



Padec-Ceta Flipped Collaborative Learning Model: An Effective Strategy to Enhance Critical Thinking Skills in Physics Education

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ABSTRACT

Purpose - Critical thinking is essential in physics education, requiring students to analyze phenomena, evaluate evidence, construct explanations, and develop solutions. This study aimed to develop and evaluate the validity, practicality, and initial effectiveness of the PADEC-CETA Flipped Collaborative Learning Model in supporting students' critical thinking skills.

Methodology - The study employed a research and development design using the ADDIE framework: Analyze, Design, Develop, Implement, and Evaluate. Model validity was assessed by three validators using 18 indicators, while two lecturers and ten students evaluated practicality. Initial effectiveness was examined with 26 students using a one-group pretest-posttest design. Data were analyzed using normalized gain, the Shapiro-Wilk test, and the Wilcoxon signed-rank test.

Findings - The model achieved a validity score of 3.80/4.00 (94.91%), categorized as very valid, and a practicality score of 95.28%, categorized as very practical. Students' mean critical thinking score increased from 57.12 (SD = 6.50) to 79.81 (SD = 6.12), with a mean gain of 22.69 points. The mean normalized gain was 0.540 (medium). The Wilcoxon test showed a significant improvement in critical thinking skills ($Z = -4.534$, $p < .001$), with 26 positive ranks and no negative ranks or ties. The effect size ($r = 0.889$) indicated a very large effect. However, the one-group design limits causal inference.

Significance - This study presents a validated and practical PADEC-CETA Flipped Collaborative Learning Model, an innovative learning framework that supports critical thinking in physics education. The findings provide initial empirical evidence for its potential effectiveness and a basis for further investigation using comparison groups, larger samples, multiple institutions, and longer intervention periods.

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INTRODUCTION

Critical thinking has become an important learning outcome in higher education because university students are expected not only to acquire disciplinary knowledge but also to analyze information, evaluate evidence, construct arguments, solve complex problems, and make reasoned decisions. In higher education, critical thinking is closely associated with students' ability to examine ideas objectively, reason from evidence, evaluate alternatives, and make informed judgments (Campo et al, 2023). (Persky et al., 2019) For example, emphasize that developing critical thinking requires learning experiences that deliberately engage students in analysis, evaluation, and reasoned judgment.

This need is particularly important in physics education because physics requires students to establish relationships among observable phenomena, conceptual representations, mathematical models, and scientific explanations. Students are therefore expected to move beyond recalling formulas toward interpreting phenomena, identifying relevant variables, evaluating explanations, and constructing solutions. Research in science education likewise emphasizes the complementary relationship between scientific and critical thinking (García-carmona, 2025). Evidence from physics learning also indicates that technology can support higher-order thinking when digital resources are accompanied by appropriate instructional scaffolding (Tuada & Suparno, 2021).

Nevertheless, physics instruction can still be dominated by lecturers' explanations, formula-oriented exercises, and procedural problem-solving. Such practices may support foundational knowledge but provide fewer structured opportunities for students to formulate initial explanations, compare alternative ideas, evaluate evidence, defend arguments, and communicate scientific reasoning. Consequently, active instructional approaches that place students in meaningful problems and require interaction, reasoning, and explanation are increasingly relevant. This concern is consistent with physics education research showing that inquiry-oriented and inquiry-creative learning can place greater emphasis on students' critical-thinking processes rather than on procedural answers alone (Prayogi et al., 2024). Problem-based learning, case studies, cooperative learning, project-based learning, and research activities have also been identified as potentially productive environments for critical-thinking development in higher education (Yu, 2023). Related work has reported positive contributions of project-based STEM learning to critical thinking in physics education (Nisah & Syukri, 2024).

However, the existing evidence also exposes several limitations that are important for model development. First, studies on problem-based, case-based, collaborative, and project-based learning often establish the effectiveness of individual approaches without specifying a single instructional sequence that deliberately connects problem interpretation, initial reasoning, alternative comparison, explanation, and creation. Second, collaborative learning should not be assumed to produce critical thinking merely because students work in groups. A meta-analysis of 36 studies found a substantial overall effect of collaborative problem solving on critical thinking, but also showed that learning scaffolds, group size, teaching type, intervention duration, and subject area moderate the effect; importantly, the effect on cognitive critical-thinking skills was smaller than the effect on attitudinal tendencies (Xu Enwei & Wang, 2023). This indicates that collaboration is valuable but requires a carefully designed cognitive structure. Third, flipped learning is not, by itself, an automatic mechanism for developing critical thinking. (Alten et al., 2019) In a meta-analysis of 114 studies, researchers found a small positive effect on learning outcomes and substantial heterogeneity; outcomes were more favorable when face-to-face time was maintained and when structured activities such as quizzes were incorporated. More recent synthesis likewise reports variation in flipped-learning implementation and emphasizes active learning and problem solving as important contributors (Spaic et al., 2025). Thus, simply transferring content delivery outside the classroom does not explain what students should cognitively do with the time released in class.

These limitations point to a research gap in instructional architecture rather than merely to the need to add another teaching strategy. The literature contains evidence for the value of problem-centered learning,

collaboration, case-based learning, ethnophysics, digital technology, and flipped learning. Still, these strands do not yet sufficiently explain how their distinct functions can be organized into a single theoretically coherent mechanism for the development of critical thinking in physics. Research on flipped higher education during the COVID-19 period, for example, further illustrates that implementation conditions and learning design are important when interpreting outcomes (Divjak et al., 2022), while reviews identify student engagement, learning outcomes, instructional design, and implementation challenges as recurring themes in flipped-classroom research (Baig & Yadegaridehkordi, 2023). Likewise, online collaboration can strengthen the interactive dimension of flipped learning, but collaboration must be deliberately designed rather than assumed to follow from the flipped format (Fischer & Yang, 2022). The unresolved issue, therefore, is how to construct a model in which the problem, context, technology, preparation, and collaboration have non-redundant pedagogical functions that converge on the cognitive processes underlying critical thinking.

The present study develops PADEC (Problem, Answer, Discuss, Explain, and Create) as the core instructional sequence. PADEC is conceptually related to the RADEC learning model (Read, Answer, Discuss, Explain, and Create), which has been proposed as an instructional approach for developing critical thinking within the Indonesian educational context (Nurhalimah et al., 2025). The distinction introduced in PADEC is theoretically consequential: the initial Read stage is replaced by Problem so that a disciplinary problem becomes the cognitive trigger for subsequent reasoning. Students first interpret a physics problem and formulate an initial answer; they then discuss and compare their ideas, explain the scientific basis of their reasoning, and finally create a solution, representation, or product. The sequence, therefore, provides an explicit cognitive pathway: Problem activates interpretation and problem representation; Answer elicits preliminary reasoning or hypothesis formation; Discuss exposes students to alternative claims and creates opportunities for comparison and evaluation; Explain requires justification and evidence-based reasoning; and Create requires synthesis, transfer, and production of an improved solution. The model is thus designed to operationalize critical-thinking processes within the instructional sequence rather than treating critical thinking as an incidental outcome.

CETA (Case Ethnophysics–Thunkable AI) provides a second, theoretically distinct function. It serves as the contextual and digital learning environment through which the PADEC cognitive sequence is activated. In the present study, ethnophysics is primarily a contextual entry point: local cultural phenomena and practices provide authentic cases from which students can identify, interpret, and explain physics concepts. This distinction is important because contextualization alone does not guarantee critical thinking. Its contribution depends on whether students are required to interrogate the case, connect observable phenomena with scientific principles, compare explanations, and construct defensible solutions. Thunkable and AI-related functionality is similarly treated as a pedagogical affordance rather than as an outcome in itself. Contemporary discussion of AI in education emphasizes that technology should be designed around clearly defined pedagogical purposes (Eaton, 2025), while research on generative AI in case-based collaborative learning highlights the importance of students' perceptions and the instructional function assigned to AI-supported activities (Ouyang & Jiao, 2021). Accordingly, CETA provides the contextual authenticity and digital resources on which students perform the PADEC reasoning processes, but does not replace those processes.

The third component, Flipped Collaborative Learning, addresses the temporal and social organization of the cognitive work. In flipped learning, students engage with learning resources before class, allowing classroom time to be devoted to application, interaction, feedback, and problem-solving. However, the literature shows that flipping is effective only when the released classroom time is deliberately used for meaningful learning activities. (Alten et al., 2019) demonstrated that outcomes were more favorable when face-to-face time was maintained and when structured activities were included, while Spaic et al. identified active learning and problem solving as important elements in effective flipped environments. Collaborative learning then provides the social mechanism through which students externalize their reasoning, encounter alternative explanations, negotiate meaning, and justify decisions. The meta-analysis by Xu Enwei & Wang reinforces this point while simultaneously showing that the effects of collaborative problem solving depend

on learning scaffolds and other design conditions. Therefore, Flipped Collaborative Learning in the present model is not an additional content-delivery technique; it is the temporal-social architecture that creates the conditions for the PADEC cognitive sequence to be enacted, challenged, and refined.

The conceptual relationship among PADEC, CETA, Flipped Collaborative Learning, and critical thinking can therefore be formulated as a mechanism rather than as a simple integration. PADEC specifies what students cognitively do; CETA specifies the contextual and technological objects on which that cognitive work is performed; and Flipped Collaborative Learning specifies when and through what social arrangement the reasoning is prepared, enacted, challenged, and refined. Before class, students interact with CETA-based ethnophysics cases and preparatory resources, establishing an initial conceptual basis for the Problem and Answer stages. During class, the flipped structure releases time for Discuss and Explain, while collaboration exposes students to alternative claims and requires them to provide reasons and evidence. The contextual authenticity of CETA makes the reasoning meaningful, whereas the Create stage requires students to synthesize physics concepts, evidence, and contextual understanding into a solution or representation. Critical thinking is consequently expected to emerge from the cumulative interaction of these functions: contextual authenticity provides something meaningful to reason about; PADEC structures the reasoning process; collaboration makes reasoning visible and contestable; and the flipped design provides the time needed for deeper application and refinement.

This theoretical architecture also clarifies why the proposed model should not be characterized merely as a combination of several existing approaches. Such a description would imply that PADEC, CETA, and Flipped Collaborative Learning are additive components whose effects simply accumulate. In contrast, the proposed model assigns non-redundant and complementary functions to each component. PADEC functions as the central instructional-cognitive mechanism; CETA functions as the contextual-technological affordance system; and Flipped Collaborative Learning functions as the temporal-social orchestration system. Critical thinking is positioned as the outcome of repeated opportunities to interpret problems, formulate claims, compare alternatives, evaluate evidence, explain reasoning, and create solutions. This argument is consistent with the literature showing that active and inquiry-oriented learning can support higher-order reasoning (Prayogi et al., 2024), that contextual and case-oriented learning can provide meaningful situations for reasoning, and that the effectiveness of flipped and collaborative environments depends strongly on their instructional design.

The research gap can therefore be stated more precisely. Previous studies have established that PADEC can be positioned as a critical-thinking-oriented learning sequence (Nurhalimah et al., 2025), that flipped learning can improve learning outcomes under appropriate design conditions (Alten et al., 2019) (Spaic et al., 2025), that collaborative problem solving can foster critical thinking, but is sensitive to scaffolding and implementation conditions (Xu Enwei & Wang, 2023), and that contextualized and technology-supported physics learning can support higher-order thinking (Tuada & Suparno, 2021). Nevertheless, these studies do not sufficiently provide a theoretically specified model in which a problem-triggered cognitive sequence, ethnophysics-based contextualization, digital affordances, and flipped collaborative orchestration are deliberately coupled to produce a coherent pathway toward critical thinking in Physics Education. The gap is therefore not simply that PADEC, CETA, and Flipped Collaborative Learning have been studied together only rarely. More fundamentally, the literature lacks an instructional model that explains why these components should interact, what function each component performs, and how their interaction is expected to generate critical-thinking processes in physics learning.

Accordingly, the novelty of the present study lies in the development of a theoretically organized instructional model rather than in the aggregation of existing pedagogical components. PADEC provides a problem-triggered cognitive progression; CETA embeds this progression in ethnophysics cases and technology-supported representations; and Flipped Collaborative Learning provides the temporal and social conditions for students to prepare individually and reason collaboratively in class. The resulting architecture is designed specifically for physics learning, where critical thinking requires students to connect phenomena,

evidence, representations, mathematical or conceptual models, and scientific explanations. The study, therefore, aims to develop and initially evaluate the validity, practicality, and effectiveness of the PADEC-CETA Flipped Collaborative Learning Model in supporting the critical thinking skills of Physics Education students, particularly in fluid physics.

METHODOLOGY

Research Design

This study employed a research and development (R&D) approach to develop and initially evaluate the PADEC-CETA Flipped Collaborative Learning Model for Physics Education. The development procedure adopted the ADDIE framework, which consists of five stages: Analyze, Design, Develop, Implement, and Evaluate. The Analyze stage was conducted to identify learning problems, students’ needs, the characteristics of physics learning, and the learning requirements associated with the development of students’ critical thinking skills (Engelia & Wardana, 2025). The Design stage focused on formulating the conceptual structure, learning syntax, supporting components, and integration of PADEC, CETA, and Flipped Collaborative Learning. The Develop stage involved constructing the learning model and its supporting learning components, followed by expert validation.

The Implement stage involved applying the developed model in Physics Education learning, while the Evaluate stage assessed its validity, practicality, and initial effectiveness. The use of a staged instructional-design framework is also consistent with recent work proposing an AI-incorporated ADDIE approach for contemporary education, although the present study applies ADDIE specifically to the development of the PADEC-CETA model (Ussainova et al., 2025). The overall R&D orientation is also consistent with Creswell’s (2014) treatment of research design as a systematic process for aligning research questions, procedures, and evidence.

The PADEC-CETA Flipped Collaborative Learning Model integrates three complementary instructional components. PADEC functions as the central instructional sequence consisting of Problem, Answer, Discuss, Explain, and Create. The Problem stage introduces students to a physics problem or phenomenon as the starting point for learning. In the Answer stage, students formulate their initial responses based on their existing knowledge. The Discuss stage provides opportunities for students to compare ideas, examine alternative explanations, and develop solutions collaboratively. In the Explain stage, students communicate and justify their scientific reasoning, while the Create stage requires students to synthesize their understanding into an appropriate solution, representation, or learning product. CETA, which refers to Case Ethnophysics-Thunkable AI, is integrated as the contextual and digital component of the model by connecting physics learning with ethnophysics cases and digital learning resources. Meanwhile, the Flipped Collaborative component organizes learning through preparatory and collaborative activities, allowing classroom learning to emphasize discussion, analysis, argumentation, problem-solving, and explanation.

The effectiveness data available for the present article consisted of one group of 26 students with paired pretest and posttest scores. Therefore, the effectiveness phase was analyzed using a one-group pretest–posttest design:

Table 1. One-group pretest–posttest design

Group	Pretest	Treatment	Posttest
Physics Education students	O ₁	X	O ₂

O₁: represented the pretest of critical thinking, X: represented learning using the PADEC-CETA-Flipped Collaborative model, and O₂: represented the posttest.

Participants

The research participants were divided into groups based on the stage of model development and evaluation. Three validators assessed the validity of the developed model using an instrument comprising 18

indicators. Two lecturers and ten students assessed the model's practicality. The initial effectiveness evaluation involved 26 Physics Education students from Universitas Sulawesi Barat.

Data Collection

Although the original proposal described a non-equivalent control group design, no control-group dataset was available for this analysis. Therefore, no control group was created or inferred. The effectiveness data were obtained by administering the pretest before the model's implementation and the posttest after the learning process. The number of implementation meetings was not specified in the available research documentation and was therefore not included in the present study.

Data were collected using a model validation instrument, a practicality questionnaire, and a critical thinking test. The validation instrument was used to assess the conceptual foundation, instructional syntax, CETA integration, Flipped Collaborative integration, supporting system, implementation, and overall integration of the developed model. The practicality questionnaire was administered to lecturers and students to gather information on the model's usability and feasibility during implementation. Students' critical thinking skills were measured using pretest and posttest scores. Since the available dataset contained overall critical thinking scores rather than indicator-level scores, the analysis focused on students' overall critical thinking performance. The use of complementary evidence from model validation, practicality assessment, and learning outcomes also reflects the broader methodological principle that different forms of evidence should be integrated carefully when addressing a multifaceted educational intervention (Säfström et al., 2025).

Instrument

The validation instrument consisted of 18 indicators and was used to assess the conceptual foundation, instructional syntax, CETA integration, Flipped Collaborative integration, supporting system, implementation, and overall integration of the developed model. The practicality questionnaire was administered to two lecturers and ten students to gather information on the model's usability and feasibility during implementation. Students' critical thinking skills were measured using pretest and posttest scores. Since the available dataset contained overall critical thinking scores rather than indicator-level scores, the analysis focused on students' overall critical thinking performance.

Data Analysis

The collected data were analyzed using descriptive and inferential statistical procedures. Validation and practicality data were analyzed descriptively by calculating mean scores and percentages according to the predetermined assessment criteria. Students' critical thinking scores were analyzed using descriptive statistics, including the mean, median, standard deviation, variance, minimum, maximum, and range.

Learning improvement was additionally examined using normalized gain (N-gain), calculated as $g = (\text{Posttest} - \text{Pretest}) / (100 - \text{Pretest})$, with 100 representing the maximum possible score. The normality of the paired difference scores was examined using the Shapiro-Wilk test to determine the appropriate inferential procedure. When the normality assumption was not satisfied, the Wilcoxon signed-rank test was used as the primary inferential analysis to examine differences between pretest and posttest scores. A paired-samples t-test was considered only as a supporting parametric analysis. The effect size for the Wilcoxon signed-rank test was calculated using $r = Z/N$. Statistical significance was evaluated at an alpha level of .05.

This methodological procedure was designed to provide evidence regarding the validity, practicality, and initial effectiveness of the PADEC-CETA Flipped Collaborative Learning Model while maintaining an appropriate distinction between the research procedures and the empirical findings. Because the effectiveness evaluation employed a one-group pretest-posttest design without a comparison group, the analysis was intended to examine changes in students' critical-thinking performance following implementation rather than to establish a definitive causal effect of the model.

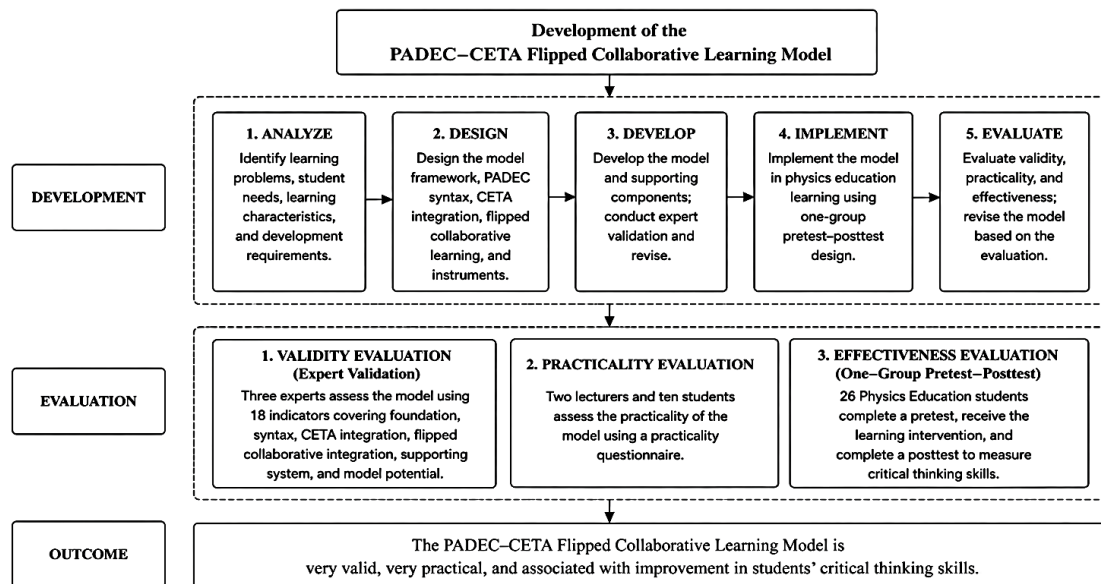


Figure 1. Research Flow for PADEC-CETA Flipped Collaborative Learning Model

FINDINGS

The results of the study provide evidence regarding the validity, practicality, and initial effectiveness of the PADEC-CETA Flipped Collaborative Learning Model in Physics Education. The findings are presented based on the expert validation, practicality assessment, and pretest-posttest evaluation of students' critical thinking skills.

The developed model is organized through an integrated learning sequence that combines the PADEC instructional syntax with CETA and flipped collaborative learning principles. The sequence is designed to guide students progressively from engaging with physics problems and formulating initial ideas to discussing, explaining, and creating solutions through collaborative learning activities. The integration of these components provides a structured learning pathway that incorporates contextual physics cases and digital learning resources. In contrast, collaborative activities provide opportunities for students to exchange ideas, develop explanations, and construct solutions. The overall learning flow of the PADEC-CETA Flipped Collaborative Learning Model is illustrated.

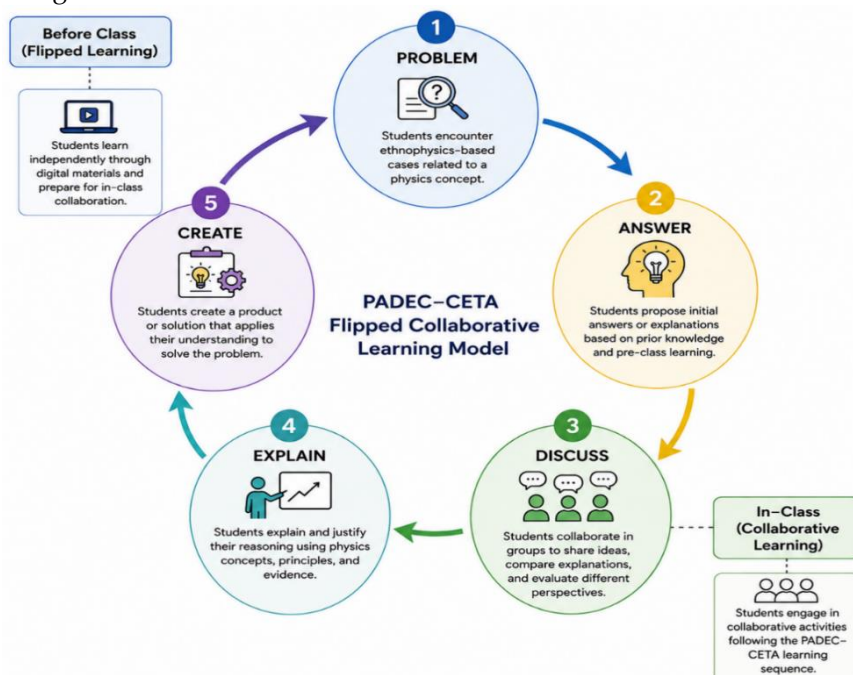


Figure 2. PADEC-CETA Flipped Collaborative Learning Model.

The learning flow of the PADEC-CETA Flipped Collaborative Learning Model is an integrated cognitive, contextual, and social learning architecture. The process begins with pre-class independent learning through digital materials, which prepares students with initial knowledge before entering the collaborative classroom environment. The Problem phase subsequently introduces ethnophysics-based cases as contextual triggers for physics reasoning. In contrast, the Answer phase requires students to articulate initial explanations based on their prior knowledge and preparation. These initial ideas are then subjected to collaborative examination in the Discuss phase, where students compare, evaluate, and refine alternative explanations. The Explain phase further requires students to justify their reasoning using physics concepts, principles, and evidence, before the Create phase engages them in synthesizing their understanding into a solution or product. Thus, the five PADEC phases establish a progressive cognitive pathway from problem engagement and initial reasoning to evaluation, justification, and synthesis, while the CETA context and flipped collaborative structure provide the contextual, digital, and social conditions that support this progression. This integrated flow is particularly relevant to the development of critical thinking because students are repeatedly required not merely to produce answers but to examine, justify, and reconstruct their reasoning throughout the learning process.

The expert validation results showed that the developed PADEC-CETA Flipped Collaborative Learning Model achieved an overall score of 94.91%, with a mean score of 3.80 out of 4.00, and was categorized as very valid. The validation was conducted by three experts with complementary expertise relevant to the model development, comprising a physics education learning expert, a learning media expert, and a physics learning developer. Their evaluation covered the model's foundation and rationale, PADEC syntax, CETA integration, Flipped Collaborative integration, supporting systems and implementation, and the model's overall integration and potential. The highest scores were obtained for the model foundation and rationale, PADEC syntax, Flipped Collaborative integration, and supporting system and implementation, each reaching 97.22%, indicating strong expert agreement on the model's conceptual foundation, instructional sequence, learning organization, and implementation feasibility. CETA integration achieved 91.67%, while model integration and potential achieved 94.44%, suggesting that the contextual and digital components were considered appropriate. However, there are opportunities for further refinement in their integration with the overall instructional architecture. Overall, the validation results indicate that the model demonstrates strong conceptual and instructional coherence, as evidenced by expert evaluation, particularly in the alignment of its learning syntax, collaborative structure, supporting system, and intended implementation in physics education.

Table 2. Model Validation Results

Validation Aspect	Percentage	Category
Model foundation and rationale	97.22%	Very valid
PADEC syntax	97.22%	Very valid
CETA integration	91.67%	Very valid
Flipped Collaborative integration	97.22%	Very valid
Supporting system and implementation	97.22%	Very valid
Model integration and potential	94.44%	Very valid
Overall	94.91%	Very valid

The practicality assessment also demonstrated a very high level of feasibility. The assessment conducted with two lecturers produced a score of 94.17%, while the assessment from ten students reached 95.50%. The combined practicality score was 95.28%, corresponding to a mean score of 3.81 out of 4.00, and was categorized as very practical.

Table 3. Model Practicality Results

Respondent	Percentage	Category
Lecturers	94.17%	Very practical
Students	95.50%	Very practical
Combined	95.28%	Very practical

The effectiveness evaluation involved 26 Physics Education students using a one-group pretest-posttest design. Students' mean critical thinking score increased from 57.12 (SD = 6.50) in the pretest to 79.81 (SD = 6.12) in the posttest. The resulting mean difference was 22.69 points. The median increased from 57.00 to 79.50, while the minimum and maximum scores increased from 46 and 69 in the pretest to 69 and 90, respectively.

Table 4. Descriptive Statistics of Critical Thinking Scores

Statistic	Pretest	Posttest
N	26	26
Mean	57.12	79.81
Median	57.00	79.50
SD	6.50	6.12
Variance	42.19	37.44
Minimum	46	69
Maximum	69	90
Range	23	21

The normalized gain analysis showed a mean N-gain of 0.540, with a median of 0.539 and a standard deviation of 0.075. The minimum N-gain was 0.415, while the maximum was 0.677. Based on the predetermined criteria, the mean N-gain was classified as medium. All 26 students were classified as medium.

Table 5. Normalized Gain Results

Statistic	Value
N	26
Mean	0.540
Median	0.539
SD	0.075
Minimum	0.415
Maximum	0.677

The Shapiro-Wilk test was conducted on the paired difference scores to assess whether the data met the assumption of normality. The analysis yielded $W = 0.881$, $p = .006$, indicating that the paired differences were not normally distributed. Therefore, the Wilcoxon signed-rank test was used as the primary inferential analysis.

The Wilcoxon signed-rank test indicated a statistically significant difference between students' pretest and posttest critical thinking scores ($Z = -4.534$, $p < .001$). All 26 students demonstrated higher posttest scores than their corresponding pretest scores, resulting in 26 positive ranks, no negative ranks, and no ties. The effect size was $r = .889$, indicating a very large within-group effect.

Table 6. Wilcoxon Signed-Rank Test Results

Statistic	Result
N	26
Positive ranks	26
Negative ranks	0
Ties	0
Z	-4.534
p	< .001
Effect size (r)	.889
Effect interpretation	Very large

As a supporting parametric analysis, the paired-samples *t*-test produced $t(25) = 119.247$, $p < .001$, with a mean difference of 22.69 points and a 95% confidence interval ranging from 22.30 to 23.08. The results of the descriptive analysis, N-gain analysis, and Wilcoxon signed-rank test consistently indicate an increase in students' critical thinking scores following implementation of the learning model.

DISCUSSION

The findings provide promising initial evidence that the PADEC-CETA Flipped Collaborative Learning Model is a coherent and feasible instructional architecture for supporting critical thinking in physics learning. However, the principal contribution of the model should not be interpreted simply from the magnitude of the pretest-posttest change. Because the effectiveness evaluation used a one-group pretest-posttest design without a comparison group, the present evidence does not permit the model to be claimed as empirically superior to problem-based learning, flipped learning, collaborative learning, or other approaches. Rather, its potential advantage lies in the deliberate integration of functions that are often implemented separately: PADEC structures the cognitive progression, CETA supplies contextual and digital resources, ethnophysics provides meaningful phenomena as an entry point, AI-supported resources extend the digital learning environment, and Flipped Collaborative Learning reallocates instructional time toward interaction and higher-order activity. The theoretical significance, therefore, lies in how these components are organized into a single learning pathway rather than in the independent effect of any one component.

The strongest conceptual contribution is the positioning of PADEC as the model's cognitive backbone. The sequence Problem-Answer-Discuss-Explain-Create does more than provide five procedural steps; it creates a progression from cognitive activation to cognitive revision and knowledge production. Conventional physics instruction may begin with exposition and then move toward exercises, whereas PADEC begins with a problem that requires students to interpret a situation before formal explanations are established. The Answer stage makes students' initial conceptions explicit, creating an object that can subsequently be examined rather than leaving their reasoning implicit. The Discuss stage then introduces social comparison of ideas, while the Explain stage requires students to articulate and justify the reasoning underlying their position. Finally, Create requires students to transform the resulting understanding into a solution, representation, or product. This progression is theoretically relevant to critical thinking because the problem initiates analysis, evaluation is stimulated by comparison among explanations, justification is made visible through explanation, and synthesis is required in the creation stage. Thus, the distinctive value of PADEC is the sequencing of cognitive demands rather than merely increasing the amount of student activity. This interpretation is consistent with the broader rationale of RADEC-based learning and with previous evidence concerning case-based RADEC learning in higher education (Hutapea B, 2024; Nurhalimah et al., 2025).

The Problem stage is particularly important for distinguishing PADEC from approaches that prioritize content transmission over problem engagement. In physics, a problem is not only an exercise to be solved after instruction; it can function as an epistemic trigger that requires students to determine what is known, what is uncertain, what evidence is relevant, and what explanation might account for a phenomenon. The Answer stage preserves this initial reasoning by requiring students to commit to an explanation based on prior knowledge. This commitment is pedagogically important because critical thinking develops through the examination and possible revision of claims, not merely through exposure to correct information. When students subsequently enter the Discuss stage, their initial answers become resources for comparison and challenge. The Explain stage further externalizes reasoning, making the quality of an explanation open to scrutiny. In this sense, PADEC creates a recurring cycle of claim formation, comparison, justification, and reconstruction that is particularly well-suited to the epistemic demands of physics. The model, therefore, extends the logic of problem-centered learning by specifying what students should cognitively do before, during, and after collaborative problem engagement.

CETA contributes a different function from PADEC and therefore should not be regarded as an additional syntax. CETA (Case Ethnophysics-Thunkable AI) operates as the contextual and digital layer through which the PADEC sequence is supplied with meaningful physics cases and interactive learning resources. The ethnophysics component is particularly relevant because it connects abstract physics concepts to phenomena

embedded in students' local cultural environment. Such contextualization can reduce the distance between observable experience and formal physics representation, which is important in physics because students must continually move between phenomena, conceptual models, and scientific explanations. The value of ethnophysics in this model, therefore, is not simply that it makes learning more culturally familiar; it provides a concrete situation from which students can generate questions, formulate explanations, compare interpretations, and connect formal physics concepts with lived phenomena. This gives the Problem stage an authentic epistemic context and gives subsequent discussion and explanation a substantive object of analysis. Previous ethnoscience and ethnophysics research has reported potential contributions to physics literacy and critical thinking, supporting the use of culturally meaningful contexts while not establishing an independent causal effect in the present study (Idul & Fajardo, 2023; Kasim, 2025).

The AI component should be approached with greater caution. Thinkable AI expands the digital environment by enabling interactive learning resources and technology-supported engagement, but the present data do not isolate AI as an independent treatment factor. Consequently, the contribution of AI cannot be reduced to the claim that AI itself caused the observed improvement. Its more defensible theoretical role is as an enabling resource within an instructional architecture in which students still have to formulate answers, discuss alternatives, explain reasoning, and create solutions. This distinction is important because technology becomes educationally meaningful when its affordances are aligned with a cognitive task. In PADEC-CETA, AI-supported digital resources can support access to representations, interaction, feedback, or exploration, but the critical-thinking demand remains located in students' reasoning activities. This position is consistent with the argument that AI in education should be designed around pedagogical purposes rather than treated as an educational outcome in itself (Eaton, 2025) and with the view that AI-supported learning should be interpreted in relation to the instructional paradigm in which it is embedded (Ouyang & Jiao, 2021). The relatively lower validation score for CETA integration (91.67%) compared with PADEC syntax and Flipped Collaborative integration (97.22%) further suggests that the digital and contextual layer is appropriate but may require continued refinement in instructional alignment.

Flipped Collaborative Learning provides the temporal and social architecture that allows the PADEC cognitive sequence to operate more intensively during face-to-face learning. The flipped component shifts preparatory engagement with learning resources to before class, thereby making it possible to use classroom time for activities that are difficult to accomplish through transmission-oriented instruction alone. However, flipping content does not automatically generate critical thinking. Its contribution emerges when the released classroom time is deliberately devoted to collaborative analysis, argumentation, explanation, and problem-solving. This is precisely the function served by the Discuss, Explain, and Create stages of PADEC. In other words, the model does not merely combine flipped learning with collaborative learning; it links the temporal structure of flipping to a defined cognitive sequence. This alignment provides a theoretical explanation for why the flipped component can strengthen the model: preparation occurs before class, while the more cognitively demanding processes are concentrated in collaborative classroom activity. This interpretation is consistent with meta-analytic evidence that the benefits of flipped learning depend on how face-to-face time is designed and used, particularly through structured active learning and problem solving (Alten et al., 2019; Spaic et al., 2025), as well as research emphasizing the importance of deliberately designed collaboration in flipped environments (Baig & Yadegaridehkordi, 2023; Fischer & Yang, 2022).

The specific strength of the integrated model consequently lies in complementarity rather than accumulation. PADEC answers the question of how cognitive activity should progress; CETA answers the question of what contextual and digital resources can mediate that activity; ethnophysics answers the question of how physics problems can be situated in meaningful local phenomena; AI provides digital affordances that can support interaction with those resources; and Flipped Collaborative Learning answers the question of when and through what social arrangement the activities should occur. Removing one layer changes the instructional function of the whole system. For example, a flipped environment without a structured cognitive sequence may simply move lectures outside the classroom without guaranteeing higher-order activity. A problem-based approach without contextual and digital support may generate problems but provide fewer

mechanisms for connecting them to students' cultural experiences or interactive representations. Ethnophysics without structured discussion and explanation may provide meaningful contexts without ensuring systematic critical examination. Similarly, AI without a defined pedagogical task may increase technological complexity without necessarily increasing reasoning quality. The model's theoretical novelty therefore resides in the functional alignment among these layers: contextual problem → individual response → collaborative comparison → scientific justification → creation, supported by preparation before class and contextual-digital resources throughout the process.

This integrated architecture also helps explain the pattern observed in the effectiveness data. Students' mean critical thinking score increased from 57.12 (SD = 6.50) on the pretest to 79.81 (SD = 6.12) on the posttest, yielding a mean difference of 22.69 points. All 26 students demonstrated higher posttest scores than their corresponding pretest scores. The mean N-gain of 0.540 was classified as medium, indicating that the improvement was meaningful but not sufficiently large to justify an interpretation of maximal development. The Wilcoxon signed-rank test yielded $Z = -4.534$, $p < .001$, with an effect size of $r = .889$, while the supporting paired-samples t-test yielded $t(25) = 119.247$, $p < .001$, with a mean difference of 22.69 points and a 95% confidence interval of 22.30 to 23.08. These results are consistent with a substantial within-group change following implementation. More importantly for the theoretical interpretation, the direction of change is compatible with the cognitive mechanisms built into the model: students were repeatedly required to encounter a problem, articulate an initial position, confront alternative reasoning, justify an explanation, and synthesize a solution. The data therefore support the plausibility of the model's proposed mechanism, but do not establish that each component independently produced the change.

The difference between the raw score increase and the medium N-gain is theoretically informative. A 22.69-point increase indicates considerable movement in observed performance, whereas the N-gain of 0.540 indicates that the students did not approach the maximum possible improvement. This suggests that the model may be effective as a scaffold for initiating and strengthening critical-thinking processes, but that critical thinking is unlikely to be transformed through a short or isolated instructional intervention. Critical thinking involves multidimensional and domain-sensitive processes, and its development requires repeated opportunities to analyze, evaluate, justify, and reconstruct reasoning. The present findings, therefore, support a developmental interpretation: PADEC-CETA Flipped Collaborative Learning can provide a structured environment in which these processes are repeatedly practiced, but longer implementation and indicator-level measurement are necessary to determine how individual dimensions of critical thinking develop over time. (Agustinih & Yuwono, 2025; Sims et al., 2026).

The very high validity and practicality results further strengthen the instructional-design argument. Expert validation reached 94.91% (mean 3.80/4.00), with PADEC syntax and Flipped Collaborative integration each receiving 97.22%, while CETA integration received 91.67%. Practicality reached 95.28% overall, based on 94.17% from lecturers and 95.50% from students. These findings indicate that the model's architecture was considered coherent and usable by the evaluators and users involved in development. The practical implication is not simply that the model is easy to use; rather, feasibility is a prerequisite for translating a theoretically demanding learning sequence into actual classroom practice. A model that requires students to prepare before class, formulate individual answers, collaborate, explain reasoning, and create products can become impractical if its stages or supporting resources are poorly organized. The high practicality score suggests that the current integration successfully made this sequence sufficiently manageable in the investigated context. At the same time, the lower CETA validation score indicates a specific area for refinement, particularly in ensuring that contextual cases and AI-supported resources are closely aligned with the cognitive objectives of each PADEC stage.

Taken together, these findings suggest a new theoretical proposition for physics learning: critical thinking may be better conceptualized within an integrated instructional model as a process of structured epistemic progression rather than as a skill produced by a single strategy. In PADEC-CETA Flipped Collaborative Learning, students do not encounter critical-thinking activities as isolated exercises. Instead, critical thinking is embedded in a sequence in which each stage prepares the cognitive conditions for the next stage. Problems

create the need for reasoning; initial answers make reasoning explicit; discussion exposes reasoning to alternative perspectives; explanation requires justification; and creation requires synthesis and transfer. Contextual ethnophysics makes the problem meaningful, digital and AI resources provide mediational affordances, and flipped collaboration allocates sufficient classroom space for social and higher-order processing. The theoretical implication is therefore a shift from component-based thinking—asking whether problem-based, flipped, collaborative, ethnophysics, or AI-supported learning is effective—to architecture-based thinking that asks how the functions of these approaches can be deliberately aligned around a critical-thinking mechanism. This represents the principal conceptual contribution of the present model to physics education.

The findings should nevertheless be interpreted within the boundaries of the research design. The effectiveness evaluation involved only 26 students from one institutional context and used a one-group pretest-posttest design without a control or comparison group. Accordingly, the observed improvement cannot be interpreted as definitive evidence that PADEC-CETA Flipped Collaborative Learning is more effective than another instructional approach. The large within-group effect size ($r = .889$) indicates a strong and consistent pretest-posttest difference. However, it does not establish comparative superiority or rule out alternative explanations, such as maturation, testing effects, or other contextual influences. Likewise, because the available data were overall critical-thinking scores, the study cannot determine which specific critical-thinking indicators were most responsive to the model. Finally, the study did not experimentally isolate the contributions of PADEC, CETA, AI, ethnophysics, or Flipped Collaborative Learning. These limitations are important not as weaknesses of the model itself but as boundaries on the strength of the causal claims that can be made from the present evidence (Miller et al., 2020).

Future research should therefore move from initial model evaluation toward mechanism and comparative testing. A quasi-experimental or randomized comparison involving PADEC alone, flipped collaborative learning, conventional problem-based learning, and the fully integrated PADEC-CETA model would determine whether the integration provides added value beyond individual approaches. Factorial or dismantling designs could further examine the independent and interactive contributions of ethnophysics, AI, and flipped collaboration. Larger samples across multiple institutions and longer implementation periods would strengthen generalizability. At the same time, indicator-level critical-thinking measures could reveal whether the model is particularly effective for analysis, evaluation, inference, explanation, or other dimensions. Such research would allow the theoretical proposition advanced here—namely, that the model's effectiveness derives from functional alignment among cognitive sequence, contextual mediation, digital affordances, and collaborative time structure—to be tested directly rather than inferred from a single-group change.

Overall, the PADEC-CETA Flipped Collaborative Learning Model should be understood as a promising integrated instructional architecture rather than simply a combination of teaching techniques. Its distinctive contribution is the deliberate alignment of PADEC's cognitive progression with contextual ethnophysics, digital and AI-supported resources, and a flipped collaborative learning environment. The empirical findings—94.91% validity, 95.28% practicality, an increase in mean critical-thinking score from 57.12 to 79.81, a medium N-gain of 0.540, and a significant Wilcoxon result of $Z = -4.534$, $p < .001$, with $r = .889$ —provide initial support for the feasibility and potential of this architecture. The most important theoretical implication is that the development of critical thinking in physics can be designed as an integrated progression in which meaningful problems initiate reasoning, collaborative interaction challenges and refine reasoning, explanation makes justification explicit, and creation requires synthesis. Nevertheless, because the present study lacks a comparison group, these findings should be interpreted as evidence of promising within-group improvement rather than proof of superiority over alternative approaches.

CONCLUSION

The PADEC-CETA Flipped Collaborative Learning Model contributes to Physics Education by providing an integrated instructional architecture that develops critical thinking through a structured progression of problem interpretation, initial reasoning, collaborative evaluation, scientific explanation, and solution

creation. The model was assessed as highly valid (94.91%) and highly practical (95.28%), while its implementation with 26 Physics Education students was associated with an increase in mean critical thinking scores from 57.12 to 79.81. The mean normalized gain of 0.540 indicated a moderate improvement, and the Wilcoxon signed-rank test showed a statistically significant pretest–posttest difference ($Z = -4.534$, $p < .001$), with a very large within-group effect size ($r = .889$). These findings provide promising initial evidence of the model's instructional potential.

The principal theoretical contribution of the model lies in positioning PADEC as the central cognitive mechanism rather than merely as a sequence of instructional activities. The Problem–Answer–Discuss–Explain–Create progression provides an explicit pathway through which students formulate initial reasoning, encounter alternative perspectives, justify explanations, and synthesize solutions. In this architecture, CETA and ethnophysics function as contextual and digital mediators, providing meaningful physics cases and representations through which students can analyze phenomena; AI functions as a technological affordance that supports interaction with learning resources rather than as an independent source of critical-thinking development; and Flipped Collaborative Learning provides the temporal and social structure that reallocates classroom time toward discussion, explanation, argumentation, and problem solving. Thus, the theoretical contribution is not the simple aggregation of five instructional elements, but their functional alignment around a common critical-thinking process.

More specifically, the model proposes that critical thinking in physics can be supported through an epistemic progression from contextualized problem engagement to individual claim formation, collaborative examination, scientific justification, and solution construction. This extends conventional problem-oriented or flipped instruction by specifying how cognitive, contextual, technological, and collaborative functions are coordinated within a single instructional sequence. The model, therefore, offers a theoretical framework for designing physics learning environments in which critical thinking is embedded in the learning process itself rather than treated as an additional learning outcome.

However, the present study cannot empirically determine that PADEC, CETA, ethnophysics, AI, or Flipped Collaborative Learning individually contributed more strongly than the other components, nor can it establish that the integrated model is superior to alternative instructional approaches. The one-group pretest–posttest design, sample of 26 students from a single institutional context, and absence of component-level comparisons restrict causal and comparative interpretations. Accordingly, the findings should be interpreted as evidence of promising within-group improvement and theoretical coherence rather than definitive evidence of comparative effectiveness. Future research should employ comparative or factorial designs to isolate the contributions of PADEC, CETA, ethnophysics, AI, and Flipped Collaborative Learning and determine whether their integration yields an additive effect beyond the sum of their individual components. Larger samples, multiple institutions, longer interventions, and indicator-level measures of critical thinking are also needed to test and refine the model's proposed theoretical mechanism.

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