorized as below average or poor. The weakest performances were found in advanced clarification, where 50% of students were categorized as poor, and strategy and tactics, where 73% were classified as poor. In contrast, no students achieved the superior category. These findings indicate that students still experience considerable difficulties in constructing logical arguments, providing evidence-based explanations, drawing valid conclusions, and designing systematic problem-solving strategies.

These conditions are largely attributed to teacher-centered instructional practices, limited use of innovative learning media, and the abstract nature of physics concepts, which often hinder students from actively constructing knowledge and engaging in higher-order thinking (Habiddin et al., 2022; Safiah et al., 2025). Alternative energy is a physics topic that particularly requires critical thinking because students must analyze real-world issues related to renewable energy resources, environmental sustainability, and technological applications. Nevertheless, previous studies show that students still struggle to understand renewable energy concepts because of their complexity and the lack of contextual learning resources (Azairok et al., 2023; Chairunnisya et al., 2023).

Digital learning media provide an opportunity to improve physics learning by presenting abstract concepts through engaging visualizations and contextual narratives. Digital comics, in particular, integrate illustrations and storytelling to transform complex physics concepts into more meaningful learning experiences while increasing students' motivation, conceptual understanding, and classroom engagement (Apriani et al., 2025; Damayanti & Kuswanto, 2020; Widyawati et al., 2024). Meanwhile, the deep learning approach emphasizes meaningful, mindful, and joyful learning through active exploration, reflection, collaboration, and authentic problem solving, thereby creating conditions that foster deeper conceptual understanding and critical thinking (Royani et al., 2024; Warman et al., 2025). This approach aligns well with Problem-Based Learning (PBL), which encourages students to identify problems, evaluate evidence, discuss alternative solutions, and formulate logical conclusions (Suhirman & Khotimah, 2020; Wardani & Fiorintina, 2023).

However, existing studies have generally investigated digital comics and deep learning independently. Most digital comic research emphasizes learning motivation,

conceptual understanding, or learning outcomes, whereas studies specifically examining their contribution to critical thinking development in physics remain limited (Lintangesukmanjaya et al., 2025). Likewise, research on deep learning has primarily focused on meaningful learning experiences without integrating contextual digital comics into physics instruction. Furthermore, few studies have combined contextual visual narratives, deep learning principles, Problem-Based Learning, and critical thinking indicators within a single instructional medium, particularly for alternative energy topics (Rosdiana & Kholiq, 2021).

Therefore, this study addresses this research gap by developing a Deep Learning-based Digital Physics Comic integrated with Problem-Based Learning for alternative energy instruction. The novelty of this study lies in integrating meaningful, mindful, and joyful learning principles, contextual visual storytelling, structured problem-solving activities, and critical thinking indicators into a single digital learning medium. Accordingly, this study aims to develop a Deep Learning-based Digital Physics Comic that is valid, practical, and effective in improving senior high school students' critical thinking skills. This study is expected to provide physics teachers with an innovative, contextual digital learning medium that supports student-centered learning, facilitates students' engagement in analyzing and solving real-world problems, and strengthens critical thinking skills in alternative energy education. More broadly, the developed medium is expected to contribute to diversifying physics learning resources that integrate Deep Learning principles and Problem-Based Learning in accordance with the demands of 21st-century education..

RESEARCH METHOD

This study employs a Research and Development (R&D) approach to develop and test the effectiveness of a product (Sugiyono, 2015). The development process follows the ADDIE model, which consists of five stages: analysis, design, development, implementation, and evaluation (Rustandi & Rismayanti, 2021). This study followed the procedure below.

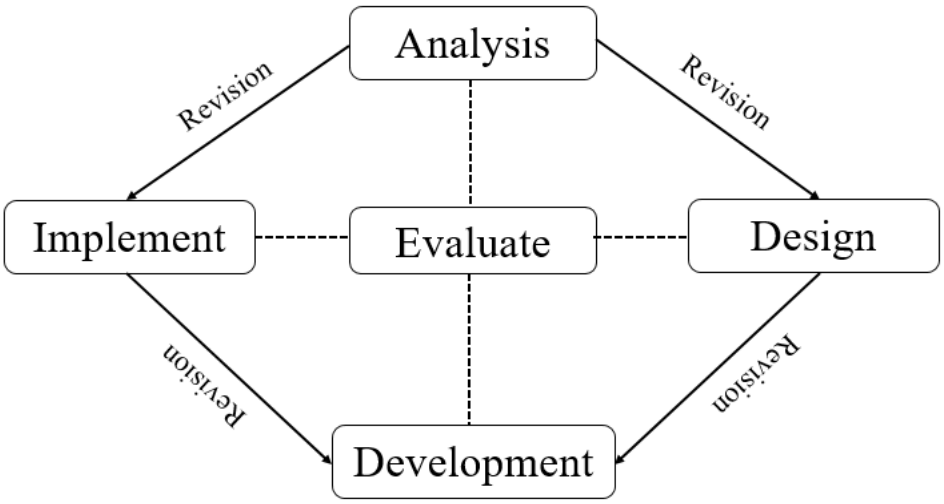

Figure 1. The ADDIE development phases (Branch, 2009)

This study was conducted at a high school in Sidoarjo, East Java, Indonesia, during the 2025–2026 school year. The developed product was a digital physics comic integrated with a deep learning approach, focusing on alternative energy. The research subjects were 72 tenth-grade students selected from two full classes. The sample was selected using purposive sampling, a technique for determining and collecting samples based on specific considerations (Subhaktiyasa, 2024). One class was designated as the experimental group and learned using the developed medium, while the other class served as the control group and received conventional instruction. The effectiveness was tested using a non-equivalent control group pretest-posttest design.

Data were collected using several instruments, including media validation sheets, lesson implementation observation sheets, critical thinking skills tests, and student response questionnaires. The validation sheets assessed the quality of the media in terms of content, design, language, and instructional aspects. The observation sheets evaluated the implementation of learning activities, while the student response questionnaires were distributed to determine the usefulness of the developed media. Critical thinking skills were measured using pretest and posttest instruments based on Ennis's critical thinking indicators: elementary clarification, basic support, inference, advanced clarification, and strategy and tactics.

The collected data were analyzed using descriptive quantitative techniques. This analysis determined the validity, practicality, and effectiveness of the Digital Physics Comics in enhancing students' critical thinking skills. The medium's validity was determined based on expert assessment and test results. The validation results were calculated as percentages using Equation (1) and interpreted using the validity criteria outlined by Riduwan (2015) in Table 1 below.

$$P\ (\%) = \frac{Total\ score\ for\ data\ collection}{Criteria\ Score} \times 100\% \qquad (1)$$

Table 1. Criteria for Interpreting Validity Scores

Percentage	Categories
0% - 20%	Invalid
21% - 40%	Somewhat Invalid
41% - 60%	Fairly Valid
61% - 80%	Valid
81% - 100%	Very Valid

A reliability analysis was also conducted to determine whether all aspects of the critical thinking skills test instrument used for data collection were reliable. In this study, Cronbach's alpha was used to test the instrument's reliability; it does not yield scores of 1 or 0 and was calculated using SPSS. The table below shows the criteria for Cronbach's alpha ranges, according to Arikunto (2006).

Table 2. Reliability test range

Range Alpha Cronbach's	Reliability Results
$\propto \geq 0,8$	Very High
$0,6 \leq \propto \leq 0,799$	High
$0,4 \leq \propto \leq 0,599$	Moderate
$0,2 \leq \propto \leq 0,399$	Low
$\propto < 0,2$	Very Low

Data collection was conducted over three learning sessions. In the first session, a pretest was administered to assess students' initial understanding of alternative energy in the experimental and control classes. The pretest consisted of five essay questions designed based on critical thinking indicators. After the pretest, students were instructed to bring their cell phones or tablets to the second session, as the experimental class would be using digital physics comics as a learning medium. During the second session, students in the experimental class were divided into 8 groups of 4–5 students each to analyze the digital physics comics. Worksheets and teacher instructions were provided to guide students if they encountered difficulties. During this session, an observer monitored the lesson implementation to assess the practicality of using digital physics comics as a teaching medium. The results of the lesson implementation were calculated as a percentage using Equation (1) and interpreted according to the practicality criteria outlined by Riduwan (2015) in Table 3 below.

Table 3. Criteria for interpreting practicality scores

Percentage	Categories
0% - 20%	Not Practical
21% - 40%	Not Very Practical
41% - 60%	Fairly Practical
61% - 80%	Practical
81% - 100%	Very Practical

In the final session, students took a posttest to assess their learning outcomes and improvements in critical thinking skills. This measured the effectiveness of the digital physics comic as a teaching medium. These improvements were analyzed using normalized gain (N-Gain) based on the criteria (Hake, 1998) in Equation (2) and interpreted according to Table 4.

$$\langle N - Gain \rangle = \frac{(\langle Post \rangle - \langle Pre \rangle)}{(100 - Pre)} \quad (2)$$

Table 4. Criteria for Interpreting N-Gain Scores

N-Gain Score	Category
$g < 0,3$	Low
$0,7 > g \geq 0,3$	Moderate
$g \geq 0,7$	High

In addition, statistical tests were conducted to compare the two groups. These tests were performed after assessing normality and homogeneity. This study used the nonparametric Mann-Whitney test, an alternative to the independent-samples t-test when the data do not meet the assumption of normality. If the significance value is less than 0.05, there is a significant difference between the two groups; if it is greater than 0.05, there is no significant difference (MacFarland & Yates, 2016). Furthermore, the students' questionnaire responses were analyzed to determine the effectiveness of the media used. The scores obtained were converted to percentages according to Equation (1) and then interpreted using the questionnaire response criteria outlined by Riduwan (2015) in Table 5.

Table 5. Criteria for interpreting survey responses

Score	Evaluation Criteria
4	Strongly Agree
3	Agree
2	Disagree
1	Strongly Disagree

RESULTS AND DISCUSSION

Results

Analysis

The analysis phase involved a literature review and an analysis of learning needs at a high school in Sidoarjo, East Java. Observations and interviews with teachers indicated that physics instruction is still dominated by lectures, discussions, and problem-solving exercises, while the use of interactive digital media remains very limited. This situation has led students to show little interest in the subject and to struggle to understand abstract physics concepts. Therefore, there is a need for learning media that is more innovative, engaging, and capable of increasing student engagement in the learning process.

In addition to the media needs analysis, the curriculum used at the school was also analyzed, specifically the Merdeka Curriculum for the Physics Phase E course for 10th-grade students. Based on the learning outcomes that emphasize problem-solving skills and responding to global issues, alternative energy was selected as the focus for media development. This analysis served as the basis for designing a Digital Physics Comic using a deep learning approach that supports contextual learning while facilitating the development of students' critical thinking skills.

Design

The design phase was based on the needs analysis results and involved developing learning materials, a digital physics comic, and research instruments. The developed product is a digital physics comic that uses a deep learning approach to alternative energy topics and is integrated with the Problem-Based Learning (PBL) model. The

design process includes formulating learning objectives in accordance with the Merdeka Curriculum, developing learning activities focused on critical thinking skills, and creating instructional modules, worksheets, assessment instruments, validation instruments, learning implementation instruments, and student response questionnaires. All components are designed to support active, contextual, and student-centered learning.

Next, the visual design of the media was carried out through the creation of storyboards, storylines, characters, illustrations, and comic layouts tailored to the alternative energy material and the principles of meaningful learning, mindful learning, and joyful learning. The comic characters were created using 3D animation to represent teachers and students, while the illustrations and dialogues were designed to facilitate problem analysis and contextual problem-solving. Produk kemudian disusun menggunakan Canva dan dikonversi menjadi buku digital interaktif melalui Heyzine. Hasil evaluasi desain oleh dosen pembimbing menunjukkan bahwa rancangan media telah sesuai dengan tujuan pembelajaran, karakteristik peserta didik, serta indikator keterampilan berpikir kritis, dengan beberapa penyempurnaan pada alur penyajian dan tampilan media sebelum memasuki tahap pengembangan.

Development

The development phase includes creating, revising, validating, and refining the product. At this stage, the Digital Physics Comic was developed from a previously designed storyboard and supplemented with learning resources, including teaching modules and worksheets. Throughout the development process, regular consultations and reviews were conducted with the supervising instructor to refine the content, storyline, dialogue, and visual presentation so that they align with the learning objectives and are easily understood by students.

After the initial product was developed, revisions were made based on feedback from the supervising lecturer, focusing on refining the dialogue, clarifying the storyline, and ensuring the accurate presentation of physics concepts to prevent misconceptions. The revisions resulted in a Digital Physics Comic that is more communicative, systematic, and tailored to students' characteristics. The final product consists of a Digital Physics Comic, teaching modules, and worksheets that are integrated to support learning about alternative energy. The following is an image from a digital physics comic in Figure 2.

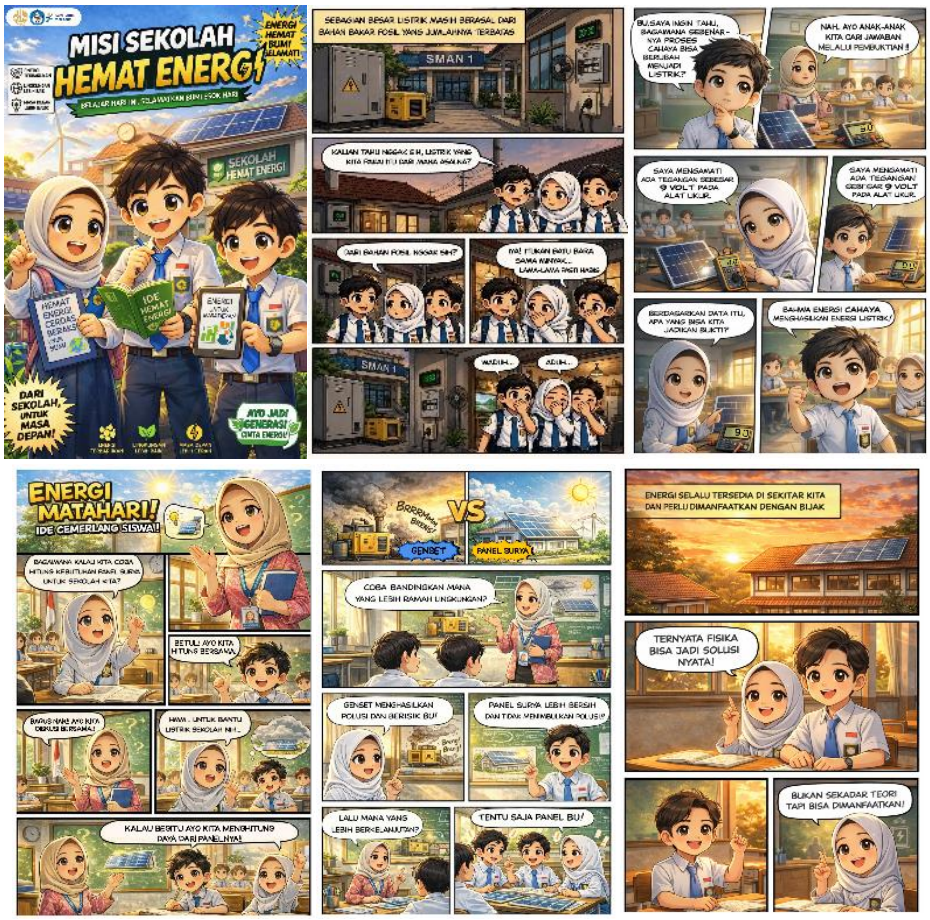

Figure 2. Digital physics comics

The next step is validation by two faculty experts in physics education and one physics teacher to evaluate the media, content, language, teaching materials, and research instruments. Below is a visualization of the validation results in Figure.

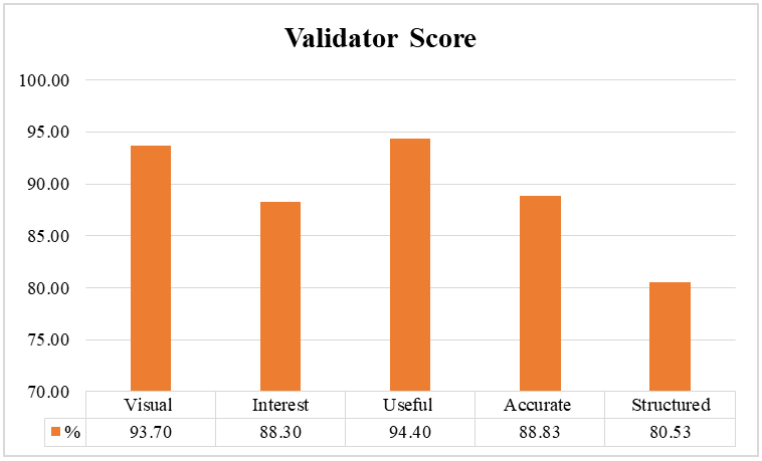

Figure 3. Graph of media validity results

The validation results show that the media achieved a validity percentage of 89.31%, placing it in the "highly valid" category. In comparison, the content and language validation scored 88.26% and 91.67%, respectively, also in the "highly valid" category. In addition, the learning tools and research instruments were also classified as "highly valid," with scores ranging from 88.89% to 91.67%. These results indicate that the media and learning tools developed have met the criteria for suitability for use in learning.

In addition to expert validation, a reliability test was conducted on the test instruments using Cronbach's Alpha. The instrument's reliability test results, analyzed using IBM SPSS Statistics, showed a Cronbach's Alpha value of 0.800. The test was conducted on five items administered to 36 student respondents. The Cronbach's Alpha value obtained indicates that the test instrument has a very high level of reliability, making it suitable for use in research.

Based on these validation and reliability results, the Digital Physics Comics and accompanying learning tools were deemed suitable for use after several refinements were made in accordance with the validators' suggestions. The final revisions focused on visual improvements, linguistic consistency, content accuracy, and learning structure to make the resulting media more effective in supporting physics learning and the development of students' critical thinking skills.

Implementation

The implementation phase took place at a high school in Sidoarjo, East Java, using a quasi-experimental design with two sample classes: Class X1 as the experimental class and Class X2 as the control class. Before instruction began, both classes took a pretest to measure their initial critical thinking skills, followed by a posttest after the learning process was completed. The experimental class used the Digital Physics Comics medium integrated with the Problem-Based Learning (PBL) model, while the control class participated in PBL instruction without the digital comics medium.

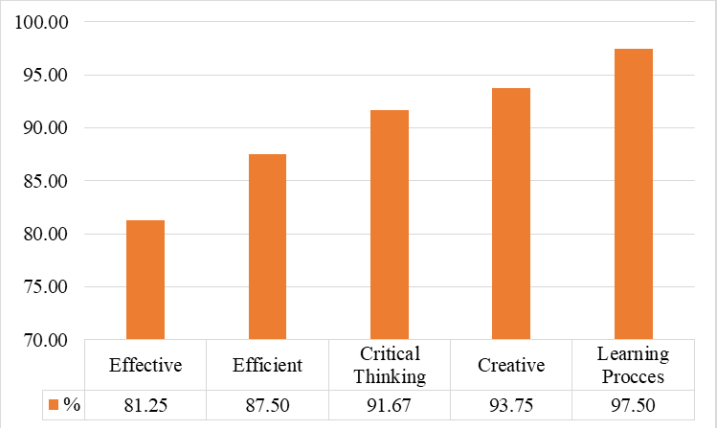

Figure 4. Graph of observation results on the implementation of instruction

The observations show that the Digital Physics Comics medium is highly practical, with a learning implementation rate of 91.67%. The learning process aspect received the highest final score, with an average of 97.5% and a rating of "highly valid," indicating that each phase of the learning activities was carried out effectively using Digital Physics Comics. The critical thinking skills test results showed improvement in both classes, but the experimental class improved more than the control class. Graph of average pretest and posttest scores in Figure 5.

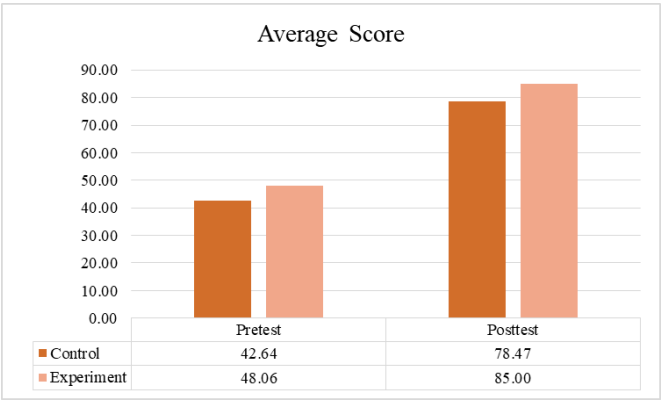

Figure 5. Graph of average pretest and posttest scores

Table 6. N-Gain score results

Class		N-Gain	Std. Error
Experiment	Mean	0.7332	0.02246
Control	Mean	0.6209	0.02798

The average pretest and posttest scores for the experimental class increased from 48.05 to 85.00, while those for the control class increased from 42.64 to 78.47. The N-Gain test results also showed that the experimental class achieved an average score of 0.7332, falling into the high category. In contrast, the control class achieved a score of 0.6209, falling into the moderate category. In addition to the overall N-Gain score, improvement in critical thinking skills can also be analyzed based on the learning outcomes of the experimental and control classes.

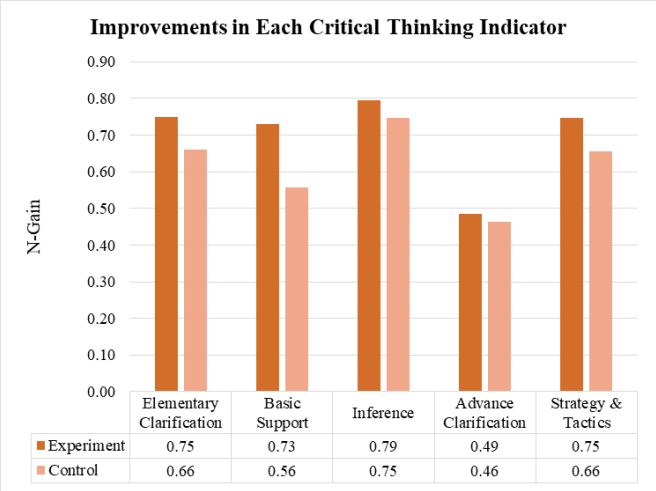

Figure 6. Graph showing the increase in n-gain for each critical thinking skill indicator

The experimental class also showed greater improvement in critical thinking skills across all measured indicators, particularly the inference indicator. However, compared to the other indicators, the advanced clarification indicator had the lowest score. The effectiveness of the medium was supported by the results of the Mann–Whitney test, which yielded a significance value of 0.007 (< 0.05), indicating a significant difference between the improvement in critical thinking skills in the experimental class and the control class. These results show that using Digital Physics Comics with a deep learning approach effectively improves students' critical thinking skills regarding alternative energy. Figure 7 below illustrates the graph of student survey results.

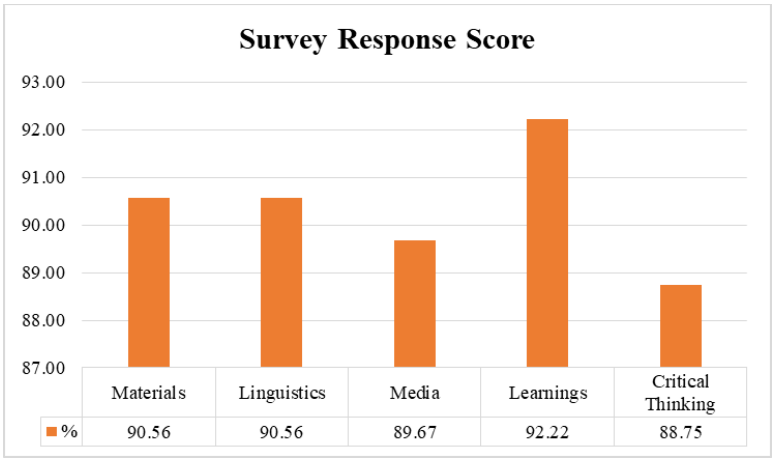

Figure 7. Graph of student survey results

In addition, students responded very positively to the use of the media, with an average response rate of 90.35%, indicating that they found it engaging, easy to use, and helpful in understanding the material on alternative energy. During the implementation, students were also more active in discussing, asking questions, and analyzing the problems presented in the comics, making the learning process more interactive and student-centered.

Evaluation

The evaluation phase assessed the feasibility, practicality, and effectiveness of the Digital Physics Comics media and its supporting tools following the analysis, design, development, and implementation phases. The evaluation results show that the developed medium is valid based on expert assessment, practical based on learning outcomes and positive student responses, and effective in improving critical thinking skills. The medium's effectiveness is demonstrated by improved learning outcomes with an N-Gain score in the moderate to high range, as well as Mann–Whitney test results showing a significant difference between the experimental and control classes. Overall, applying the ADDIE model produced a Digital Physics Comic with a deep learning approach that meets learning needs, is easy to use, and can enhance students' critical thinking skills on alternative energy topics, making it a viable alternative learning medium for high school physics.

Discussion

Validity

The validation results show that all evaluation aspects of the Digital Physics Comics medium were categorized as "highly valid," with a final score of 89.31%. The "useful" aspect received the highest score at 94.40%, followed by the "visual" aspect at 93.70%, "accurate" at 88.83%, "interesting" at 88.30%, and "structured" at 80.53%. These results indicate that the developed media meets the criteria for suitability in physics instruction on alternative energy.

The "usefulness" aspect received the highest percentage because the developed media was assessed as capable of providing tangible benefits in supporting the learning process. Digital comics not only convey information but also help students understand the abstract concept of alternative energy through illustrations, storylines, and contextual problem examples (Khasanah et al., 2019). Furthermore, integrating a deep learning approach enables students to actively engage in the learning process through activities such as observing, analyzing, and reflecting on the information presented (Mulyani et al., 2025). These factors contribute to the medium's high utility value in supporting the achievement of learning objectives while simultaneously developing students' critical thinking skills.

Meanwhile, the "structured" aspect received the lowest percentage (80.53%), although it still falls within the "highly valid" category. These results indicate that, overall, the flow of the material and the narrative are well organized, but some sections still require refinement. Several validators provided feedback on transitions between subtopics, the connection between scenes, and the placement of key information, which could be organized more systematically. This is likely due to the effort to integrate narrative elements, physics concepts, and critical thinking activities into a single medium, resulting in sections that require a more coherent flow so that students can follow the learning process more easily and in a more focused manner (Rendi et al., 2020; Sembiring & Waruwu, 2020).

Practicality

The implementation results were obtained from observations of the learning process conducted to determine the practicality of using Digital Physics Comics. Two observers conducted the observations and assessed effectiveness, efficiency, critical thinking skills, creativity, and the learning process. The classroom observation results indicated that Digital Physics Comics achieved a practicality percentage of 91.67%, falling into the "highly practical" category. These results demonstrate that the medium can be effectively used in the learning process and can support students' learning activities in an effective, efficient, and focused manner.

Based on the practicality graph, all aspects were categorized as "highly practical," with percentages ranging from 81.25% to 97.50%. The learning process aspect received the highest score (97.50%), indicating that digital comics effectively support a systematic, interactive, and student-centered learning process. This aligns with PBL theory, which emphasizes learning through active and collaborative problem-investigation processes so that students are more engaged in constructing their own knowledge (Arrul et al., 2024). Observers assessed that all stages of learning were carried out very well and in accordance with the designed learning syntax. This is consistent with the theory proposed by Harista (2021), which states that the primary purpose of using instructional media is to help educators convey material more clearly and in a way that is easier to understand.

Meanwhile, the "effectiveness" aspect received the lowest score (81.25%), although it still fell within the "highly practical" category. Observers assessed that the Digital Physics Comics help teachers explain alternative energy concepts more easily through contextual illustrations and dialogues, enabling students to understand the connection between physics concepts and real-life problems. This finding aligns with Pangestu & Rahmi (2022), who argue that instructional media clarify the presentation of material, enhance learning effectiveness, and facilitate students' understanding. Furthermore, digital comics can make abstract physics concepts more tangible and engaging through contextual learning (Khoiriyah & Suprapto, 2021). Nevertheless, some students still require teacher guidance to understand certain parts of the storyline, so teacher support remains necessary to ensure full understanding.

The high scores in critical thinking (91.67%) and creativity (93.75%) indicate that presenting contextual problems in comics encourages students to discuss and analyze problems and actively develop solutions. Furthermore, the efficiency score of 87.50% indicates that the medium is easily accessible and usable via digital devices, thereby supporting flexible learning. During the learning process, students also showed great enthusiasm for using digital comics. The storyline, engaging illustrations, and the material's relevance to daily life encouraged students to ask questions, discuss, and engage more actively in the learning process. These findings suggest that Digital Physics Comics are not only practical but also capable of creating an engaging and meaningful learning experience for students.

Effectiveness

The effectiveness of digital physics comics based on a deep learning approach was evaluated based on the improvement in students' critical thinking skills after participating in lessons on alternative energy. The effectiveness analysis was conducted by comparing pretest and posttest results, calculating N-Gain scores, analyzing improvements in each critical thinking indicator, testing for differences between the experimental and control classes, and analyzing student response survey results. The results of this analysis were used to determine the extent to which the developed medium was able to improve students' critical thinking skills compared to conventional learning.

1. Improvement in Test Scores

The improvement in students' critical thinking test scores was analyzed by comparing pretest and posttest scores in the experimental and control classes. This analysis aimed to determine the effect of using deep learning-based digital physics comics on the improvement of students' critical thinking skills regarding alternative energy. The results of the comparison of average scores and the N-Gain calculation were used to assess the level of improvement that occurred after the learning process.

Based on the average score graph, both classes showed improvement after the instruction. However, the improvement in the experimental class was greater than that in the control class. The experimental class's average posttest score showed a larger increase from the pretest score compared to the control class, which used conventional instruction. These results indicate that the use of deep learning-based digital physics comics can help students better understand the concept of alternative energy and support the development of critical thinking skills during the learning process. This aligns with the view expressed by (Slamet et al., 2025), who emphasize the learning aspects of deep learning so that students not only memorize concepts but are also able to connect knowledge to real-life contexts and use it to analyze and solve problems. Furthermore, the use of digital comics as a visual and narrative medium allows students to understand abstract physics concepts in a more concrete and engaging way, thereby enhancing their engagement in learning and their critical thinking skills (Khoiriyah & Suprapto, 2021).

Furthermore, the N-Gain calculations showed that the experimental class achieved a higher improvement score than the control class. This difference indicates that learning using Digital Physics Comics contributes more effectively to improving students' critical thinking skills. This improvement is supported by the presentation of contextual material through storylines, illustrations, and problems closely related to daily life, which encourages students to be more active in analyzing information, engaging in discussions, and finding solutions to the problems presented (Khasanah et al., 2019). Thus, the developed medium has proven capable of facilitating a more meaningful learning process compared to learning that focuses solely on the conventional delivery of material.

2. Analysis Based on Critical Thinking Indicators

To determine the impact of the media in greater detail, an analysis was conducted on each critical thinking skill indicator, including elementary clarification, basic support, inference, advanced clarification, and strategy and tactics. This analysis aimed to identify the indicators that showed the greatest improvement after students used the deep learning-based Digital Physics Comics.

Based on the graph showing the improvement in critical thinking indicators, the experimental class demonstrated higher N-Gain values than the control class across all indicators. These results indicate that the use of deep learning-based Digital Physics Comics and Problem-Based Learning (PBL) is more effective in improving students' critical thinking skills than conventional learning. Presenting material through stories, illustrations, and contextual problems helps students understand the concept of alternative energy while training them to think more deeply.

The graph shows that the Inference indicator achieved the highest improvement in the experimental class, with an N-Gain value of 0.79. These results indicate that students are better able to draw conclusions based on the information and concepts they have learned. This finding aligns with the theory of critical thinking according to (Ennis, 1985), which states that the ability to draw conclusions is an essential part of the rational and reflective thinking process. This is supported by problem-based learning activities that encourage students to analyze phenomena, discuss solutions, and draw conclusions independently. Furthermore, the visualizations in the comics help students understand the relationship between physics concepts and problems encountered in daily life. This aligns with the view of (Khasanah et al., 2019) that digital comics can help students understand abstract physics concepts through more concrete visual representations and narratives.

Meanwhile, the Advanced Clarification indicator showed the smallest improvement in both classes, although the experimental class still performed better than the control class. These findings suggest that the ability to provide advanced explanations and make more complex connections between concepts still requires ongoing practice. According to (Reynders et al., 2020), higher-order critical thinking skills require a consistent practice process through in-depth analysis and reflection activities. Nevertheless, improvements across all indicators suggest that the developed media are capable of supporting various aspects of critical thinking skills, ranging from identifying problems, using evidence and reasoning, drawing conclusions, to systematically determining problem-solving strategies. However, it not only improves students' learning outcomes but also contributes to a more comprehensive enhancement of critical thinking skills. This is evident from the consistent improvement across all indicators, which shows that students are more active in analyzing, evaluating, and solving problems during the learning process.

3. Results of the Class Comparison Test

After obtaining data on the improvement in learning outcomes for both classes, a comparison test was conducted to determine whether there was a significant difference

between the experimental class and the control class. This analysis was used to confirm that the observed improvement in critical thinking skills was attributable to the use of deep learning-based digital physics comics. The test used in this analysis was the Mann-Whitney test, with a sample size of 72 students, consisting of 36 students in the experimental class and 36 students in the control class.

The results of the Mann–Whitney test showed an Asymp. Sig. (2-tailed) value of 0.007 (< 0.05), indicating a significant difference between the experimental class and the control class. These results indicate that the improvement in students' critical thinking skills in the class that used the Digital Physics Comics was greater than in the class that followed conventional instruction. Thus, the use of the developed medium had a positive effect on the improvement of students' critical thinking skills.

This improvement is supported by the presentation of contextual material through illustrations, storylines, and problem-solving activities integrated into the deep learning and Problem-Based Learning (PBL) approaches. This aligns with the view (Hutauruk & Rosana, 2025) that the application of the Problem-Based Learning model also supports students in actively investigating and solving problems systematically. Through this learning process, students are encouraged to analyze information, engage in discussions, and formulate solutions to the problems presented. This aligns with the view (Sudrajat, 2020) that deep learning is characterized by students' active cognitive, affective, and social engagement in the learning process. These findings indicate that Digital Physics Comics are an effective learning medium for teaching alternative energy to support the development of students' critical thinking skills.

4. Student Response Questionnaire

In addition to being measured through test results, the effectiveness of the medium was also assessed based on student responses after using the Digital Physics Comics in the learning process. A response questionnaire was administered to determine the students' level of acceptance regarding the content, language, medium, learning process, and critical thinking in supporting the learning process. Based on the survey results, the Digital Physics Comics received a rating of 90.35%, falling into the "highly effective" category. These results indicate that the developed media was very well received by students and effectively supported the physics learning process regarding alternative energy topics. The high response rate indicates that the medium not only helps students understand the material but also enhances their comfort and engagement during the learning process. These results align with the view that visually appealing and interactive learning media can increase students' attention, motivation, and active engagement during the learning process (Aziz et al., 2022).

Based on the student response chart, all aspects were rated as "very effective," with percentages ranging from 88.75% to 92.22%. The learning aspect received the highest score (92.22%), indicating that the use of digital comics can create a more active, engaging, and student-centered learning experience. Learning that takes place through discussion and problem exploration also supports the creation of joyful learning and mindful

learning within the deep learning approach, as students are actively engaged, mindful, and comfortable throughout the learning process (Mulyani et al., 2025).

Meanwhile, the critical thinking aspect received the lowest score (88.75%), although it still fell within the "very effective" category. These results indicate that the media has helped students analyze problems and find solutions; however, critical thinking skills still require ongoing practice through various learning activities. This finding aligns with the view (Ennis, 1985) that critical thinking is a rational and reflective thinking process focused on making decisions based on adequate reasoning and evidence.

The high scores in the areas of content, language, and media indicate that students found the content easy to understand, the language used to be communicative, and the comic's presentation engaging for learning. This aligns with the finding that using media with language appropriate to students' characteristics facilitates their understanding of the material (Utami et al., 2020). During the learning process, students also demonstrated high enthusiasm for the use of digital comics. The storyline, illustrations, and contextual problems presented were able to spark curiosity, encourage discussion, and make students more active in the learning process. These findings reinforce the notion that Digital Physics Comics are not only effective in improving conceptual understanding but are also capable of creating a more engaging and meaningful learning experience.

CONCLUSION

Fundamental Finding : This study successfully developed a deep learning-based digital physics comic on alternative energy that meets the criteria of validity, practicality, and effectiveness for use in high school physics instruction. The developed medium achieved a validity score of 89.31% (highly valid), a practicality score of 91.67% (highly practical), and an effectiveness score based on the average N -Gain in the experimental class of 0.7332, which was higher than that of the control class at 0.6209; the Mann–Whitney test results indicated a significant difference between the two classes; and student response at 90.35% (highly effective). Additionally, the use of this medium was proven to significantly improve students' critical thinking skills. All critical thinking skill indicators showed improvement, with the inference indicator showing the highest increase. **Implication:** The results of the study show that integrating deep learning and Problem-Based Learning (PBL) into digital comics can create a more meaningful, reflective, and enjoyable learning experience. Presenting material through illustrations, contextual narratives, and problem-solving activities helps students understand the concept of alternative energy while developing critical thinking skills. Therefore, this medium has the potential to serve as an innovative alternative for physics teachers in supporting student-centered learning and strengthening 21st-century skills. **Limitation:** This study has several limitations. First, the instructional materials were implemented in only one school with a limited sample size, so the generalizability of the study's findings must be approached with caution. Second, the development of the instructional materials focused on alternative energy topics, so their effectiveness for other physics topics remains unknown. Third, the study measured only the short-term impact of the instructional

materials on critical thinking skills during the learning process, without examining the long-term sustainability of these skill improvements. **Future Research:** Future research is recommended to implement the Digital Physics Comics with a larger and more diverse sample size to enhance the generalizability of the research findings. Additionally, the development of this educational medium could be expanded to cover other physics topics and incorporate more complex interactive features, such as virtual simulations, adaptive quizzes, or artificial intelligence technology. Future research could also examine the impact of this medium on other 21st-century skills, such as creativity, digital literacy, problem-solving, and collaboration, as well as evaluate its long-term effectiveness.

AUTHOR CONTRIBUTIONS

Nur Lailatul Ilmiah contributed to the conceptual framework, research design, and validation process; **Muhammad Satriawan** was involved in methodology development, data analysis, sourcing references, and drafting the manuscript. All listed authors have reviewed and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as supporting tools during the research and writing process of this article. Specifically, ChatGPT was used to assist in improving sentence structure, refining the clarity and coherence of the academic writing, and supporting the organization of ideas. Consensus was utilized to assist in identifying and searching for relevant scientific articles and academic sources related to the research topic. DeepL was used to assist with the translation of text between Indonesian and English and to improve the linguistic accuracy of the translated content. All outputs generated or assisted by these digital tools were critically evaluated, verified against relevant academic sources, and revised by the authors to ensure accuracy, originality, academic rigor, and adherence to ethical standards. The use of these tools did not replace the authors' scholarly judgment, analysis, or interpretation. The authors retain full responsibility for the content, accuracy, originality, and final version of the manuscript.

REFERENCES

Apriani, S. P., Supriyatin, S., & Rusdi, R. (2025). Development of digital comics SIPROMAN to improve students' criticaltthinking and creative thinking skills. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, *11*(1), 237–252. https://doi.org/10.22219/jpbi.v11i1.39563

Arikunto, S. (2006). Prosedur penelitian suatu pendekatan praktik. Edisi Revisi VI. *Rineka*

Cipta.

Arrul, A. H., Yuliani, F., & Gusmaneli. (2024). Penerapan model pembelajaran problem based learning dalam membentuk konsep berpikir peserta didik. *La-Tahzan: Jurnal Pendidikan Islam*, *16*(1), 13–27. https://10.62490/latahzan.v16i1.414

Azairok, M., Sriyanti, I., & Wiyono, K. (2023). Analysis of needs for e-modules based problem based learning on renewable energy materials to improve creative thinking skills of SMA Negeri 1 Namang students. *Jurnal Geliga Sains: Jurnal Pendidikan Fisika*, *11*(1), 27. https://jp.ejournal.unri.ac.id/index.php/jgs/id/article/view/928

Azis, A. N. A., Haris, A., & Usman. (2025). Keterampilan berpikir kritis peserta didik dalam pembelajaran fisika di SMA Timika. *Jurnal Sains Dan Pendidikan Fisika (JSPF)*, *21*(2), 193–202. https://doi.org/10.35580/jspf.v21i2.7490

Aziz, R. R., Degeng, I. N. S., & Soepriyanto, Y. (2022). Pengembangan media video podcast pada pembelajaran sejarah kelas xi materi pendudukan bangsa Jepang di Indonesia. *JKTP: Jural Kajian Teknologi Pendidikan*, *5*(3), 265–273. https://doi.org/10.17977/um038v5i32022p265

Azrai, E. P., Suryanada, A., Wulaningsih, R. D., & Sumiyati, U. K. (2020). Kemampuan berpikir kritis dan literasi sains siswa sma di Jakarta Timur. *Jurnal Edusains*, *12*(1), 89–97. https://doi.org/10.15408/es.v12i1.13671

Branch, R. M. (2009). *Instructional design: The ADDIE approach*. Springer. https://doi.org/10.1007/978-0-387-09506-6

Chairunnisya, S., Abdurrahman, Distrik, I. W., Herlina, K., Rosidin, U., & Rabbani, G. F. (2023). Engineering design process (EDP) strategy integrated pjbl-stem in learning program: need analysis to stimulate numeracy literacy skills on renewable energy topic. *Jurnal Penelitian Pendidikan IPA*, *9*(12), 11197–11206. https://doi.org/10.29303/jppipa.v9i12.6088

Damayanti, A. E., & Kuswanto, H. (2020). The use of android-assisted comics to enhance students' critical thinking skill. *Journal of Physics: Conference Series*, *1440*(1), 1–7. https://doi.org/10.1088/1742-6596/1440/1/012039

Ennis, R. H. (1985). A logical basis for measuring critical thinking skills. E*ducational Leadership.*

Habiddin, H., Ashar, M., Hamdan, A., & Nasir, K. R. (2022). Digital comic media for teaching secondary school science. *International Journal of Interactive Mobile Technologies*, *16*(3), 159–166. https://doi.org/10.3991/IJIM.V16I03.28967

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American journal of Physics*, *66*(1), 64-74. https://doi.org/10.1119/1.18809

Harista, E. (2021). Penggunaan media pembelajaran bahasa indonesia untuk anak berkebutuhan khusus di sekolah menengah pertama luar biasa (SMPLB) Negeri Sepulau Bangka. *SIirok Bastra*, *9*(1), 1–14. https://doi.org/10.37671/sb.v9i1.271

Hutauruk, N. E., & Rosana, D. (2025). Development of PBL-based interactive physics e-books to improve students' critical thinking abilities and digital literacy. *JIPF (Jurnal Ilmu Pendidikan Fisika)*, *10*(1), 92–103. https://doi.org/10.26737/jipf.v10i1.5669

Irmayanti, Khaeruddin, Wahyuni, A. S. A., & Swandi, A. (2025). Analisis keterampilan berpikir kritis peserta didik dalam pembelajaran fisika tingkat SMA di Kabupaten Gowa. *Jurnal Ilmiah Ecosystem*, *25*(3), 576–586. https://doi.org/10.35965/eco.v25i3.7956

Khasanah, I. M., Nurhidayat, M., & Ferawati. (2019). Studi komparasi penggunaan media pembelajaran komik dengan media modul pembelajaran pada metode resitasi pada hasil belajar fisika SMA. *RADIASI: Jurnal Berkala Pendidikan Fisika*, *12*(2), 61–69. https://doi.org/10.37729/radiasi.v12i2.53

Khoiriyah, S., & Suprapto, N. (2021). Effectiveness of comics to train students' critical thinking skills in physics learning: A mini-review. *Studies in Learning and Teaching*, *2*(1), 5–15. https://doi.org/10.46627/silet.vi.49

Lintangesukmanjaya, R. T., Mahendra, A., Anugrah, S., Prahani, B. K., Dwikoranto, D., Satriawan, M., & Rizki, I. A. (2025). EFA analysis of digital technology teaching materials in improving students' critical thinking in physics learning. *JPPS (Jurnal Penelitian Pendidikan Sains)*, *14*(1), 23–38. https://doi.org/10.26740/jpps.v14n1.p23-38

MacFarland, T. W., & Yates, J. M. (2016). *Introduction to nonparametric statistics for the biological sciences using r.* Springer. https://doi.org/https://doi.org/10.1007/978-3-319-30634-6_4

Mulyani, M., Widaningsih, S., Wiyati, R., Novianti, A., & Darmana, F. (2025). Sosialisasi proses implementasi deep learning dalam pembelajaran bahasa: Mewujudkan pengalaman belajar yang bermakna, reflektif, dan menyenangkan. *KOMUNITA: Jurnal Pengabdian Dan Pemberdayaan Masyarakat*, *4*(3), 699–708. https://doi.org/10.60004/komunita.v4i3.246

Nurhayati, Asniar, & Khaeruddin. (2022). Analisis keterampilan berpikir kritis dalam pembelajaran fisika peserta didik di SMAN 11 Makassar. *Jurnal Sains Dan Pendidikan Fisika (JSPF)*, *18*(2), 140–151. http://eprints.unm.ac.id/id/eprint/29128

Pangestu, D. M., & Rahmi, A. (2022). Metaverse : media pembelajaran di era society 5.0 untuk meningkatkan kualitas pendidikan Indonesia. *Journal of Pedagogy and Online Learning*, *1*(2), 52–61.https://10.24036/jpol.v1i2.17

Rendi, R., Sumaryati, S., & Purwanti, P. (2020). Pengembangan media pembelajaran komik fisika materi pokok pengukuran untuk siswa SMA Negeri 1 Compreng. *Navigation Physics: Journal of Physics Education*, *2*(2), 74–83. https://doi.org/10.30998/npjpe.v2i2.488

Reynders, G., Lantz, J., Ruder, S. M., Stanford, C. L., & Cole, R. S. (2020). Rubrics to assess critical thinking and information processing in undergraduate STEM courses. *International Journal of STEM Education*, *7*(9), 1–15. https://doi.org/10.1186/s40594-020-00208-5

Riduwan. (2015). *Skala pengukuran variabel – variabel penelitian.* Alfabeta.

Rosdiana, D. R., & Kholiq, A. (2021). The development of physics digital comics on temperature and heat material to improve the critical thinking ability. *Jurnal Ilmiah Pendidikan Fisika*, *5*(2), 83–93. https://doi.org/10.20527/jipf.v5i2.2959

Royani, R., Ahda, S., & Silalahi, S. (2024). Model pembelajaran deep learning untuk meningkatkan pemahaman IPS di sekolah dasar: Studi kasus di SD Global Garuda. *Jurnal Ilmiah Guru Madrasah (JIGM)*, *3*(2), 77–88. https://doi.org/10.69548/jigm.v3i2.27

Rustandi, A., & Rismayanti. (2021). Penerapan model ADDIE dalam pengembangan media pembelajaran di SMPN 22 Kota Samarinda. *Jurnal Fasilkom*, *11*(2), 57–60. https://10.37859/jf.v11i2.2546

Safiah, I., Fitri, A., Martines, Achdar, A. N., & Zaharatunnisa. (2025). Pelatihan dan pendampingan guru dalam pengembangan pembelajaran *deep learning* terintegrasi media digital untuk meningkatkan literasi digital di sekolah dasar. *Kreatif : Jurnal Pengabdian Masyarakat Nusantara*, *5*(3), 366–378. https://doi.org/10.55606/kreatif.v5i3.8245

Sembiring, R. A., & Waruwu, E. (2020). Eksistensi media dalam pembelajaran melalui media sosial dan media audiovisual di fakultas keguruan dan ilmu pendidikan (FKIP) Universitas Prima Indonesia. *SEJ (School Education Journal)*, *10*(4), 352–360. https://jurnal.unimed.ac.id/2012/index.php/school/article/view/19876/14843

Slamet, Hendriana, B., & Supiat. (2025). Mengungkap perspektif siswa: Peran deep learning dalam visualisasi konsep dan pemecahan masalah matematika. *Internasional Journal of Progressive Mathematics Education*, *5*(1), 225–237. https://doi.org/10.22236/ijopme.v5i1.19310

Subhaktiyasa, P. G. (2024). Menentukan populasi dan sampel: Pendekatan metodologi penelitian kuantitatif dan kualitatif. *Jurnal Ilmiah Profesi Pendidikan*, *9*(4), 2721–2731. https://doi.org/10.29303/jipp.v9i4.2657

Sudrajat, Y. (2020). Implementasi pembelajaran aktif (active learning) untuk meningkatkan kompetensi spiritual dan sosial siswa dalam pembelajaran pendidikan pancasila. *AoEJ : Academy of Education Journal*, *11*(2), 142–167. https://doi.org/10.47200/aoej.v11i2.398

Sugiyono, S. (2015). *Metode penelitian kuantitatif kualitatif dan R&D*. ALFABETA.

Suhirman, & Khotimah, H. (2020). The effects of problem-based learning on critical thinking skills and student science literacy. *Lensa : Jurnal Kependidikan Fisika*, *8*(1), 31–38. https://doi.org/10.33394/j- lkf.v8i1.2794

Utami, L. S., Sabaryati, J., Darmayanti, N. W. S., & Fitriani, E. (2020). Pengaruh komik lipat sederhana terhadap hasil belajar fisika di MTs Nurul Ishlah Gegelang. *JUSTEK : Jurnal Sains dan Teknologi*, *3*(1), 50–57. https://doi.org/10.31764/justek.vXiY.3756

Wardani, I. S., & Fiorintina, E. (2023). Building critical thinking skills of 21st century students through problem based learning model. *JPI (Jurnal Pendidikan Indonesia)*, *12*(3), 461–470. https://doi.org/10.23887/jpiundiksha.v12i3.58789

Warman, E., Sajidin, Setiawan, R., Gifary, A., Warta, W., Mulyanto, A., & Hanafiah. (2025). Pendekatan deep learning pada pembelajaran di Sekolah Dasar Gekbrong 1 Cianjur. *Jurnal Pengabdian Masyarakat dan Riset Pendidikan*, *4*(1), 1521–1528. https://doi.org/10.31004/jerkin.v4i1.1773

Widyawati, A., Suyanta, Kuswanto, H., & Prodjosantoso, A. K. (2024). E-comic based on sets: a digital learning media to improve student's character and critical thinking skills. *International Journal of Religion*, *5*(2), 47–56. https://doi.org/10.61707/mwpgtt04

*__Nur Lailatul Ilmiah (Corresponding Author)__
Bachelor of Science in Physics Education, Universitas Negeri Surabaya
Jl. Ketintang, Surabaya, East Java, 60231, Indonesia
nur.22090@mhs.unesa.ac.id

Muhammad Satriawan
Department of Physics Education, Universitas Negeri Surabaya
Jl. Ketintang, Surabaya, East Java, 60231, Indonesia
muhammadsatriawan@unesa.ac.id