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The Effect of STEM-Based Physics Learning and Local Wisdom of Bengkulu on Students' Critical Thinking Skills in the Concept of Particle Dynamics

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A B S T R A C T

Physics teaching practices in schools generally still focus on low-level thinking through routine exercises, so critical thinking skills as a 21st-century competency are not being maximised. This research attempts to look into the impact of STEM-based physics learning integrated with traditional Bengkulu games affect pupils' ability to think critically about particle dynamics. The research employed a nonequivalent control group and a quasi-experimental design. A total of 66 Grade XI students served as research subjects: 33 in the experimental class and 33 in the control class, 28 Grade XII students participated in the critical thinking test trial, and three expert validators (lecturers and physics teachers) were involved. The research instruments were an essay test and Facione's Critical Thinking Skills Assessment Rubric. The data were analysed using non-parametric inferential tests and descriptive statistics (Mann-Whitney U). The findings demonstrated that Grade XI students' critical thinking abilities were significantly impacted by STEM-based physics instruction combined with Bengkulu local knowledge, with Sig< 0.001 and an effect size of 0.54 (High). It was concluded that STEM-based physics Learning combined with Bengkulu traditional knowledge was successful in enhancing critical thinking abilities in the idea of particle dynamics.

1. Introduction

Learning in the 21st century no longer places teachers at the centre of the learning process, but rather emphasises the development of skills through a learner-centred approach. In this approach, students are guided to develop life skills and abilities relevant to current needs. The main focus is on developing critical thinking skills and contextual learning processes in line with current global challenges (Afifah et al., 2025). These skills are summarised under the term '4C Skills', which comprises Critical thinking and problem solving, communication, Collaboration, creativity, and innovation. (Putri et al., 2021; Nazifah & Effendi, 2024; Rizaldi & Fatimah,

2024) These four skills are outlined in the 21st Century Partnership Skills framework and are essential competencies aligned with the Merdeka Curriculum's goals.

In physics education, critical thinking skills are essential for helping students understand abstract concepts, analyze natural phenomena systematically, and solve problems based on scientific laws (Ginting et al., 2022). One topic that strongly requires these skills is Particle Dynamics, which focuses on the relationship between motion and force as described in Newton's Laws (Nurlina & Riskawati, 2017; Sari et al., 2025). Students must not only apply mathematical equations but also identify forces, represent them in free-body diagrams, and logically interpret their effects on motion. This process involves key aspects of critical thinking such as interpretation, analysis, evaluation, inference, and explanation (Facione, 1990;2006;2015), often through contextual, multi-representational problems (Docktor & Mestre, 2014).

However, implementing Particle Dynamics instruction in schools still faces several challenges. Based on discussions with physics teachers at State High School 10 in Bengkulu City, although the Merdeka Curriculum has been implemented using a student-centered approach, students' critical thinking skills remain relatively low and have not yet developed adequately. This is reflected in their difficulties analyzing physics problems, linking concepts to real-world phenomena, and presenting logical scientific arguments. Teachers also noted that low student motivation and limited variation in instructional models contribute to this issue. Therefore, physics instruction needs to be redesigned to be more engaging, contextual, and student-centered, incorporating learning models that promote active participation and connect concepts to everyday life to enhance students' critical thinking skills (Bao & Koenig, 2019).

Given these conditions, an instructional approach that promotes active engagement, problem-solving, and interdisciplinary integration is needed to address students' low critical thinking skills. One effective strategy is integrating Problem-Based Learning (PBL) with the STEM approach. This PBL-STEM integration is well-suited for teaching particle dynamics, as both emphasize problem-solving as the core of learning (Putri et al., 2024). PBL provides structured stages, including presenting contextual problems, conducting investigations, developing solutions, and reflecting on outcomes (Subiyantoro, 2025; Herlinda et al., 2026). Meanwhile, STEM integrates scientific concepts, technology, engineering design, and mathematics into a unified framework (Khoiriyah & Wahyudi, 2018; Asri et al., 2021; Muttaqiin, 2023).

To prevent the STEM approach from becoming abstract, it is important to incorporate contextual learning media that are closely connected to students' environments, such as local wisdom. In Bengkulu, the traditional game Palak Babi offers strong potential for integration into physics instruction, as it includes concepts such as force, momentum, impulse, and Newton's laws (Jamalludin et al., 2021; Rohmawati, 2021). Using two wooden sticks, students can directly observe interactions of force and motion during gameplay (Jamalludin et al., 2021; Rohmah et al., 2024; Rohmawati, 2021). Integrating local knowledge creates meaningful learning experiences and fosters cultural appreciation (Harahap et al., 2024; Yanti et al., 2024). This aligns with findings that culture-based learning makes scientific concepts more concrete and relatable (Yanti et al., 2024).

Several studies show that the STEM approach effectively develops students' critical thinking, creativity, and interdisciplinary literacy (Azizah & Angelina, 2025; Yuniar et al., 2025; Octafianellis et al., 2021). However, most have not explicitly integrated cultural contexts or local wisdom, and some remain limited to literature reviews without empirical Classroom implementation (Isnaniah & Masniah, 2022). Research on the traditional game Palak Babi mainly focuses on descriptive analyses of physics concepts, without linking them to instructional models or the development of critical thinking skills (Rohmah et al., 2024; Jamalludin et al., 2021; Rohmawati, 2021). Meanwhile, students respond positively to STEM integrated with local wisdom, as it is more relevant and engaging, thereby enhancing motivation and learning quality (Isnaniah & Masniah, 2022; Hayati et al., 2024; Khotimah et al., 2025).

To strengthen this study's position within existing research, a systematic review through research trend mapping is necessary. A bibliometric analysis of 412 Scopus-indexed articles (2020–2024) using Biblioshiny and VOSviewer shows increasing interest in STEM integration and critical thinking, with strong links to particle dynamics and active learning. However, Bengkulu's local wisdom, such as the Palak Babi game, is underrepresented, suggesting limited empirical research integrating STEM with local culture. This reveals a clear research gap. Therefore, this study proposes a novel approach that integrates STEM with Bengkulu's local wisdom through Palak Babi in physics learning, with the aim of testing its effects and determining its impact on students' critical thinking skills, thereby contributing to a contextual and culturally grounded learning model.

2. Methodology

Research Type and Design

There is one experimental class and one control class in this quantitative, quasi-experimental study using a nonequivalent control group design. (Cohen et al., 2007). The research design used in this study is presented in Figure 1.

Experiment	O_1	X	O_2
Control	O_3	-	O_4

Figure 1. Nonequivalent Group Design Research Design

Description
X: STEM-based physics learning and local wisdom
O1: Pre-test on the experimental group,
O2: Post-test on the experimental group,
O3: Pre-test on the control group,
O4: Post-test on the control group.

The study was conducted at State Senior High School 10 in Bengkulu City, located on Jalan Padang Cengkeh, Sukarami Village, Selebar District, Bengkulu City, Bengkulu 38212. The school holds an A accreditation status and has over 700 students and 69 teachers. This school was selected as the research site because SMAN 10 has implemented the Merdeka curriculum, and obtaining research permission was easy. Additionally, the learning conditions at this school were deemed representative for assessing students' critical thinking skills, particularly in physics.

The research population consisted of class XI, comprising 8 study groups (class XI A-H) with 272 pupils in all. Class XI was chosen as the research population because the focus of this research is on the Particle Dynamics material, which is taught curricularly in phase F of class XI. At this level, students have covered basic physics concepts in class X, so they are cognitively ready to learn about Particle Dynamics. In addition, in the subject selection mechanism in class XI, class XI E, XI F, XI G, and XI H, each has a teaching hours per week of 5 hours of learning (45 minutes x 1 JP). The school uses a subject-selection mechanism based on each student's interests, talents, and career plans. Students who choose physics tend to be more ready and willing to learn.

The research samples were Class F and Class G, which were determined using purposive sampling based on factors pertinent to the goals of the study (Arikunto, 2013), such as (1) the willingness of the homeroom teachers and physics teachers who taught both classes, (2) the number of students in both classes was the same (33 students), and (3) the students' readiness to participate in learning and the allocation of learning time in both classes was relatively the same. Based on the physics teacher's explanation, the average mastery of physics ideas and students' enthusiastic involvement in the educational process in classes F and G were similar. However, the physics teacher provided advice and recommended designating the experimental class as class XI F, while the control class was class XI G.

To maintain the study's internal validity, several external variables were controlled for throughout the research process. First, the equality of students' initial abilities between the experimental and control classes was controlled for by administering a pretest of critical thinking. The results of the analysis using the Mann–Whitney U nonparametric statistical test showed that there was no significant difference between the two groups at the initial stage of the study ($p = 0.77 > 0.05$), so that the initial abilities of students in both classes could be considered relatively equal before the treatment was given. Second, the learning process in both classes was carried out by the same physics teacher to minimize the influence of differences in teaching styles on the research results. Third, both classes received the same material, namely the concept of particle dynamics, with equal learning time, namely 5 JP per week, in accordance with the school's physics subject schedule. By controlling these variables, we expect the differences in students' critical thinking skills at the end of the study to better reflect the influence of STEM-based physics learning integrated with Bengkulu's local wisdom.

Research Procedure

The research procedure consists of three main stages: planning, implementation, and final. In the planning stage, the research began with administrative procedures to determine the research location and obtain permission from the education office. Next, the researcher identified the research population and sample and established the experimental and control groups. A curriculum analysis was conducted to determine the learning materials, namely, particle dynamics, and the learning outcomes and objectives to be achieved. In addition, the researcher developed learning tools that included a "palak babi" game-based learning medium and student worksheets. Research instruments were then designed, developed, and tested for validity and reliability to ensure their suitability for use in the study. This research procedure is illustrated in Figure 2.

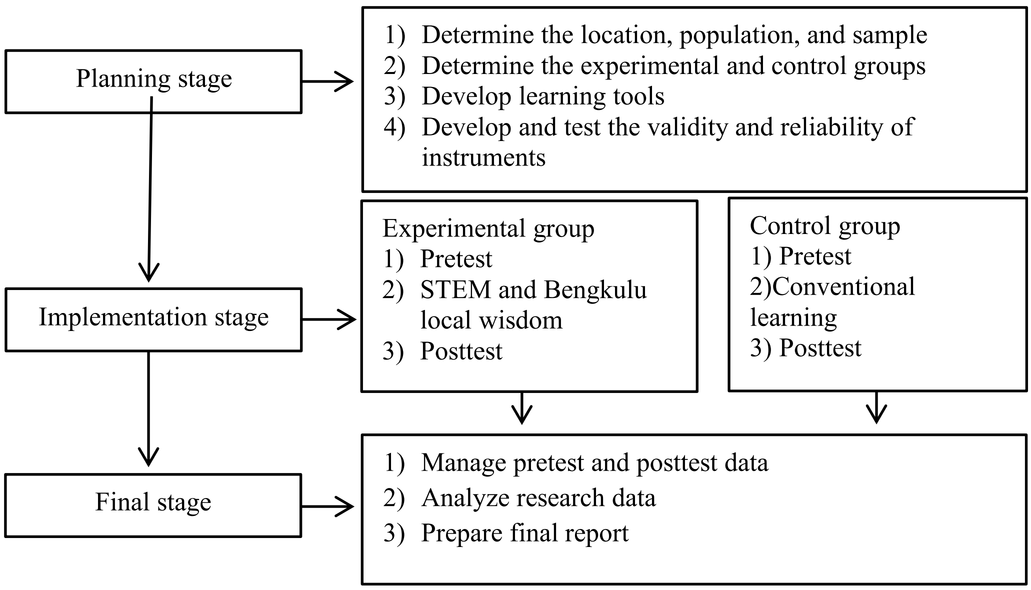

Figure 2. Research Procedure

The research implementation stage began with administering a pretest to both groups (experimental and control) to determine their initial critical thinking abilities. Learning in the experimental class was conducted over four sessions, with a time allocation of 2 × 45 minutes and 3 × 45 minutes per session (5 JP per week), focusing on the concept of Particle Dynamics. The learning process used the Problem-Based Learning (PBL) model integrated with the STEM approach and Bengkulu local wisdom through the traditional game of Palak Babi. The learning stages included problem orientation, investigation, solution development, and presentation and reflection. In the problem orientation stage, the teacher presented the Palak Babi game phenomenon through videos and demonstrations to raise contextual problems related to the concepts of force and motion.

Next, in the investigation stage, students work in groups using STEM-based worksheets to formulate hypotheses and conduct investigations through direct observation of the Palak Babi game and by collecting data using simple measuring instruments. This stage integrates aspects of science through Newton's laws, technology through the use of measuring instruments, engineering in the design of experimental procedures, and mathematics in data processing. In the solution development stage, students analyze the observation data to determine the relationship between force, mass, and acceleration using Newton's Second Law equation. Next, in the presentation and reflection stage, each group presents the analysis results and draws conclusions, which are then discussed together to relate the experimental results to the theoretical concepts studied.

Meanwhile, the control class followed a teacher-centered lecture method. The material was delivered through the teacher's explanation of concepts and examples of textbook questions. In this learning method, students tended to act as recipients of information, with their main activities being listening to explanations, taking notes, and doing exercises based on the examples given. After the entire learning series was completed, both groups were given a posttest to assess improvement in students' critical thinking skills following the treatment. In the final stage, the researcher managed the pretest and posttest data, analyzed the data according to the analysis technique used, and compiled a final report to report the results of the research conducted.

Research Instruments

The research instruments consisted of observation sheets, interviews, assessment rubrics, and critical thinking tests. Observation sheets and interview guidelines were used to obtain preliminary information on learning conditions, student characteristics, and problems encountered in physics learning. The data obtained from these observations and interviews were used as supporting evidence in the introduction, particularly in the background of the research problem. A critical thinking assessment rubric was used as a guideline for scoring students' answers. The rubric was compiled based on each of Facione's indicators, with assessment criteria covering conceptual accuracy, completeness of argumentation, and clarity of reasoning, using a scale of 0-5 to ensure assessments were carried out objectively and consistently. The critical thinking test is in essay form and was developed based on Facione's five indicators: specifically, interpretation, analysis, assessment, deduction, and justification (Facione, 1990). The material used in this study was particle dynamics through the traditional game of palak babi. The instruments were used using a grid and validated by two physics education lecturers and physics teachers to assess linguistic aspects and the suitability of the indicators to the questions. Then, a trial was conducted to test empirical validity and determine the questions' discriminating power and level of difficulty, as well as reliability.

Data Analysis

Descriptive statistics were used to analyze the pretest and posttest data, determining the maximum, minimum, mean, standard deviation, skewness, and kurtosis of students' critical thinking abilities. Furthermore, inferential statistical analysis was conducted as a prerequisite for hypothesis testing, beginning with normality and homogeneity tests. An examination of the variations in learning outcomes between the experimental and control groups based on the outcomes of these preparatory tests was conducted using the Mann-Whitney U test, a nonparametric test (Mushuri, 2022). In addition, effect size calculations were used to determine the magnitude of the influence of STEM-based learning and Bengkulu local wisdom on students' critical thinking skills using the following equation:

$$r = \frac{Z}{\sqrt{N}} \qquad \text{Equation 1}$$

Explanation
r: Effect size
Z: Nonparametric test output,
√N: Number of samples.

The absolute value of r is considered as small (≥ 0.10), moderate (≥ 0.30), or large/high in accordance with Cohen's recommendations. (≥ 0.50) (Cohen, 1992; Inayah et al., 2025; Peres, 2026).

3. Results and Discussion

Results

a. Instrument standard test

The research instrument began with the development of questions designed to hone and stimulate students' critical thinking skills. The development of the test instrument was based on Facione's indicators of critical thinking, which include the abilities to interpret, analyze, evaluate, infer, and explain. Each item is structured as a contextual stimulus that requires students to understand the problem, analyze the information provided, and draw conclusions based on relevant physics concepts. Additionally, each question is designed to encourage students to provide logical, systematic reasoning in their answers. The instrument also undergoes a validation process to ensure content appropriateness, linguistic clarity, and alignment with established learning objectives.

Instrument validation testing was conducted in two stages, namely content validation by experts (validators) and empirical testing. The first stage was expert validation, which aimed to determine whether the instrument's materials and structure are appropriate, including the alignment of the indicators with the research objectives, the clarity of the language, and the applicability of the stimulus questions to the study's title and context. Expert validation's findings demonstrated that the instrument was generally suitable for use, but some improvements were still needed, particularly in the presentation of the question stimuli to better align with the research context. The instrument was improved based on the recommendations and feedback provided by the validators before it was used in the next stage.

The second stage was empirical validity testing, which was conducted by trialing the instrument on 28 Year 12 MIPA 1 students at SMAN 10 Kota Bengkulu. The trial data were then analyzed to assess the empirical validity of each item, as well as the questions' discriminating power and level of difficulty. In addition, a reliability test was conducted to ensure the instrument's consistency in measuring students' critical thinking skills. The results of the empirical validity test of the instrument are presented in Table 1.

Table 1. Results of Empirical Validity Testing of Critical Thinking Ability Instruments

Dimensions of Critical Thinking	Indicator	Concept	No questions	Item Validation			
				Koef r (criteria)	p-value (criteria)	DP (criteria)	TK (criteria)
Interpretasi	a. categorization	Hukum I Newton	1a	0.652** (Height)	<0.001 (Valid)	0.543 (Good)	0.846 (Easy)
	b. explaining the meaning		1b	0.546** (Enough)	0.003 (Valid)	0.341 (Good)	0.836 (Easy)
Analisis	checking ideas	Hukum II Newton	2	0.483** (Enough)	0.009 (Valid)	0.296 (Enough)	0.736 (Easy)
Evaluasi	a. Evaluating claims or statements	Hukum III Newton	3a	0.733** (Height)	<0.001 (Valid)	0.736 (Very good)	0.796 (Easy)
	b. evaluate arguments		3b	0.583** (Enough)	0.001 (Valid)	0.586 (Very good)	0.68 (Currently)
Inferensi	Questioning evidence	Jenis-Jenis gaya	4	0.506** (Enough)	0.006 (Valid)	0.420 (Very good)	1.02 (Easy)
Eksplanasi	a. Presenting the results	Momentum dan implus	5a	0.746** (Height)	<0.001 (Valid)	0.735 (Very good)	0.88 (Easy)
	b. validating procedures		5b	0.626** (Height)	<0.001 (Valid)	0.608 (Very good)	0.713 (Easy)

Explanation
DP : Discrimination Power
TK : Item difficulty level

Based on the above results, five questions were used in this study, each representing one of Facione's critical thinking abilities: interpretation, analysis, evaluation, inference, and explanation. The instrument has a very high level of reliability and is appropriate for use as a data collection tool, as evidenced by the reliability study of the categorized valid data, which yielded a Cronbach's Alpha of 0.810.

b. The learning process

The experimental class used the Problem-Based Learning (PBL) approach in conjunction with the STEM approach and local wisdom of Bengkulu through the traditional game of Palak Babi. Learning began with the presentation of contextual problems related to game activities to help students relate the concept of particle dynamics to real phenomena in their surroundings. Next, students were organized into small groups and worked using STEM-based worksheets to identify problems, formulate hypotheses, and design investigation steps. At the investigation stage, students conducted observations and collected data through direct play of the Palak

Babi game and the use of simple tools, with the teacher acting as a facilitator who guided students' thinking and discussion.

The LKPD is systematically arranged, beginning with the identities of the students and groups, followed by an introduction that outlines the learning objectives and the contextual issues raised by the traditional game of Palak Babi. In the material section, relevant physics concepts are presented and linked to the phenomena in Palak Babi. Furthermore, the LKPD includes work steps that guide students in conducting scientific investigations, with observation tables to record observations and data obtained during the task. Analysis and discussion questions are offered to foster critical thinking and encourage students to interpret data, relate concepts to observations, and conclude. At the end, the LKPD includes reflection and evaluation questions to help students reflect on the learning process and results, and to assess their understanding of the concepts they have learned.

The integration of the STEM approach is evident in the application of scientific concepts such as Newton's laws, force, and acceleration; the use of technology through educational media and measuring instruments; the application of engineering to design problem-solving strategies for games; and the use of mathematics to analyze and interpret observational data. Learning activities are carried out both outdoors and indoors, with outdoor learning on the school grounds to provide direct experience of the physics phenomena in the Palak Babi game. In contrast, indoor learning takes place in the Classroom for discussions, data analysis, conclusions, and presentation of group work results. Through these stages, the learning process is designed to encourage students' active engagement and develop their critical thinking skills in a contextual and meaningful way, as shown in Figure 3.

Figure 3. The traditional game of palak babi

In contrast, the learning process in the control group employed a teacher-centered lecture approach. The content was delivered. directly through explanations of concepts and examples from the textbook, while student activities were focused more on routine and procedural exercises. Learning interactions in the control class tended to be one-way, so students' active involvement in analyzing problems, expressing opinions, and developing critical thinking skills remained limited.

c. Descriptive Analysis

Results of the descriptive statistical analysis of students' critical thinking skills, including minimum, maximum, mean, standard deviation, skewness, and kurtosis for the control and experimental groups. This analysis was conducted to provide an initial overview of the data characteristics, central tendency, and dispersion of students' critical thinking skills within each group, while also identifying patterns in pretest and posttest scores and detecting initial differences between groups as a basis for inferential hypothesis testing. These descriptive statistics are presented in Table 2.

Table 2. Descriptive Analysis Data (n = 33)

Test	Group	Min	Max	Mean	Std. Deviation	Skewness	Kurtosis
Pre	Control	0	64	24.95	20.27	0.36	-1.31
	Experiment	0	52.50	27.94	16.63	-0.64	-0.94
Post	Control	10	70.50	43.42	16.49	0.09	-0.67
	Experiment	40.75	86.25	62.52	10.58	0.13	0.13

Distribution and dispersion of students' critical thinking ability data on the pretest and posttest for the control class and the experimental class. The data are presented in the form of box plots to clearly illustrate differences in the median, interquartile range, and data variation across groups, thereby facilitating the observation of trends in changes in students' critical thinking ability and differences in data dispersion between the control class and the experimental class before and after the intervention. This data visualization is presented in Figure 4.

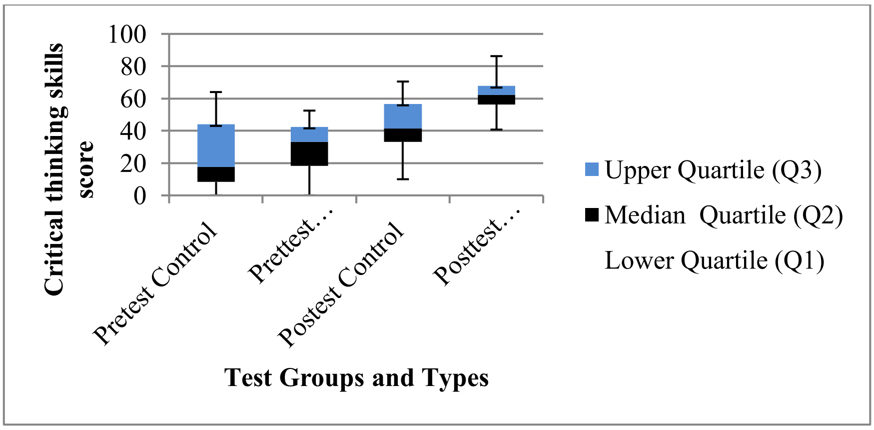

Figure 4. Boxplot of Descriptive Analysis Data

Based on the descriptive statistical analysis, Students in the experimental class improved their critical thinking skills on average far more than those in the control group. The experimental class's lower standard deviation and higher average scores show that STEM-based physics instruction combined with Bengkulu local knowledge not only enhances critical thinking abilities but also more fairly distributes students' talents. Additionally, the experimental class's post-test data skewness and kurtosis values fall within the range of -1 to +1, suggesting that the distribution is approximately normal.

d. Normality Test

The normality of the critical thinking ability data was assessed by interpreting results at the α = significance level of 0.05. The results of the normality test are presented in Table 3.

Table 3. Results of the Normalcy Test Data

Class	Shapiro-Wilk		
	Statistic	**df**	**Sig.**
Pretest Control	0.90	33	0.005
Posttest Control	0.96	33	0.189
Prettest Experiment	0.87	33	<0.001
Posttest Experiment	0.22	33	<0.001

The results of the normality test in Table 3 indicate that only the post-test in the control class is normally distributed ($p = 0.189 > 0.05$). Meanwhile, the pre-test in the control class, the pre-test in the experimental class, and the post-test in the experimental class are not normally distributed, as indicated by the significance less than 0.05. A homogeneity test must be performed following the normalcy test.

e. Homogeneity Test

The critical thinking ability data were then tested for homogeneity of variance as a prerequisite for statistical analysis. The homogeneity test was conducted at the α = 0.05 significance level. The results of the homogeneity of variance test are presented in Table 4.

Table 4. Homogeneity Test Results Data

	Sig.
Based on Mean	0.145
Based on Median	0.431
Based on Median and with adjusted df	0.434
Based on trimmed mean	0.439

Since the data were not regularly distributed, the Levene Test with the median-based reference was used to conduct the homogeneity of variance test (Isnawan, 2020). The test results indicated that the variance of the data between the experimental class and the control class was homogeneous, with a significance value of 0.431 > 0.05.

f. *Mann-Whitney U test*

After conducting data assumption tests, including tests for normality and homogeneity of variance, the results indicated that the data were not normally distributed, although they exhibited homogeneity of variance. Therefore, the subsequent hypothesis testing was conducted using a nonparametric test, specifically the Mann–Whitney U test (Mushuri, 2022), with the test results presented in Table 5.

Table 5. Mann-Whitney U test

	Learning Outcomes
Mann-Whitney U	201.500
Wilcoxon W	762.500
Z	-4.400
Asymp. Sig. (2-tailed)	<0.001

After conducting a hypothesis test using the Mann-Whitney U test, the outcomes in Table 5 show a p-value of < 0.001, which is < 0.05. These results indicate a significant difference in students' critical thinking abilities between the experimental and control classes. Different learning treatments caused this difference: the experimental class received STEM-based physics learning integrated with Bengkulu local wisdom through the traditional game of palak babi. This learning required students to be actively involved in contextual problem solving, exploring concepts, and relating the concept of particle dynamics to real phenomena in everyday life. Meanwhile, the control class used conventional learning methods focused on lectures and textbook problems, resulting in relatively limited student involvement in the learning process. Differences in learning approaches led to significant differences in pupils' capacity for critical thought. Thus, the alternative hypothesis (Ha) is accepted, as STEM-based physics education combined with Bengkulu's local knowledge has a major impact on students' critical thinking regarding the concept of particle dynamics.

g. Improvement in critical thinking in each indicator

To obtain a more detailed picture of improvements in students' critical thinking skills, an analysis was conducted for each indicator using Facione's framework, which includes interpretation, analysis, assessment, deduction, and justification. A comparison of the average pretest and posttest scores for each indicator is presented in Figure 5.

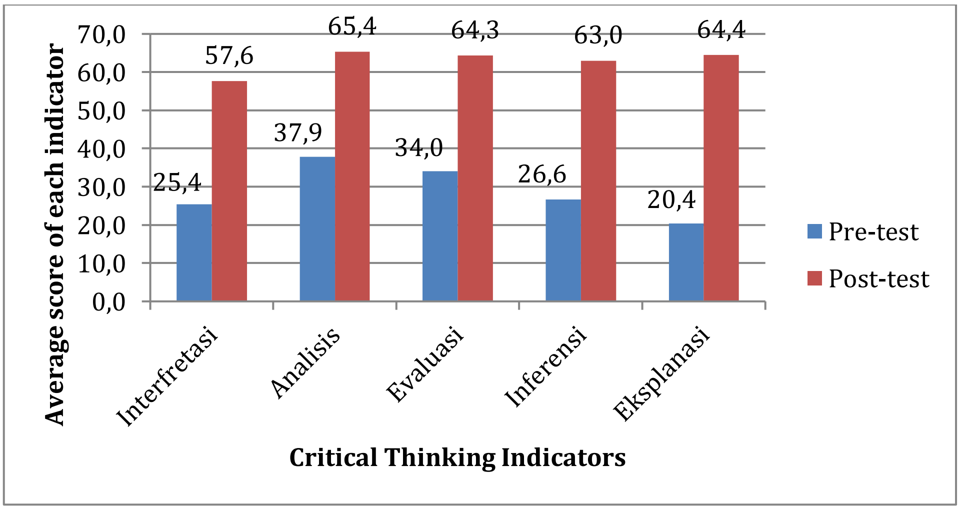

Figure 5. Improvement in critical thinking for each indicator

Based on Figure 5, each critical thinking indicator experienced a significant rise following the introduction of STEM-based physics instruction combined with

Bengkulu traditional knowledge. The explanation indicator showed the largest rise, followed by inference, interpretation, evaluation, and analysis. This demonstrates how learning is created through STEM-focused PBL activities combined with the classic Palak Babi game, which encouraged students not just to understand concepts but also to explain, draw conclusions, and present scientific arguments more systematically and logically.

h. Effect size test

In addition to statistical significance tests, this study calculated effect sizes using Equation 1 to assess the magnitude of the treatment's effect. The results of the calculation showed an effect size of r = 0.54, which falls into the high category (Cohen, 1992; Peres, 2026). This finding indicates that the implemented treatment had a strong effect on improving students' critical thinking skills. Thus, the results are not only statistically significant but also possess substantial effect strength and practical significance. This demonstrates that the implemented learning model effectively enhances students' critical thinking skills. Furthermore, these findings suggest that this learning strategy is worth considering for broader educational contexts.

Discussion

Students' critical thinking abilities regarding particle dynamics were found to be significantly influenced by STEM-based physics education and Bengkulu local knowledge, as indicated by the analysis and hypothesis testing results. The Mann-Whitney U test revealed a significant difference between the experimental and control groups ($p < 0.05$). Compared with the control group, the experimental group's average post-test score was higher, and its score distribution was more homogeneous. These findings indicate that contextual, integrative, and student-centered learning can optimize the development of students' critical thinking skills (Bybee, 2013; Kelley & Knowles, 2016; Aprianti et al., 2023).

Further analysis of each critical thinking indicator shows that all indicators improved after implementing a STEM-based PBL model integrated with the traditional game Palak Babi. This improvement indicates that learning activities designed through investigation, group discussion, and empirical data analysis can comprehensively stimulate various aspects of pupils' critical thinking capacity (Farkhan et al., 2022). In terms of interpretation, students' improved abilities were evident in their problem-solving syntax as they watched videos and demonstrations of the Palak Babi game to identify the phenomenon of the wooden child's movement. Based on the analysis results, the average score for the interpretation indicator increased from 25.4 on the pretest to 57.6 on the posttest. The integration of science and technology was evident in the introduction of the concepts of force and inertia, while technology was utilized through video media as a contextual learning stimulus. At this point, the majority of students could explain that the wood remained stationary before being subjected to force and began to move after being struck, then linked this to Newton's First Law of Inertia. They also understood that force causes a change in motion, while velocity is the result of force acting on an object. Thus, this visual, context-based, problem-oriented strategy is effective in building students' cognitive readiness before entering core learning activities. These findings align with previous studies indicating that using contextual visual stimuli might boost students' willingness to study, improve their attention span, and stimulate their prior knowledge (Khoiriyah & Wahyudi, 2018; Hidayat et al., 2024; Tarigan et al., 2025).

The analysis indicators developed in the syntax organized the students and guided their investigation. Based on the analysis results, the average score for the interpretation indicator increased from 25.4 on the pretest to 57.6 on the posttest. At this point, pupils could formulate hypotheses about the relationship between force, mass, and acceleration, then conduct experiments by varying the type of impact. The majority of students were able to present the experimental data systematically in tabular form and calculate the acceleration value using Newton's Second Law equation with the correct procedure. The calculations also demonstrate accuracy in entering units and sequential mathematical steps. However, the analysis indicators show the least improvement, as some students remain focused on mathematical calculations without explaining the physical meaning of the results they obtain. The integration of Science is evident in Newton's Second Law in action; Technology through the use of stopwatches and digital measuring instruments; Engineering in the design of the experimental procedure, namely in the variation of the types of throws; and Mathematics in data processing using the equation $F = m \times a$. This approach aligns with research findings showing that STEM-based learning (Gusman et al., 2026) and problem-based learning can improve students' analytical skills in solving scientific problems (Suci et al., 2025).

The evaluation indicators were developed in the syntax of developing and presenting results. Based on the analysis, the average score for the evaluation indicators increased from 34.0 on the pretest to 64.3 on the posttest. In the class discussion, students began comparing experimental results across groups and assessing the suitability of the experimental data to the theoretical concepts studied. Students were also able to identify possible sources of experimental errors, such as inaccurate time measurements. However, the improvement in evaluation indicators was still relatively low compared to several other indicators, because evaluating requires more complex reasoning to assess evidence and determine solutions logically. This aligns with research showing that students' critical thinking skills, especially in evaluation, remain relatively low because they are not yet accustomed to critically assessing information during learning (Oktaviyanti & Fadly, 2023; Andraini et al., 2021).

Inference indicators develop in syntax analysis and evaluating problem-solving processes (reflection). Based on the analysis, the average score for the inference indicator increased from 26.6 on the pretest to 63.0 on the posttest. At this stage, students can draw generalizations from empirical data obtained during experimental activities. They conclude that because acceleration is inversely proportional to mass and directly proportional to force, as stated by the equation $a = F/m$. Students can predict that a smaller piece of wood will move further when given the same force, because the acceleration produced is greater. This process of conclusion demonstrates evidence-based inference skills, where the combination of mathematical and scientific aspects in the STEM approach strengthens the process of conceptual generalization from the quantitative data obtained (Rosilawati & Abidin, 2025; Hasrini et al., 2025).

The explanatory indicators show the highest increase and optimal development in the syntax of presentation and final reflection. Based on the analysis, the average score for the explanation indicator increased from 20.4 in the pretest to 64.4 in the posttest. Students reported the findings of their experiments at this point orally and in writing, supported by tables of observation results. STEM integration appeared comprehensive, as students explained scientific concepts (Science), utilized measurement data (Technology), reflected on experimental design (Engineering), and presented numerical calculations (Mathematics) in their arguments. The results of the study show that most students can relate experimental data to Newton's laws of motion coherently and maintain their arguments during question-and-answer sessions. This significant improvement shows that a learning context close to students' lives makes it easier for them to communicate scientific ideas logically and evidence-based (Adanur-sönmez et al., 2025)

In addition to learning strategies and models, the treatment given in the experimental class played an important role in increasing student motivation and Engagement, because contextual and meaningful learning has been proven to encourage active participation among students (Baruno et al., 2025; Suci et al., 2022). The use of the traditional game Palak Babi as a learning context makes students feel closer to the material because these activities are part of their daily experiences and local culture that they are familiar with (Agustinaningrum & Deta, 2023). This closeness fosters interest and enthusiasm for learning, in order to encourage students to actively participate in discussions, ask questions, and attempt to comprehend the physical events that take place. In addition, the palak babi game embodies social values such as cooperation, sportsmanship, responsibility, and solidarity. The value of cooperation is evident when students work in groups, dividing tasks in a structured manner, such as conducting experiments, measuring and observing results, recording data, and analysing the results together. The value of sportsmanship is reflected in the students' attitude toward following the learning activities. The value of responsibility is evident when each group member fulfills their role in the observation and discussion process. Meanwhile, the value of solidarity is evident in the mutual help and support among group members during the learning activities. Thus, the palak babi game not only serves as a regional cultural heritage but also as a relevant educational tool for integrating character building into the contextual learning process.

In contrast, learning in the control class was systematically and optimally designed and implemented, with a planning process equivalent to that of the experimental class, including setting learning objectives, preparing materials, and conducting evaluations. However, because the learning approach remained conventional and teacher-centered, treating students as mere recipients of information, the room for pupils to actively explore ideas and engage in deep reasoning was not optimally developed (Farkhan et al., 2022). Teacher-centered learning makes students passive and unresponsive when lessons are not linked to the surrounding environment, resulting in a lack of critical thinking skills (Fitriani & Sukidjo, 2018).

The impact of this learning is reinforced by the effect size calculation, which shows that STEM-based physics learning and Bengkulu local wisdom have a high effect size (0.54) on improving students' critical thinking skills. An effect size value in the high category indicates that the difference between the experimental and control classes is not only statistically significant but also meaningful in the context of learning (Agustin, 2021). Compared to direct learning applied in the control class, STEM-based learning and local wisdom provide a comprehensive learning experience. Conventional learning tends to position students as passive recipients of information, thereby limiting opportunities to practice critical thinking skills (Putri et al., 2021). In contrast, STEM-based learning and local wisdom are effective strategies for enhancing students' critical thinking skills, aligned with the requirements of 21st-century education and the implementation of the autonomous curriculum.

4. Conclusion

STSTEM-based physics instruction integrated with the local wisdom of Bengkulu through the traditional game of "palak babi" has been shown to significantly influence students' critical thinking skills in the topic of Particle Dynamics, as indicated by an effect size in the high category. This finding implies that integrating the STEM approach with local wisdom can make learning more contextual and meaningful, as it is directly related to students' real-life experiences. Furthermore, this approach has proven effective in stimulating students' critical thinking through active engagement in analysis, evaluation, and problem-solving. This learning model can serve as an innovative teaching strategy for physics teachers to enhance learning quality and optimize student engagement.

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