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Examining Changes in Critical Thinking Performance in Scientific Approach-Based Learning: Evidence from Wave Physics

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Abstract

Critical thinking is essential in physics education, particularly when students must interpret representations, evaluate evidence, and explain relationships among wave phenomena. This study examined changes in secondary school students' critical thinking performance during scientific approach-based learning on wave characteristics and determined whether pretest and posttest scores differed significantly. A quantitative one-group pretest–posttest design involved 28 Grade XI students at a private secondary school in West Lombok, Indonesia. Instruction was implemented over three classroom meetings through five interconnected scientific practices: observing, questioning, experimenting or gathering information, associating or reasoning, and communicating. Critical thinking performance was assessed using eight open-ended wave physics questions scored with a four-level analytic rubric. Data were analyzed using descriptive statistics, the Shapiro–Wilk normality test, a paired-samples t-test, and the Wilcoxon signed-rank test. The mean score increased from 47.214 (SD = 5.287) at pretest to 83.179 (SD = 9.911) at posttest, representing an average improvement of 35.964 points. All participants obtained higher posttest scores, although the magnitude of individual changes varied. The paired-samples t-test revealed a statistically significant difference, $t(27) = -18.929$, $p < .001$, supported by the Wilcoxon signed-rank test ($W = 0$, $p < .001$). These findings demonstrate substantial improvement in assessed critical thinking performance within scientific approach-based wave physics learning. The study contributes discipline-contextualized empirical evidence connecting scientific learning practices with critical thinking performance in secondary physics education. Its findings emphasize the educational relevance of integrating scientific investigation, conceptual reasoning, graphical interpretation, and evidence-based explanation into wave physics learning experiences.

Keywords: Critical thinking; Scientific approach-based learning; Wave physics; Scientific reasoning; Secondary education

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INTRODUCTION

Critical thinking has become a central objective of contemporary science education because scientific understanding requires learners to interpret information, evaluate evidence, examine competing explanations, and construct defensible conclusions. These competencies are especially important in physics, where students must coordinate conceptual knowledge, mathematical representations, and empirical observations to explain physical phenomena. Critical thinking extends beyond obtaining correct answers; it involves examining the reasoning underlying explanations and judging whether conclusions are supported by appropriate evidence. Scientific thinking and critical thinking are distinguishable but mutually supportive intellectual processes, particularly when

learners evaluate the plausibility of scientific claims and the adequacy of their supporting evidence (García-Carmona, 2025). Developing critical thinking in physics therefore requires opportunities to question assumptions, compare interpretations, and justify conclusions rather than rely exclusively on formula-based procedures.

A clearer account of critical thinking is also necessary when the construct is assessed within a particular school subject. The widely used framework associated with Facione (1990) identifies six interconnected cognitive skills: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Interpretation concerns understanding the meaning of information and situations; analysis concerns identifying relationships among ideas and evidence; evaluation addresses the credibility of claims and the strength of reasoning; inference involves drawing warranted conclusions; explanation concerns presenting and justifying reasoning; and self-regulation involves monitoring and reconsidering one's judgments. In science education, these capacities are expressed through disciplinary problems and evidence rather than exercised independently of content (García-Carmona, 2025). The six skills consequently provide a conceptual orientation for discussing critical thinking performance, although their inclusion in a framework should not be taken as evidence that a particular assessment captures all six dimensions equally.

Wave physics represents a pertinent setting for examining this form of disciplinary reasoning. Understanding wave propagation requires students to differentiate disturbance motion from the motion of the medium, connect frequency, wavelength, period, amplitude, and propagation speed, and interpret the behavior of waves in different physical conditions. Reflection, refraction, interference, diffraction, and standing waves add further demands because students must coordinate diagrams, mathematical relationships, experimental observations, and verbal explanations. Research has documented difficulties in integrating knowledge about mechanical wave propagation and relating formal representations to the underlying phenomena (Xie et al., 2021). Persistent problems in explaining propagation, reflection, superposition, and standing waves have likewise been documented in secondary physics education (Kanyesigye et al., 2022). These difficulties suggest that learning about waves requires explicit attention to how students interpret observations and justify conceptual relationships.

Comparable challenges emerge in wave optics, where explaining interference and diffraction requires students to relate observable patterns to abstract wave models. Research developing a conceptual survey of wave optics illustrates the importance of examining students' conceptual reasoning rather than treating numerical problem solving as sufficient evidence of understanding (Cvenic et al., 2022). Historical scientific dialogue about sound waves has also been proposed as a way to engage learners with competing explanations and the development of scientific ideas (Volfson et al., 2022). Physics education research on evaluating the scientific accuracy of explanations similarly emphasizes that judging a response requires content knowledge and attention to the reasoning presented (Dahlkemper et al., 2023). Together, these studies position wave physics as a meaningful context in which disciplinary understanding and evidence evaluation intersect.

Scientific approach-based learning offers one pedagogical framework for engaging students with these demands. In school science, the approach commonly organizes learning around observing phenomena, questioning, experimenting or gathering information, associating evidence with concepts, and communicating conclusions. Observation provides a basis for noticing patterns and identifying problems; questioning helps transform uncertainty into investigable issues; experimentation allows claims to be confronted with evidence; reasoning connects observations with scientific principles; and communication requires explanations to be made explicit and open to scrutiny. A systematic review of scientific inquiry assessment identifies question formulation, investigation, data analysis, and evidence-based conclusions as recurring dimensions of scientific inquiry (Vo & Simmie, 2025). These practices offer plausible opportunities for critical thinking, although participation in them does not automatically establish improvements in the assessed construct.

The relationship between these scientific practices and critical thinking can be articulated in more specific conceptual terms. Observing wave phenomena may invite interpretation of physical situations and analysis of relevant variables, while questioning may require analysis of assumptions and inference about possible explanations. Experimenting provides opportunities to evaluate claims against observations and infer relationships from evidence. Associating experimental information with wave principles can support the analysis and evaluation of competing explanations, and communicating conclusions can require explanation and reflection on the adequacy of one's reasoning. Self-regulation may operate across these activities as learners reconsider initial judgments in response to new information. These connections are conceptual and overlapping, rather than a fixed one-to-one mapping between classroom phases and cognitive skills (Facione, 1990; García-Carmona, 2025). Their educational significance depends on whether instruction actually requires students to justify, revise, and critically examine their claims.

The quality of instructional guidance is therefore important. Conducting experiments or group discussions does not necessarily ensure that students evaluate evidence or construct coherent explanations. Inquiry-oriented learning may be strengthened when investigative opportunities are combined with appropriately timed explanations, questioning, and teacher guidance. A synthesis of evidence on inquiry-based and direct instruction challenges the view that the two must be treated as mutually exclusive alternatives (de Jong et al., 2023). Related scholarship emphasizes teacher guidance, coherence of learning tasks, and the relationship between inquiry practices and disciplinary knowledge as conditions for meaningful learning opportunities (de Jong et al., 2024). Reviews of open inquiry in science education likewise identify potential benefits alongside differences in student preparedness and implementation contexts (Dah et al., 2024). Thus, scientific approach-based learning is best understood through the reasoning demands of its activities rather than through the presence of experiments alone.

Empirical literature provides a basis for examining the contribution of scientifically oriented learning activities to cognitive outcomes. Inquiry-based laboratory learning has been investigated in relation to students' scientific literacy and their engagement with scientific practices (Eymur & Çetin, 2024). Studies of

inquiry teaching have also drawn attention to teachers' facilitation of investigation and student participation in scientific discourse (Twizeyimana et al., 2024). Reviews of collaborative inquiry indicate that shared investigation and interaction can contribute to science learning, although the activities and outcomes investigated vary across settings (Chen & Chen, 2025). An overview of inquiry-oriented instruction further suggests that its educational value depends on the match between learning goals, support, and assessment (de Jong et al., 2024; Vo & Simmie, 2025). These insights encourage careful distinction between learning to conduct an investigation and demonstrating critical thinking on physics-related assessment tasks.

Broader research syntheses have examined whether inquiry-based science learning is associated with critical thinking outcomes. A systematic review and meta-analysis reported positive pooled effects of inquiry-based learning on critical thinking alongside substantial variation across the included studies (Arifin et al., 2025). Such heterogeneity cautions against treating inquiry as a uniform instructional condition and suggests that subject matter, implementation, and the definition of the measured outcome warrant attention. Research on inquiry activities in physics has also considered the development of experimental reasoning competencies, including skills associated with controlling variables (Gkagkas et al., 2026). Investigations of simulation-based inquiry examine how student characteristics and task demands relate to inquiry performance (Gerdesmann et al., 2026). These lines of evidence support a contextualized examination of critical thinking performance rather than assuming that gains in inquiry competence, conceptual knowledge, and critical thinking necessarily coincide.

Within physics, intervention research on wave learning has largely investigated particular conceptual difficulties and the conditions that support conceptual change. Problem-based instruction has been examined as a means of addressing difficulties with mechanical waves (Kanyesigye et al., 2022, 2023). Inquiry-based teaching sequences have also been studied in relation to students' understanding of wave optics, including interference and diffraction (Planinic et al., 2024). Such studies provide important foundations for understanding how students learn wave phenomena, but conceptual achievement and critical thinking performance remain related rather than interchangeable outcomes. A student may correctly describe a wave pattern without independently assessing competing claims or explaining why a conclusion follows from the available observations. The disciplinary context of wave physics consequently offers a useful opportunity to investigate critical thinking as a focal learning outcome.

Scientific approach-based activities can connect these reasoning demands with accessible classroom phenomena. Observations of vibrating strings can prompt interpretations of wave propagation and particle motion; experiments involving reflection or interference can invite comparisons between theoretical expectations and observations; and discussion of changes in frequency, wavelength, or medium can require students to justify proposed explanations. Scientific communication creates opportunities for students to make their reasoning inspectable to others. These activities are consistent with investigations emphasizing the value of meaningful inquiry and student participation in science classrooms (Aidoo, 2024; Eymur & Çetin, 2024). Nevertheless, their relationship to

assessed critical thinking performance should be examined rather than presumed, particularly when the construct is operationalized through subject-specific test items.

Three connected concerns therefore motivate the present investigation. Critical thinking in science involves evaluating and explaining claims with reference to evidence; wave physics presents disciplinary problems that demand coordinated conceptual reasoning; and scientific approach-based learning creates opportunities for inquiry activities whose cognitive outcomes may vary across contexts. Although these areas have been addressed in prior research, the intersection between explicitly assessed critical thinking performance and scientific approach-based learning in wave characteristics warrants additional context-specific examination (García-Carmona, 2025; Arifin et al., 2025; Planinic et al., 2024). This focus provides a basis for articulating the aims of the present study without presupposing its empirical findings.

Study Purpose and Research Questions

The purpose of this study is to examine changes in secondary school students' critical thinking performance in scientific approach-based learning within the context of wave physics. It focuses on students' performance in interpreting physical situations, analyzing relationships, evaluating explanations, and drawing reasoned conclusions in tasks concerning wave characteristics. By positioning critical thinking within specific disciplinary content, the study seeks to contribute context-sensitive evidence to discussions of scientific learning practices and reasoning in secondary school physics education.

The study is guided by the following research questions:

- RQ1. How does students' critical thinking performance change between pretest and posttest assessments in scientific approach-based wave physics learning?
- RQ2. Is there a statistically significant difference between students' critical thinking performance before and after scientific approach-based learning in wave physics?

The questions concern changes in assessed performance within a particular learning context. They do not presuppose that an instructional approach is the exclusive cause of any observed difference.

Novelty of the Study

Previous studies have investigated inquiry-oriented learning in physics, but much of the wave-related literature has focused on knowledge integration, conceptual difficulties, and the development of conceptual understanding. Investigations of mechanical waves have addressed the interpretation of propagation and the remediation of conceptual problems (Xie et al., 2021; Kanyesigye et al., 2022, 2023), whereas research on wave optics has concentrated on assessing conceptual understanding and examining learning through inquiry-oriented teaching sequences (Cvenic et al., 2022; Planinic et al., 2024). At the broader science education level, research syntheses have addressed inquiry-based learning and critical thinking across varied subjects and instructional contexts (Dah et al., 2024; Arifin et al., 2025). The present study differs in its explicit focus on critical thinking performance as the central learning outcome in wave physics, rather than treating conceptual mastery, scientific literacy, or inquiry competence as

interchangeable measures of students' reasoning. It thereby connects disciplinary wave content with the interpretation, analysis, evaluation, and justification of physics-related claims.

A second substantive distinction lies in the way the study brings together scientific approach-based learning practices and the reasoning demands of observable wave phenomena. Previous work has addressed inquiry-based laboratory learning and scientific literacy (Eymur & Çetin, 2024), collaborative inquiry in science learning (Chen & Chen, 2025), and experimental reasoning and inquiry performance in physics contexts (Gkagkas et al., 2026; Gerdesmann et al., 2026). These studies illuminate important dimensions of inquiry but do not place the same emphasis on critical thinking performance in a school-level sequence centered on the characteristics of waves. The contribution of the present study is therefore a discipline-contextualized examination of critical thinking in learning organized around observing, questioning, experimenting, associating evidence with wave concepts, and communicating explanations. This distinction is proposed as a contextual and conceptual contribution, not as a claim that scientific inquiry or critical thinking in physics has previously been unexamined.

METHODS

Research Design

This study employed a quantitative pre-experimental design using a one-group pretest-posttest approach to examine changes in students' critical thinking performance in scientific approach-based physics learning. A single intact class completed a critical thinking assessment before and after instructional activities focusing on wave characteristics. The pretest documented performance before instruction, while the posttest assessed performance after the instructional sequence.

The study involved one intact classroom group assessed before and after a structured learning sequence. The one-group pretest–posttest arrangement was used to quantify changes in critical thinking performance within the same learning context.

Participants and Research Setting

The study was conducted at a private secondary school in West Lombok, Indonesia. Participants were 28 Grade XI science students, comprising 13 male and 15 female students. The intact class was selected as the study group, without random assignment to different instructional conditions.

The learning content focused on wave characteristics in the secondary school physics curriculum. Classroom activities included demonstrations, simple investigations, worksheet-guided tasks, and discussions of physical phenomena.

Scientific Approach-Based Learning Intervention

The instructional intervention was implemented over three classroom meetings, excluding the separate pretest and posttest sessions. The intervention followed five related scientific practices: observing, questioning, experimenting or gathering information, associating or reasoning, and communicating. These activities were intended to connect observable wave phenomena with conceptual explanations through a combination of student investigation and teacher guidance,

consistent with the importance of guided inquiry in science learning (de Jong et al., 2024).

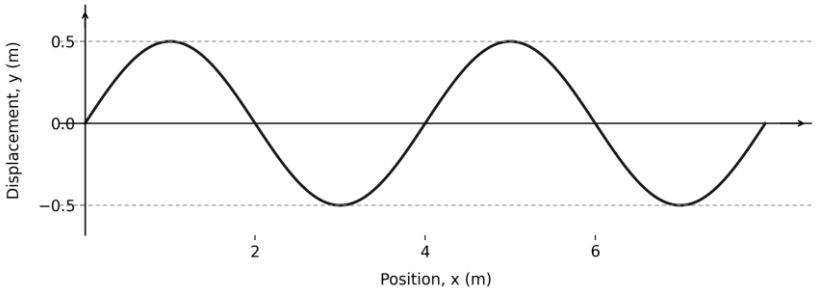
During observing, students examined wave-related phenomena presented through classroom demonstrations and learning materials. Questioning encouraged the formulation of problems about wave characteristics and behavior. During experimentation and information gathering, students engaged with simple investigations of phenomena such as reflection, refraction, and interference. Associating or reasoning involved comparing observations, identifying relevant physical relationships, and connecting evidence to conceptual explanations. Communicating provided opportunities for students to present findings and discuss conclusions supported by their observations.

The learning activities were supported by lesson plans and student worksheets. The teacher facilitated observations, supervised investigations, guided classroom discussion, and supported students in formulating and presenting scientific explanations.

Research Instrument

Critical thinking performance was measured using eight open-ended physics questions addressing wave characteristics. The instrument blueprint incorporated six dimensions of critical thinking: interpretation, analysis, evaluation, inference, explanation, and self-regulation. The questions involved graphical representations, physical relationships, mathematical expressions, and conceptual explanations. Although individual questions were assigned a primary dimension in the blueprint, responding to a question could draw upon more than one cognitive process. This interpretation is consistent with the conceptual relationship between scientific thinking and critical thinking in science education (García-Carmona, 2025).

Figure 1 presents an example of an assessment item intended primarily to assess interpretation. The question asks students to interpret the graphical representation of a transverse wave, identify relevant wave parameters, and formulate a wave equation using the given period.



Sample item. *The figure above shows a transverse wave propagating along a string. If the wave period is 2 s, what is the wave equation?*

Figure 1. Example of an assessment item primarily targeting interpretation in wave physics.

In Figure 1, students interpret the graphical information to identify amplitude and wavelength and relate these characteristics to the specified wave period. Constructing the corresponding equation also requires analysis and inference;

interpretation represents the primary assessment focus assigned to this item in the instrument blueprint.

Responses were scored using a four-level analytic rubric, assigning 1 to 4 points per item according to the accuracy and conceptual quality of the answer. The eight item scores were summed to a maximum of 32 and converted to percentage-based values by dividing the total score by 32 and multiplying by 100.

The instrument underwent expert evaluation and item analysis. Expert evaluation yielded an average rating of 3.50 on a four-point scale. Items that did not satisfy the item-validity criterion were revised before the eight-item assessment was used for pretest and posttest measurement. The revised version was administered without an additional psychometric testing cycle. Item-level correlations and internal-consistency statistics from the instrument analysis are presented in Table 1. Attention to alignment between assessment items and the intended construct is also emphasized in research on science assessment (Vo & Simmie, 2025).

Table 1. Item-level correlations and internal-consistency statistics for the critical thinking assessment

Item	Pearson item-total r	Corrected item-total r	α if item deleted
1	0.662	0.421	0.590
2	0.489	0.298	0.623
3	0.645	0.481	0.575
4	0.137	-0.036	0.684
5	0.628	0.443	0.583
6	0.682	0.462	0.574
7	0.607	0.471	0.587
8	0.293	0.134	0.653

Note. N = 28; Pearson item-total correlations are uncorrected; overall Cronbach's α = 0.644.

Table 1 presents Pearson item–total correlations, corrected item–total correlations, and Cronbach's alpha coefficients calculated after removing each item. Using the adopted Pearson correlation criterion ($r > 0.374$), items 1, 2, 3, 5, 6, and 7 met the threshold, whereas items 4 and 8 fell below it. The corrected item–total coefficients ranged from −0.036 to 0.481, providing additional information about the relationship between individual items and overall test performance.

The eight-item analysis yielded a Cronbach's alpha coefficient of 0.644. The alpha-if-item-deleted estimates ranged from 0.574 to 0.684 and were considered alongside the item correlations during instrument refinement. Following the item review, the questions requiring improvement were revised, and the eight-item assessment was used for the pretest and posttest. Scores were interpreted at the overall test level.

Data Analysis

Individual pretest and posttest scores were paired and analyzed using JASP. Means, standard deviations, medians, minimums, and maximums were calculated for both assessment occasions. Individual paired changes were also examined to describe the direction and variability of performance differences.

The paired-samples t-test was specified to evaluate the mean difference between pretest and posttest scores, with 95% confidence intervals. Normality of the paired score differences was assessed using the Shapiro–Wilk test. A Wilcoxon signed-rank test was also applied to provide a complementary nonparametric

assessment of the paired differences. Two-sided tests were used with a significance level of .05. Effect-size measures were considered to describe the magnitude of differences between the two assessments.

RESULTS AND DISCUSSION

Results

Students' critical thinking performance was examined through pretest and posttest assessments conducted in the context of scientific approach-based wave physics learning. The initial stage of the analysis focused on descriptive characteristics of the scores in order to identify differences in central tendency, dispersion, and score distribution across the two assessment occasions. These descriptive indicators provide an overview of how students' assessed performance shifted from the beginning to the end of the instructional sequence. The corresponding summary statistics for the 28 participating students are presented in Table 2.

Table 2. Descriptive Statistics of Students' Critical Thinking Performance

Assessment	N	M	SD	SE	Median	Min	Max	Q1	Q3
Pretest	28	47.214	5.287	0.999	47.000	37	53	44	53
Posttest	28	83.179	9.911	1.873	84.500	56	97	81	90

Note. M = mean; SD = standard deviation; SE = standard error; Q1 = 25th percentile; Q3 = 75th percentile.

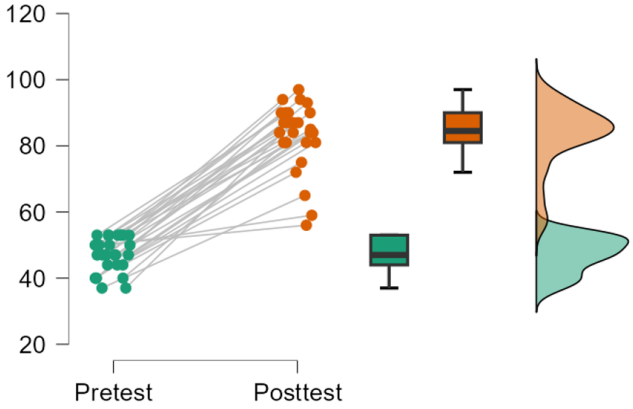
The descriptive statistics in Table 2 indicate a substantial upward shift in students' critical thinking performance between the two assessments. The mean score increased from 47.214 in the pretest to 83.179 in the posttest, corresponding to an average increase of 35.964 points. A similar pattern is visible in the median values, which rose from 47.000 to 84.500. The minimum and maximum scores also moved upward, from 37-53 in the pretest to 56-97 in the posttest. These results show that the distribution of posttest scores was located considerably higher than the distribution of pretest scores.

The variability of students' critical thinking performance also differed across the two assessment occasions. The standard deviation increased from 5.287 in the pretest to 9.911 in the posttest, indicating that score dispersion became wider after the instructional sequence. However, the interquartile range remained stable at nine points, with the middle 50% of scores extending from 44 to 53 in the pretest and from 81 to 90 in the posttest. This pattern suggests that the increase in overall dispersion was influenced primarily by observations outside the central portion of the distributions, while the central cluster of scores remained relatively compact.

To complement the numerical summary, the distributions of pretest and posttest scores were visualized using a raincloud plot that combines paired observations, boxplots, and density curves. This figure makes it possible to inspect the relative position of the two score distributions while also displaying the direction of change for each participant. Figure 2 therefore provides a visual comparison of the two assessments by integrating individual trajectories with distributional features, allowing the descriptive differences identified in Table 2 to be examined in a more detailed manner.

Figure 2 shows a clear separation between the two score distributions. The pretest scores were concentrated in the lower portion of the scale, with most observations clustered around the mid-40s to low-50s. In contrast, the posttest

scores were concentrated much higher, primarily within the low-80s to low-90s. The boxplots reinforce this difference by showing a substantially higher median and interquartile range for the posttest condition. The density curves also confirm that the central mass of the posttest distribution was shifted upward relative to the pretest distribution.



Note. The figure combines paired observations, boxplots, and density curves for the pretest and posttest scores (N = 28).

Figure 2. Raincloud Plot of Students' Critical Thinking Performance

The paired observations displayed in Figure 2 further show that all participant trajectories moved upward from pretest to posttest. No student recorded a lower or unchanged score in the second assessment, indicating a consistent direction of change across the participating group. At the same time, the spacing among the posttest points was wider than among the pretest points, which is consistent with the larger posttest standard deviation reported in Table 2. Thus, the figure not only demonstrates a higher overall level of performance in the posttest, but also reveals that the magnitude of improvement varied across students.

To determine whether the observed differences between pretest and posttest scores were statistically significant, paired inferential analyses were conducted. The normality of the paired differences was examined using the Shapiro-Wilk test, which indicated a departure from normality ($W = 0.855$, $p = .001$). For this reason, the paired-samples t-test was accompanied by the Wilcoxon signed-rank test. Table 3 summarizes the statistical comparison of the two assessments, including the mean difference, confidence interval, significance values, and effect-size estimates.

Table 3. Paired Statistical Comparisons of Students' Critical Thinking Performance

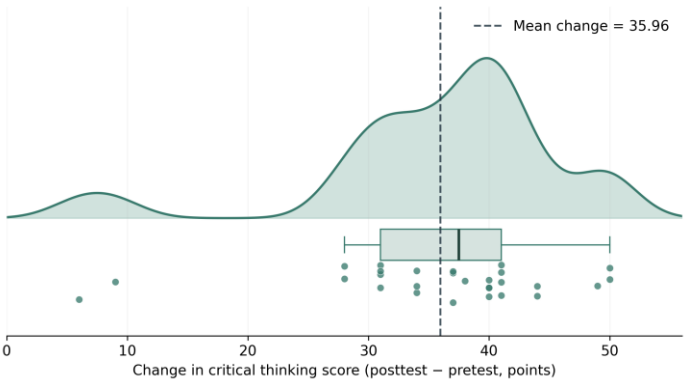
Analysis	Statistical indicator	Estimate	p
Paired-samples t-test	t(27)	-18.929	< .001
	Mean difference	-35.964	-
	95% CI	[-39.863, -32.066]	-
	Cohen's d (correlation-corrected)	-4.412	-
Wilcoxon signed-rank test	W	0	< .001
	Matched rank-biserial correlation	-1.000	-

Note. N = 28. Differences were calculated as Pretest - Posttest; negative values indicate higher posttest scores. CI = confidence interval.

The paired-samples t-test revealed a statistically significant difference between pretest and posttest critical thinking scores, $t(27) = -18.929$, $p < .001$. The estimated mean difference was -35.964 points, with a 95% confidence interval extending from -39.863 to -32.066. Because the difference was calculated as pretest minus posttest, the negative estimate indicates higher scores in the posttest. The confidence interval did not include zero, which supports the conclusion that the two assessments differed statistically. These findings demonstrate a large separation between the average levels of performance observed before and after the instructional sequence.

The nonparametric analysis produced the same overall conclusion. The Wilcoxon signed-rank test yielded $W = 0$ with $p < .001$, indicating that the difference between the two assessments remained statistically significant when examined using a rank-based procedure. The matched rank-biserial correlation was -1.000, reflecting the uniform direction of the paired differences under the pretest minus posttest convention. In addition, the correlation-corrected Cohen's d from the paired-samples t-test was -4.412, indicating a very large standardized difference. Taken together, the inferential results consistently show that posttest performance exceeded pretest performance.

The magnitude and distribution of individual score changes were further examined to complement the inferential statistics. Whereas Table 3 summarizes the statistical significance of the difference between the two assessments, a distributional plot provides a more detailed picture of how those changes were spread across participants. Figure 3 presents a raincloud plot of the individual changes, combining a density estimate, a boxplot, and the observed differences for each student. In this figure, changes were calculated as Posttest - Pretest so that positive values represent higher posttest scores.



Note. Changes were calculated as Posttest - Pretest (N = 28). Positive values indicate higher posttest scores; the dashed line represents the mean change.

Figure 3. Distribution of Individual Changes in Students' Critical Thinking Performance.

Figure 3 shows that the distribution of individual score changes was entirely positive, which is consistent with the upward trajectories observed in Figure 2. The mean increase was 35.964 points and the median increase was 37.500 points. The middle 50% of changes ranged from 31 to 41 points, indicating that most students

experienced substantial score gains between the two assessments. The individual observations were concentrated around the central portion of the distribution, although changes extended from 6 to 50 points. The density curve summarizes this pattern by showing a clear concentration of improvements in the range surrounding the median.

The distribution also demonstrates that the magnitude of change varied across the participating students. Most observations were grouped within a relatively narrow interval around the median, whereas a small number of participants showed more modest increases and several others recorded gains approaching 50 points. This spread indicates meaningful individual variation in the size of the improvement even though the overall direction of change was the same for all participants. Accordingly, the distributional evidence complements the inferential results by showing that the statistically significant difference between pretest and posttest scores was accompanied by positive change across the entire class.

Discussion

The findings reveal a pronounced improvement in students' critical thinking performance within scientific approach-based wave physics learning. This pattern is educationally significant because reasoning in physics involves more than recognizing scientific terminology or applying mathematical procedures. Students must interpret representations, distinguish relevant physical relationships, evaluate the consistency of explanations, and connect theoretical principles with observable phenomena. These intellectual demands are particularly evident in wave physics, where graphical representations describe dynamic processes that can be difficult to interpret through static visual information. Research on students' understanding of wave propagation has demonstrated the conceptual challenges associated with coordinating spatial representations and temporal changes, while investigations of wave equations have emphasized the importance of developing meaning beyond symbolic manipulation (Rangkuti & Karam, 2022, 2023). The present findings provide complementary evidence that critical thinking performance can change substantially within a learning context organized around the characteristics of waves. This relationship reinforces the view that scientific thinking and critical thinking are interconnected forms of disciplinary reasoning rather than interchangeable cognitive constructs (García-Carmona, 2025).

The improvement in assessed performance can also be interpreted through the relationship between conceptual understanding and the cognitive processes required to construct scientifically defensible answers. Physics problems frequently require students to decide whether a mathematical expression is physically meaningful, whether its assumptions are appropriate, and whether the resulting explanation agrees with known principles. Research on solution evaluation has shown that students often rely on computational procedures rather than systematically evaluating the physical plausibility of their answers (Akinyemi et al., 2025). Similarly, investigations of reasoning instruction have demonstrated the educational relevance of helping students recognize the difference between intuitive responses and more deliberate analytical judgments (McInerny et al., 2025). Research distinguishing conceptual knowledge from reasoning approaches further indicates that scientifically appropriate knowledge does not always translate automatically into accurate responses when students encounter unfamiliar

problems (Kellar et al., 2025). These findings suggest that critical thinking performance in wave physics should be understood through the interaction of disciplinary knowledge and evaluative reasoning. The upward change observed in the present study is consistent with this interpretation, particularly because the assessment required students to coordinate physical representations, relationships, and explanations.

The instructional organization of scientific approach-based learning offers another perspective for interpreting the observed change. The learning sequence incorporated observation, questioning, experimentation, reasoning, and communication, creating opportunities for students to engage with physical phenomena through interconnected scientific practices. These activities are consistent with contemporary accounts of physics inquiry that place evidence evaluation and the justification of conclusions at the center of investigative learning. Pols et al. (2022) conceptualized physics inquiry through students' understanding of evidence and their ability to justify investigative decisions, while subsequent research demonstrated the value of integrating argumentation into inquiry activities (Pols et al., 2023). Related work examining the development of inquiry and argumentation skills found that combining these processes can strengthen students' use of evidence and the quality of their arguments (Xiao & Kuhn, 2024). Together, these perspectives indicate that the educational significance of scientific activities emerges from the reasoning required to connect observations with claims. The present findings align with this interpretation by demonstrating improved performance following instruction that incorporated investigation, evidence-based reasoning, and scientific communication.

A central characteristic of scientific approach-based learning is its capacity to connect concrete experiences with abstract scientific representations. Wave physics is particularly relevant because students must coordinate diagrams, mathematical expressions, and conceptual descriptions to explain phenomena such as propagation, reflection, and interference. Research on representational learning has demonstrated that students' ability to interpret and translate between forms of scientific information is essential to developing coherent physical understanding (Marshman et al., 2024). Investigations of students' conceptual resources further emphasize that learners draw on different forms of prior knowledge when interpreting physical situations, and these resources influence how they organize explanations (Robertson et al., 2023). Research on qualitative inferential reasoning also highlights the importance of constructing coherent chains of explanation rather than treating conceptual understanding as equivalent to selecting correct answers (Speirs et al., 2024). Within the present instructional context, activities connecting observations, worksheets, and conceptual explanations provided opportunities for students to encounter wave phenomena through complementary forms of representation. The observed improvement is consistent with the educational significance of coordinating these representational and inferential demands during physics learning.

The findings can also be situated within broader evidence concerning inquiry-oriented instruction and the development of higher-order cognitive performance. Research syntheses have reported favorable relationships between inquiry-based learning and critical thinking, while demonstrating that educational outcomes differ

according to instructional arrangements and comparison conditions (Harapan et al., 2026). This evidence is relevant because scientific approach-based learning shares important characteristics with guided inquiry, particularly when students are encouraged to formulate questions, examine evidence, and develop explanations rather than receive completed conceptual accounts. A systematic review of critical thinking instruction has likewise highlighted the importance of learning activities that engage students in dialogue, practical investigation, and the critical examination of subject matter (Jegstad et al., 2025). Research in secondary science classrooms has further shown that collaborative questioning can support deeper engagement with scientific ideas when learning activities invite students to reconsider assumptions and elaborate their reasoning (Wijesekera & Hameed, 2026). The present findings are consistent with this wider literature, while contributing evidence from a school physics context in which critical thinking performance was examined through discipline-specific assessment tasks rather than general measures of classroom participation.

The relationship between scientific questioning and critical thinking deserves particular attention because questioning connects initial observations with the evaluation of possible explanations. Questions about wave behavior can encourage students to identify relevant variables, compare competing interpretations, and anticipate relationships among physical quantities. The resulting inquiry process requires learners to move beyond identifying observable features toward examining why particular patterns occur. Research investigating inquiry and academically productive classroom talk has reported that combining investigation with structured discussion can strengthen critical thinking in secondary education (Leung & Fung, 2026). Similarly, argumentation-based inquiry has been associated with changes in preservice teachers' understanding of scientific inquiry, the nature of science, and scientific literacy (Mesci et al., 2025). These findings suggest that questioning and dialogue serve complementary intellectual functions: questioning identifies issues requiring explanation, whereas dialogue creates opportunities to examine the adequacy of proposed answers. In the present study, the integration of questioning and communication within scientific approach-based learning provides a meaningful pedagogical context for interpreting the improvement in students' assessed critical thinking performance.

Scientific reasoning also requires learners to monitor the quality of their thinking and evaluate whether their explanations remain consistent with available information. Metacognitive processes are therefore closely connected to critical thinking, especially when physics problems involve multiple conceptual relationships or unfamiliar representations. Research involving secondary physics students has shown that metacognitive knowledge and regulation influence how learners approach, monitor, and evaluate problem-solving activities (Dulger & Ogan-Bekiroglu, 2025). Investigations of reflective prompts in physics problem solving have further demonstrated that explicit opportunities to reconsider solutions can activate evaluative strategies that students may not use spontaneously (Sijmkens et al., 2026). These findings provide a conceptual basis for understanding the role of reasoning and communication during scientific approach-based learning. When students compare observations with physical principles and articulate their conclusions, they encounter opportunities to examine the internal

consistency of their explanations. Such experiences connect the procedural dimensions of scientific investigation with the reflective and evaluative dimensions of critical thinking. The present findings are consistent with the educational relevance of these interconnected processes in physics learning.

The consistent upward direction of students' performance, accompanied by variation in the magnitude of individual changes, provides another perspective on the relationship between learning activities and cognitive development. Individual differences in physics learning can emerge from variations in prior knowledge, conceptual resources, representation use, and the organization of problem-solving strategies. Research examining secondary students' written physics solutions has identified distinct patterns of performance, demonstrating that students can differ in their capacity to structure explanations even when they engage with comparable problem-solving tasks (Meyer et al., 2026). Related research on physics learning through representations has shown that the coordination of graphical, mathematical, and conceptual information constitutes an important aspect of developing scientific understanding (Hartanto et al., 2026). Studies of wave-related laboratory activities have also documented variation across science process skills, indicating that participation in a common investigative setting does not necessarily produce identical patterns of cognitive performance (Meutia et al., 2024). The present findings are consistent with this differentiated view of learning, in which a shared instructional experience is accompanied by individual differences in the extent of observed performance change.

The interpretation of critical thinking performance also depends on recognizing its relationship with, and distinction from, conceptual understanding and scientific argumentation. Recent work on assessing wave concepts has emphasized the importance of designing tasks that capture students' understanding of physical relationships and their ability to interpret relevant information (Rasyid et al., 2025). Research using diagnostic assessments of waves, sound, and related phenomena has likewise demonstrated the value of examining how students organize and apply conceptual knowledge across connected physics topics (Fauzi et al., 2026). These perspectives are complemented by research synthesizing the relationship between critical thinking and scientific argumentation, which identifies the evaluation of claims and supporting evidence as important connections between the constructs (Fauziah et al., 2024). Studies of argument-driven inquiry in physics further suggest that investigative learning and the construction of scientific arguments can be integrated to support cognitive engagement with scientific content (Nurjannah et al., 2025). Within the present study, critical thinking was assessed through open-ended wave physics questions requiring students to work with representations, conceptual relationships, and scientific explanations. This disciplinary assessment orientation provides a meaningful connection between students' performance and the intellectual practices emphasized in contemporary science education.

The findings further highlight the importance of understanding scientific assessment as a means of examining how students make sense of disciplinary problems. A response to a physics question may reflect conceptual recognition, mathematical manipulation, inferential reasoning, and evaluative judgment, making assessment design central to the interpretation of learning outcomes. Research

examining the alignment of science assessment tasks with disciplinary practices emphasizes the need for questions that elicit students' scientific sense-making rather than merely reproduce factual information (Nguyen & Hayward, 2025). Reviews of conceptual change research in physics also show that learning involves the organization and revision of scientific ideas, with attention to the intellectual processes through which students develop more coherent explanations (Aryani et al., 2024). These perspectives support an interpretation of critical thinking performance that remains connected to scientific content while recognizing the importance of reasoning expressed through students' answers. In the present study, the use of open-ended assessment tasks situated in wave physics provides a disciplinary context for interpreting the observed improvement as a change in students' overall performance when responding to problems requiring scientific explanation and judgment.

The broader significance of the findings lies in the integration of scientific learning practices with the disciplinary reasoning demands of wave physics. Scientific approach-based learning organizes classroom experiences around observing phenomena, developing questions, examining information, reasoning with evidence, and communicating explanations. These practices provide a coherent framework for engaging students with physical situations in which conceptual understanding and critical judgment operate together. Contemporary scholarship on science instruction emphasizes the importance of meaningful guidance and the integration of investigative activities with scientific knowledge (de Jong et al., 2024). Research on scientific inquiry assessment similarly identifies question formulation, investigation, evidence interpretation, and conclusion development as interconnected components of scientific competence (Vo & Simmie, 2025). The present study contributes to this discussion by demonstrating a substantial improvement in discipline-contextualized critical thinking performance within a learning sequence organized around these practices. Its conceptual contribution is to position critical thinking as an observable dimension of students' engagement with wave physics problems, connecting scientific inquiry, representational reasoning, and evidence-based explanation within secondary physics education.

CONCLUSION

This study demonstrated a substantial improvement in secondary school students' critical thinking performance between pretest and posttest assessments conducted within scientific approach-based wave physics learning. The findings revealed a consistent upward shift in students' performance, with all participants obtaining higher scores following the instructional sequence. Descriptive analyses indicated improvements in both central tendency and overall score distribution, while the paired-samples t-test and Wilcoxon signed-rank test confirmed statistically significant differences between the two assessment occasions. These findings provide affirmative answers to the research questions by demonstrating that students' assessed critical thinking performance changed substantially and that the observed difference was statistically significant.

The study contributes to physics education research by positioning critical thinking as a discipline-contextualized learning outcome associated with scientific approach-based instructional experiences. Learning activities organized around

observing phenomena, questioning, experimenting, associating evidence with scientific concepts, and communicating explanations provided a meaningful context for engaging students with the reasoning demands of wave physics. The findings highlight the relevance of connecting graphical interpretation, conceptual relationships, and evidence-based explanations when examining students' critical thinking performance. The principal contribution of this investigation lies in documenting meaningful changes in overall critical thinking performance within an authentic secondary physics classroom, thereby enriching the empirical understanding of scientific approach-based learning in the context of wave characteristics.

LIMITATION

Several limitations should be considered when interpreting the findings. The one-group pretest–posttest design did not include a comparison group or random assignment, preventing the observed performance changes from being attributed exclusively to scientific approach-based learning. The study involved a relatively small sample from a single secondary school, which restricts the generalizability of the findings to other student populations and educational settings. The instructional sequence was implemented over a limited number of classroom meetings, and the assessment was administered immediately after instruction without a delayed follow-up to examine the retention of critical thinking performance. Furthermore, critical thinking was measured through an eight-item, wave-specific assessment, and the revised instrument was administered without an additional psychometric evaluation. The available validity and reliability evidence therefore warrants caution when interpreting measurement precision and construct coverage. The findings are consequently most appropriately understood as changes in overall assessed performance within the specific instructional context, rather than evidence of equivalent development across individual critical thinking dimensions or a definitive causal effect of the instructional approach.

RECOMMENDATION

Physics teachers are encouraged to integrate meaningful scientific practices into wave physics instruction by providing structured opportunities for students to observe physical phenomena, formulate investigable questions, examine evidence, connect experimental observations with conceptual and mathematical representations, and communicate scientifically justified explanations. Instructional activities should emphasize the quality of students' reasoning rather than procedural completion, particularly when addressing relationships among wave characteristics and interpreting graphical representations. Future research should employ controlled or quasi-experimental designs involving larger and more diverse student populations to examine the contribution of scientific approach-based learning to critical thinking performance. Longer instructional periods and delayed assessments would help establish whether observed performance changes are sustained over time. Further instrument development and validation, including more comprehensive evidence of internal structure and reliability, are also recommended to support differentiated assessment of critical thinking dimensions and improve the interpretability of learning outcomes across physics contexts.

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