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Transformation of Critical Thinking in Environmental Education: Integration of Project-Based Learning and Technology

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Abstract

Critical thinking is essential in environmental education, helping students address ecological and sustainability challenges. However, current learning models often lack a structured framework for developing critical thinking in environmental science courses. The advancement of digital technology offers both opportunities and challenges. This research aims to develop critical thinking dimensions for environmental science courses using a project-based learning (PjBL) approach, integrated with digital technology (AI-assisted data analysis, GIS for mapping, and cloud-based tools for collaboration). The Delphi method was used to create critical thinking indicators, involving 15 experts from various fields. Data was collected via interviews, Focus Group Discussions (FGD), and a Likert scale-based validation questionnaire. Results show that the developed dimensions Inference, Clarifying & Interpretation, Analyze & Evaluate Arguments, and Explanation met validity and reliability criteria through Rasch analysis and Confirmatory Factor Analysis (CFA). Technology integration in PjBL enhances data-driven analysis and predictive modeling but may reduce critical reflection due to AI reliance. A hybrid learning approach is recommended to balance hands-on interaction with technology use. This study contributes to designing more effective strategies for improving students' critical thinking skills in environmental education.

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INTRODUCTION

Critical Thinking Skills (CTS) are essential for students to navigate complex challenges in both academic and professional contexts. These skills enable individuals to systematically analyze information, make reasoned judgments, and solve problems effectively (Ennis, 2018; Hitchcock, 2017; Rohmah et al., 2023). In today's rapidly changing world, particularly within STEM disciplines, the ability to think critically is crucial for addressing global issues and making informed decisions. As such, CTS has become a key focus in education, preparing students to think analytically, cooperatively, and creatively across various domains (Hudha et al., 2023; Ayu et al., 2021).

In the context of environmental education, the importance of CTS is even more pronounced. Environmental challenges ranging from climate change to biodiversity loss require solutions that are grounded in critical thinking. Students must not only understand environmental concepts but also develop the capacity to analyze complex ecological data, synthesize information, and devise sustainable solutions. Environmental education, therefore, necessitates a structured approach to developing CTS, ensuring that students are equipped to tackle environmental issues in both local and global contexts (Sukro et al., 2021; Haghparast & Hanum, 2014).

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One of the most effective ways to cultivate CTS in environmental education is through Project-Based Learning (PjBL) (Fadilah et al., 2023). This approach encourages students to engage with real-world problems, promoting active learning and critical reflection throughout the process. PjBL fosters skills such as problem-solving, collaboration, and analysis, all of which are core components of CTS (Luo & Wu, 2015; Chang & Hwang, 2018). Furthermore, when combined with digital technology, PjBL can enhance the learning experience by providing students with tools to collect, analyze, and interpret environmental data more efficiently. Technologies like Geographic Information Systems (GIS), Artificial Intelligence (AI) for predictive modeling, and cloud-based collaboration tools allow students to engage in more sophisticated, data-driven projects that require higher-order thinking (González, 2017; Kumar & Pande, 2017).

Despite the growing interest in the application of Project-Based Learning (PjBL) and digital technology in education, the integration of these two components for fostering Critical Thinking Skills (CTS) within the context of environmental education remains underexplored. Existing studies have demonstrated the positive impact of PjBL on students' CTS in science learning (Fadilah et al., 2023) and highlighted the role of environment-based STEAM projects in enhancing students' ability to think critically, particularly in chemistry education (Sukro et al., 2021). However, these studies tend to examine either pedagogical models or technology tools in isolation, without providing a cohesive framework that aligns CTS indicators with specific learning activities and technological affordances. Furthermore, while hybrid learning environments are known to support analytical and reflective thinking (Sujanem et al., 2018), there is still a lack of structured CTS frameworks that are empirically validated and contextually designed for hybrid PjBL models in environmental science courses.

This study addresses this gap by constructing and validating a set of CTS dimensions: Inference, Clarifying & Interpretation, Analyze & Evaluate Arguments, and Explanation, specifically tailored for hybrid project-based learning in environmental education. The novelty of this research lies in the development of CTS indicators through the Delphi method, supported by rigorous validation using Rasch analysis and Confirmatory Factor Analysis (CFA). Unlike existing models, this study integrates AI-assisted data analysis, GIS mapping, and cloud-based collaboration platforms into a unified learning framework that promotes higher-order thinking. The findings are expected to contribute to more effective learning designs that empower students to engage critically with environmental issues using both conceptual understanding and data-driven reasoning, while offering educators a valid and practical instrument to assess CTS in diverse learning environments. Accordingly, this study aims to develop critical thinking dimensions for environmental science courses through a technology-integrated PjBL approach, and to validate these dimensions to ensure their feasibility and relevance in hybrid learning environments.

METHOD

This research utilized the Delphi method to develop new dimensions of Critical Thinking Skills (CTS) relevant to project-based learning (PjBL) integrated with technology. The Delphi method is a systematic process that involves gathering expert opinions through multiple rounds of feedback to reach a consensus. This section provides a detailed explanation of the steps involved in the Delphi procedure, as well as the sampling approach, experimental design, and applied learning model.

Delphi Procedure

The Delphi method was implemented in three rounds. Each round consisted of two key components: (1) feedback from experts and (2) refinement of critical thinking dimensions based on this feedback. The procedure was designed to ensure a structured consensus on the relevant CTS dimensions for project-based learning with technology integration.

1. Round 1:
   In the first round, an initial set of critical thinking dimensions was developed based on a literature review and expert input. Experts were asked to evaluate the relevance and clarity of the proposed dimensions using a Likert scale (1-5), where 1 indicated "not relevant" and 5 indicated "highly relevant."

2. Round 2:
   Based on the feedback from the first round, the dimensions were refined and sent back to the experts for further evaluation. In this round, the experts also rated the clarity of the descriptions and the feasibility of applying each dimension in environmental education. They were asked to suggest modifications or additions to the dimensions if necessary.
3. Round 3:
   In the final round, experts reviewed the revised dimensions and provided final feedback on their agreement. The goal was to achieve a consensus on the most relevant dimensions of critical thinking in project-based environmental education. Consensus was measured by calculating the median score for each dimension; a consensus was considered achieved when 75% or more of the experts rated a dimension at least 4 on the Likert scale.

Data Coding

The responses from the experts in each round were coded according to the following steps:
- Initial Coding: Experts' feedback was transcribed and organized into categories corresponding to each dimension of critical thinking.
- Thematic Analysis: The coded data were analyzed to identify patterns, similarities, and differences across experts' opinions.
- Refinement: Based on the analysis, the dimensions were refined, and any conflicting opinions were addressed by seeking further clarification from the experts.

The coding was performed using qualitative analysis software to ensure consistency and reliability across rounds. Data were further validated using Rasch analysis to evaluate the validity of the dimensions and Confirmatory Factor Analysis (CFA) to assess the construct validity of the framework.

Sampling

The participants in this study included 25 experts selected based on their qualifications in the fields of pedagogy, technology integration, critical thinking, and environmental science. These experts were involved in all three rounds of the Delphi process to ensure that the final framework was comprehensive and relevant to both environmental education and technology-enhanced learning. Table 1 presents the distribution of expert qualifications involved in the Delphi panel.

Table 1. Expert Qualifications

Qualification	Total
Pedagogy	5
Technology	5
CTS	5
Assessment	5
Environmental Science (Science)	5

In addition to the expert panel, 175 students from four universities and two vocational schools participated in the validation phase of the final instrument. These students were selected from a range of academic disciplines, particularly those with a focus on environmental science courses, to ensure that the instrument's applicability spans diverse educational contexts. The institutional distribution of these student participants, along with their accreditation levels, is presented in Table 2.

Table 2. Institution of Instrument Testing

Level	Institution Level
University	Accredited Superior
	Accredited Excellent
	Accredited B
	Accredited C
Vocational School	Accredited Superior
	Accredited B

Experimental Design

To test the effectiveness of the developed critical thinking dimensions, an experimental study was conducted. The study followed a quasi-experimental design with two groups of students:

1. Experimental Group: This group engaged in a project-based learning model that integrated digital technology, including AI-assisted data analysis, GIS for environmental mapping, and cloud-based collaborative tools.
2. Control Group: This group participated in traditional, non-technological project-based learning activities.

The experiment was conducted over 12 weeks, with students working on environmental projects that involved data collection, analysis, and presentation. The topics covered in the projects included Environmental Impact Assessment, Sustainability Solutions, Ecological Data Analysis, and Conservation Planning.

The projects were designed to encourage students to apply critical thinking in real-world environmental problem-solving, utilizing both the skills developed through PBL and the technological tools integrated into the learning process. The students' critical thinking skills were assessed at the beginning and end of the study using pre- and post-tests designed to measure the CTS dimensions developed during the Delphi process. To provide a clearer overview of the research design and methodological procedures from the formulation of the problem to data interpretation, the overall research workflow is summarized in Figure 1.

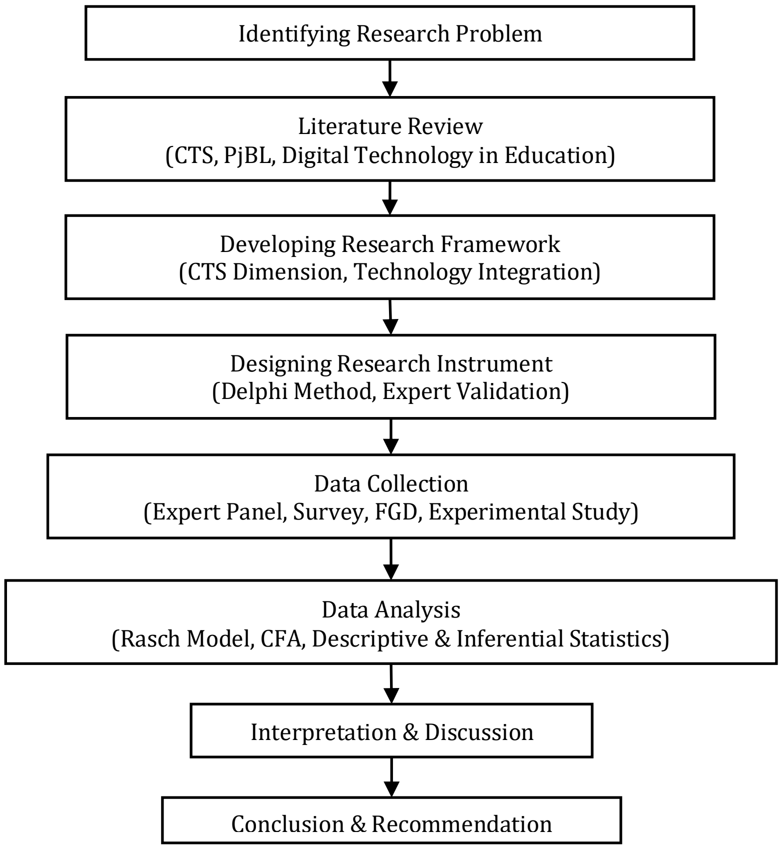

Figure 1. Research Flowchart

RESULTS AND DISCUSSION

Instruments and Dimensions of CTS

Several studies have shown that CTS have been measured using questions of choosing answers (matching questions, multiple choice questions), arising (essay questions, short answer questions, and project questions), and has explained (giving reasons for a choice or answer chosen in a question (Rahmawati et al., 2021). Watson and Glaser have developed several choices of questions to measure CTS, namely with a choice of questions related to a phenomenon and facts presented in verbal indicators. Students have been asked to choose the answer according to what they think. Watson and Glaser have provided answer options for questions in the category of making inferences, namely definitely true, probably true, not enough data, probably wrong, and wrong. As for recognizing assumptions, the choice is whether there is an assumption or not. The choice in the form of a conclusion, is by deduction or the conclusion is not by deduction is an indicator of recognizing deduction. In the ability of interpretation, the choice that has been made is whether the interpretation is by the facts or not. The ability of student arguments can be seen from whether the arguments submitted are strong enough or very weak (Clark, 2014). CTS can also be seen based on the ability to find alternative solutions to solve problems using a mind map (mind map / graphic organizer). Students' answers in making mind maps can be used to see their ability to analyze problems. In addition, the ability to analyze problems can also be seen by asking 5W questions (who, why, when, where, what) and 1 H (how) to find alternative solutions to problems (Sujanem et al., 2018). Ennis has argued that assessments that have been developed to assess CTS should be more in the form of open-ended tests than multiple-choice tests, because open-ended tests are more comprehensive. Some kinds of critical thinking ability assessments in open-ended test format are: Multiple choice tests with written explanations, Critical thinking ability essay tests, and Performance assessment (Facione et al., 2016; Jufriadi et al., 2019).

There are several standardized critical thinking instruments, including the following. 1) California Critical Thinking Dispotition Inventory (CCTDI), this test has been provided from in-depth assessment (California Academic Press), to measure students' internal motivation to use CTS to solve problems and make decisions; 2) Academic Profile, 3) College Base; 4) California Critical Thinking skill Test (CCTST) which accesses critical thinking and reasoning skills both individually and in groups; 5) Collegiate Assessment of Academic Proficiency (CAAP); 6) Collegiate Learning Assessment Project (CLA); 7) Task in Critical Thinking; 8) Watson-Glaser Critical Thinking Appraisal; 9) Test of Everyday Reasoning; 10) Holistic Critical Thinking Scoring Rubric; 11) Community College Survey of Student Engagement (CCSSE); 12) Logical Reasoning developed by A. Hertzka and J.P. Guilford; 13) The Ennis-Weir Critical Thinking Essay Test, 14) New Jersey Test of Reasoning Skill; 15) Ross Test of Higher Cognitive Processes; 16) Judgment: Deductive Logic and Assumption Recognition; 17) Test of Enquiry Skills, 18) Test of Inference Ability in Reading Comprehension; and 19) Cornell Class Reasoning Test developed by R.H. Ennis, W.L. Gardiner, R. Morrow, D. Paulus, and L. Ringel.

Researchers have critically analyzed several experts' views on CTS. Some of the results of the analysis are: 1) Halpern (1994) is more focused on the orientation of CTS in problem solving and practical decision making in everyday life. Halpern has provided a detailed, but not comprehensive explanation of CTS in the cognitive domain; 2) Ennis (1996) has claimed his taxonomy of CTS is easy to understand and apply, but Ennis questions performance-based assessment on the grounds of cost, focus and context (the more realistic the performance, the more complex the problem) new problems also arise if the assessment of CTS is carried out over a long period; 3) Paul (1997) has taken into account the cognitive, affective, and conative components of CTS. The model that Paul has formulated is very flexible; it can be applied to all subject matter and at any level of thinking. Paul has put forward 8 standards to identify CTS. However, in practice, his observations become more complicated and tend to be biased. The CTS assessment instrument, based on Facione, has been widely developed and used by several researchers, especially in science research with hybrid learning. The CTS formulated by Facione has also been developed and used by the American Philosophical Association Delphi Research, which has produced various instruments to measure CTS (Facione et al., 2016). Someone who is said to think critically does not have to fulfill all aspects of critical thinking ability as a cognitive ability (Kuh et al., 2014). So that a person's critical thinking ability can be selected among several aspects according to the focus of the discipline being researched and studied. Meta-analysis has been conducted by researchers on 60 Scopus-indexed scientific articles, which have shown a correlation between the use of hybrid learning to improvement in the CTS of university students. This has been shown by the largest effect size value of 1.79 with a very large effect category (Ayu et al., 2021). The results of meta-analysis have also shown that most of the most widely used CTS instruments are instruments with the dimensions of CTS that have been proposed by Facione. Based on the review of several experts, several analyses and syntheses of several theories regarding the dimensions of critical thinking have been carried out to produce new CTS, as shown in Table 3.

Table 3. Theoretical Synthesis of Critical Thinking Dimensions

Watson (1941)	Facione (1990)	Halpern (1994)	Paul (1997)	Synthesis Result
• Inference • Recognition of Assumption • Deduction • Interpretation • Evaluation of Arguments	• Interpretation • Analysis • Inference • Evaluation • Explanation • Self regulation	• Verbal reasoning • Argument Analysis • Thinking as Hypothesis • Likehood and uncertainty • Decision Making/ problem solving	• Purpose • Attempt • Assumption • Point of View • Data and Evidence Concepts and Ideas • Inferences and Interpretations • Implications and Consequences	• Inference • Clarifying and Interpretation • Analyze and Evaluate Arguments • Explanation

The researcher has conducted a comparison of critical thinking dimensions based on the level of use by research subjects in previous studies. The results of the analysis showed that the dimensions of critical thinking most frequently used are those developed by Facione (1990), Ennis (1996), and Halpern (1994), due to their clarity, practical structure, and relevance to educational settings (Hudha et al., 2023). In contrast, the dimensions proposed by Watson (1941) are rarely used, as they are considered outdated and less aligned with modern learning contexts. Meanwhile, Paul's model (1997), though conceptually comprehensive and philosophically grounded, is often avoided in practice due to its complexity and the time required for implementation. A comparative summary of these four frameworks, Facione, Ennis, Halpern, and Paul, along with the newly synthesized dimensions, is presented in Table 4.

Table 4. Comparison of Critical Thinking Dimensions

Aspects	Facione Dimensions (1990)	Ennis Dimensions (1985,1996)	Halpern Dimensions (1994)	New Dimensions (Synthesis Result)
Main dimensions	Interpretation, Analysis, Evaluation, Inference, Explanation, Self-Regulation	Deduction, Induction, Assumption Recognition, Critical Response, Logical Thinking	Verbal Reasoning, Argument Analysis, Likelihood & Uncertainty, Decision Making	Inference, Clarifying & Interpretation, Analyze & Evaluate Arguments, Explanation
Main focus	Assess CTS in academic and professional contexts	Assess reflective and evaluative skills in a variety of contexts	Use critical thinking in everyday problem solving	Measuring critical thinking in the context of hybrid learning and PjBL Solving case-based problems in everyday life
Assessment method	California CTS Test (CCTST)	The Ennis-Weir Critical Thinking Essay Test	Halpern Critical Thinking Assessment	Essay-based test and Activity Observation Test
Context of application	Higher education, professional	Secondary and higher education	Education and work environment	Project-based higher education and hybrid learning

Aspects	Facione Dimensions (1990)	Ennis Dimensions (1985,1996)	Halpern Dimensions (1994)	New Dimensions (Synthesis Result)
Pros	Has been widely validated and has standardized assessment instruments	Using a more flexible open-ended approach	Focuses on solving practical problems	Developed specifically for project-based learning with technology integration especially environment-based learning
Weaknesses	Lack of flexibility in various learning contexts	Assessments tend to be subjective and difficult to analyze quantitatively, Difficult to conduct in longitudinal studies	Focus more on practical application than conceptual	Still being tested on environment-based learning

The description of the dimensions of CTS that are by project-based learning and technology in this study is;

1. Inference
   According to Watson (1941), inference is a person's ability to clarify phenomena based on the relationship between information and concepts, with questions in the problem (Kong, 2015). Inference indicates the ability of students to make or assess conclusions from the information presented (Valenzuela et al., 2014). Based on the definition of some experts, inference in this study has been defined as the ability of individuals to explain phenomena that occur by considering information that is relevant to a problem and its consequences based on existing data.
2. Clarifying and Interpretation
   Clarifying has been interpreted as an individual's ability to provide an explanation, which is shown by how their ability to focus and formulate questions, clarify by providing answers accompanied by an explanation of the problems given based on existing data and phenomena (Sujanem et al., 2018).
3. Interpretation is a person's ability to interpret, categorize the meaning of a question, criteria, procedures, ideas, phenomena, and data (Smith et al., 2018). These two dimensions can be combined into one definition because these abilities are interrelated and overlapping. Clarifying and Interpretation is thus defined as an individual's ability to understand, express, explain, and determine the meaning of a situation, idea, data, judgment, rule, procedure, or varied criteria.
4. Analyze and Evaluate Arguments
   Analyze has been defined as the ability to identify opinions, ideas, and analyze them (Valenzuela et al., 2014). Ennis has interpreted analysis as the ability of students to understand the context of the problem to be solved (Ayu et al., 2022). Halpern (1994) has more specifically made the Analyze dimension into Argument Analysis, which has been defined as the ability to understand and recognize an argument to support and make correct conclusions (Kong, 2015).
5. Evaluation has been defined as the ability to judge a conclusion based on the relationship between concepts and information through questions in a problem. A person can assess the credibility of a representation or other statements of one's opinion. Watson (2010) states that the Evaluation of Arguments is the ability of individuals to distinguish strong and weak arguments (Bagdasarov et al., 2017). Strong arguments are defined as relevant and realistic arguments based on existing information and phenomena (Kimmons & Hall, 2018). The ability to analyze and evaluate is a dimension of critical thinking that cannot be separated so that researchers combine this dimension into a new critical thinking dimension, namely Analyze and Evaluate Arguments which means the ability of individuals to assess the credibility of ideas, and assess a conclusion based on the relationship between data information, reasons, concepts and consequences according to the problem.

6. Explanation
   Explanation is a person's ability to express their reasoning when giving reasons for the justification of reasons for the justification of evidence, concepts, methodologies, and logical criteria based on existing information or data, where this reasoning is presented in the form of arguments (Hitchcock, 2017). Meanwhile, Ennis (1985) explains that explanation is the ability to provide reasons based on relevant facts and data in making conclusions. Based on this, the explanation dimension can be interpreted as the individual's ability to express reasoning when providing reasons for justification or refutation of results based on existing evidence, concepts, procedures, and logical criteria.

Exploration of CTS

Some activities that have had a direct impact on several dimensions of CTS include the assessment process, providing materials. Assessments have been able to be in the form of pretests and post-tests that function to determine student understanding of the concepts taught. The questions that have been given are able to train students' analytical skills, namely understanding the intended and actual inferential relationship between statements, questions, concepts, descriptions, or other forms of representation intended to answer questions (Setyonoaji & Diantoro, 2017). The presentation of materials has also had an impact on the interpretation dimension. The presentation of material through modules/writing and data has trained them to distinguish the main idea from subordinate ideas in a text; build a temporary categorization or a way of organizing a concept they learn (Pratiwi et al., 2018). Problem presentation activities have also impacted the analysis and evaluation dimensions. Presenting a problem before starting a new concept has stimulated students to identify similarities and differences between existing concepts and new concepts (Ayu et al., 2018). Some researchers have found the relationship between aspects of hybrid learning, PjBL syntax, and CTS. In its implementation, not all aspects have to appear in a learning process. These aspects can appear as part of the learning model chosen for hybrid learning. Table 5 presents the relationship between Hybrid Learning, PjBL, and CTS according to Facione (2013).

Table 5. Linkage of Hybrid Learning, PjBL with CTS

No.	Skill	HL Aspect (Technology)	PjBL Activity
1	Inference	Practicum Guidance	Planning research project
2	Clarifying	Presentation of material Practicum Discussion/collaboration	Planning research project
3	Interpretation	Presentation of material Practicum Discussion/collaboration	Planning research project
3	Analyze	Assessment Problem Presentation Practicum Structured assignment/project	Project implementation Project presentation and submission
5	Evaluate	Assessment Problem Presentation Structured assignment/project Discussion/collaboration	Project evaluation Project presentation and submission
6	Arguments	Assessment Guidance	Project evaluation
7	Explanation	Assessment Discussion/collaboration Guidance	Project presentation and submission

The coding results linking the synthesized CTS dimensions with PjBL and hybrid learning activities are summarized in Tables 6 and 7.

Table 6. Synthesis Coding Results of New Critical Thinking Dimensions and PjBL

PjBL	Inference	Clarifying	Interpretation	Analyze	Evaluate	Arguments	Explanation
Planning research project	15	15	15	2	3	4	4
Project implementation	3	5	5	15	15	15	2
Project presentation and submission	4	8	8	15	15	15	15
Project evaluation	2	5	5	15	15	15	10
Total	24	33	33	47	48	49	31
Percent (%)	40	55	55	78	80	82	52

*PjBL: Project-Based Learning

Table 7. Coding Results of Synthesis of New Critical Thinking Dimensions and Hybrid Learning

HL	Inference	Clarifying	Interpretation	Analyze	Evaluate	Arguments	Explanation
Presentation material	3	15	15	15	15	15	2
Practicum	15	15	15	15	15	15	4
Discussion	4	15	15	15	15	15	15
collaboration	4	6	3	15	15	15	6
Assessment	3	2	5	15	15	15	15
Structured assignment	3	5	6	15	15	15	10
Guidance	15	5	6	15	15	15	15
Total	47	63	65	105	105	105	67
Percent (%)	45	60	62	1	1	1	64

*HL; Hybrid Learning

The following is a review of the analysis results for the coding data in the table 7, related to the relationship between Hybrid Learning, PjBL, and critical thinking dimensions. The data has shown that the Analyze and Evaluate aspects have the highest percentages (80% and 82%, respectively), indicating that technology in Hybrid Learning greatly contributes to students' ability to analyze and critically evaluate information and arguments. Inference has a lower score (45%), indicating that the role of technology in helping students make inferences from data still needs a more systematic approach. Clarifying & Interpretation (60%) and Explanation (64%) have shown that technology is sufficient to help students understand and explain concepts, but there are still gaps in providing immersive experiences that help them clarify and interpret data better (Ayu et al., 2023).

Analyze and Evaluate also had the highest scores (78% and 80%), confirming that the project-based approach directly encouraged students to explore, critique, and assess their solutions. Clarifying & Interpretation, and Inference scored higher than Hybrid Learning (55% and 40%), indicating that project-based activities encourage students to understand and formulate questions better. Explanation (52%) is at a moderate level, indicating that students still need guidance in developing and communicating systematic explanations of their project results (Aji et al., 2023).

In general, PjBL has tended to be more effective in developing Clarifying & Interpretation and Inference aspects, while Hybrid Learning has been more effective in Analyze and Evaluate aspects. Hybrid Learning has contributed more to the process of data and technology-based analysis and evaluation, while PjBL has been more oriented towards hands-on exploration and application of concepts in real projects. To optimize the development of students' critical thinking, both approaches should be combined to cover various aspects of critical thinking more comprehensively (Hudha et al., 2023).

In conclusion, the coding data has shown that the use of technology in project-based learning can significantly improve the critical thinking dimension, but there needs to be a balance between the exploration of projects in the field and the use of AI-based technology to ensure that students continue to think critically and not just rely on technology as an instant solution (Ayu et al., 2023).

Practical activities have made students learn to understand and express the meaning or significance of various situations, data, events, rules, and procedures. Students have learnt to assess the meaning and clarify the meaning of the phenomena that appear in their practical results (Pratiwi & Ayu, 2017). Practical activities have triggered students to skilfully retrace the reasons for the phenomena. They have identified assumptions to build inferences of reasons supporting the practical activities (Hamilton et al., 2016).

The provision of structured tasks or projects has trained students to identify concepts, actual inferential relationships, descriptions, questions, or other forms of representation that have been intended to express understanding, experience, information, judgements, reasons, or opinions. Students have examined ideas, have detected arguments, and have analyzed arguments as sub-abilities of analysis to complete the given task/project. Students have sketched the relationship of sentences or paragraphs to each other, structuring these essays graphically to complete the task/project (González, 2017).

Both discussion and collaboration activities have helped students to understand and express the meaning or significance of various experiences, situations, data, events, judgements, conventions, beliefs, rules, procedures, or criteria. In these activities, students have paraphrased someone's ideas in their own words or clarified what statements and arguments mean (Kilbane & Milman, 2014). Discussion and colloquy have made students familiar with giving conceptual explanations or points of view, and presenting full and reasoned arguments, in the context of seeking the best possible understanding. Students have learnt to review and reformulate one of their explanations. Students are also trained to defend their reasoning correctly and structurally (Titova, 2017).

Analysis of Question Validation with New Critical Thinking Dimensions

Before being used, the CTS instrument was validated by the Expert during the FGD activities. The results of the analysis are shown in Table 8. The results of the analysis have shown that all critical thinking instrument questions have fulfilled all aspects and are valid.

Table 8. Results of Expert Analysis on Critical Thinking Instrument

Aspects	Aiken's V	Validity
Rules for making essay questions	0,79	Valid
Linguistics	0,91	Valid
Dimensions of CTS	0,89	Valid
Question indicator	0,82	Valid

To further examine the validity of the instrument, a Rasch model analysis was conducted using Winstep. The visual output of this analysis is presented in Figure 2.

```
+-------------------------------------------------+
| Cat  Score  Exp.   Resd StRes|                  |
|-----------------------------+-------------------|
| 3.73  3.73  3.73   .00  .05 | Mean (Count: 56)  |
|  .44   .44   .24   .38  .91 | S.D. (Population) |
|  .45   .45   .24   .38  .92 | S.D. (Sample)     |
+-------------------------------------------------+
Data log-likelihood chi-square = 48.5545
Approximate degrees of freedom = 43
Chi-square significance prob.  = .2591
                                    Count   Mean    S.D.   Params
Responses used for estimation      =    56   3,73   0,44       13
Count of measurable responses      =    56
Raw-score variance of observations   =  0,20 100.00%
Variance explained by Rasch measures =  0,05  26,38%
Variance of residuals                =  0,14  73,62%
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Figure 2. Results of Critical Thinking Ability Instrument Analysis with Winstep

Figure 2 presents the results of the Rasch model analysis, obtained through a systematic statistical approach. This Figure is an image screenshot of the analysis output, displaying key validity indicators for the CTS instrument. Based on the measurable data summary has shown the value of variance explained by the Rasch measure is 26.38% (minimum value of 20%), so that the data can be said to be unidimensional that which can be continued in the analysis of Rasch. The suitability of the data with the model has been seen from the chi-square value is 0.2591 with a probability of 0.0003. This value shows that the data fit the model so that it can be analyzed using Rasch.

In addition, the results of the Wright map analysis have displayed 3 aspects, namely experts (7), question items (7), and criteria (4). The results of the analysis have shown that the criterion that is most difficult to achieve by experts is "the rules for making essay questions" because it has the highest logit. Meanwhile, the criterion "questions are easy to understand" has been very easy to achieve because it has the lowest logit. In general, the experts have given the highest score. They have assumed that all questions have covered the 4 criteria.

The expert fit analysis results in Figure 3 show that all MnSq and ZStd values have met the criteria. The mean values of Outfit mean square (MNSQ) and standardized (ZSTD) are 1.00 and 0.00, respectively. Both values are within the range that indicates items that fit the model. The limits are 0.5 < MNSQ < 1.5 and -2 < ZSTD < +2. Meanwhile, when viewed based on the separation value of 0.00, it has been shown that the grouping of values given by the experts is the same, which means they have the same perception.

Total Score	Total Count	Obsvd Average	Fair(M) Average	- Measure	Model S.E.	Infit MnSq	Infit ZStd	Outfit MnSq	Outfit ZStd	Estim. Discrm	Correlation PtMea	Correlation PtExp	Exact Agree. Obs %	Exact Agree. Exp %	N Expert Judgement
97	28	3.46	3.52	-1.86	.39	.83	-.6	.75	-.5	1.22	.48	.49	61.3	58.0	6 F
98	28	3.50	3.57	-2.01	.39	1.20	.8	1.05	.2	.80	.50	.48	54.2	58.7	4 D
99	28	3.54	3.61	-2.17	.40	1.13	.5	1.28	.6	.80	.51	.47	57.7	59.4	2 B
100	28	3.57	3.65	-2.33	.40	1.10	.4	1.02	.2	.84	.32	.45	55.4	59.8	3 C
102	28	3.64	3.72	-2.67	.42	.99	.0	.87	.0	1.02	.38	.42	58.3	60.3	1 A
102	28	3.64	3.72	-2.67	.42	.96	.0	.85	.0	1.06	.39	.42	68.5	60.3	5 E
102	28	3.64	3.72	-2.67	.42	.82	-.7	.71	-.3	1.25	.48	.42	68.5	60.3	7 G
100.0	28.0	3.57	3.64	-2.34	.41	1.00	.1	.93	.0		.44				Mean (Count: 7)
1.9	.0	.07	.08	.31	.01	.13	.6	.18	.4		.07				S.D. (Population)
2.1	.0	.07	.08	.34	.01	.15	.6	.20	.4		.07				S.D. (Sample)

Figure 3. Analysis Results of Critical Thinking Ability Instrument Based on Image of Rasch Output

Analysis of CTS questions has been based on the results of a trial of critical thinking questions as many as 8 essay questions, that have been done by 175 students from various undergraduate and vocational institutions. The differentiation of questions in Winstep has been carried out by identifying groups of respondents based on the respondent separation index (Yujobo, 2014), as shown in Figure 4. The value of item separation that has been getting bigger shows the quality of the instrument that has been getting better in terms of items, and overall, respondents are getting better (Keane & Keane, 2014). Grouping more thoroughly has used the strata equation (H). Analysis of respondents has obtained a separation value of 2.02, then the value of H = 3.027, so it can be interpreted that the respondent group can be divided into 3 groups.

PERSON	175 INPUT		175 MEASURED		INFIT		OUTFIT	
	TOTAL	COUNT	MEASURE	REALSE	IMNSQ	ZSTD	OMNSQ	ZSTD
MEAN	12.6	8.0	-2.38	1.03	1.02	.1	.95	.0
P.SD	3.4	.0	2.45	.34	.41	.9	.45	.8
REAL RMSE	1.09	TRUE SD	2.20	SEPARATION	2.02	PERSON RELIABILITY		.80
ITEM	8 INPUT		8 MEASURED		INFIT		OUTFIT	
	TOTAL	COUNT	MEASURE	REALSE	IMNSQ	ZSTD	OMNSQ	ZSTD
MEAN	274.8	175.0	.00	.21	1.01	-.5	.95	-.8
P.SD	33.7	.0	1.14	.03	.53	4.3	.56	3.1
REAL RMSE	.21	TRUE SD	1.12	SEPARATION	5.34	ITEM RELIABILITY		.97

Figure 4. Results of Analysis of Critical Thinking Ability Test Questions

Analysis of CTS questions has been carried out by conducting factor analysis. The selection of institutions has been based on institutions with departments that study a lot about soil characteristics with distribution in several regions with different cultural characteristics. Each dimension of critical thinking ability has been represented by 2 questions. The results of Kaise Mayer Olkin and Bartlett's analysis (Table 9) show a value of 0.873 (greater than 0.5) and communalities (Table 10) with a sig value of 0.000 (less than 0.05), have shows all variable values are greater than 0.5. So, it can be concluded that factor analysis of CTS and dimensions of CTS can be done because it fulfils the prerequisite test, and the variables studied can explain the factor.

Table 9. Kaise Mayer Olkin and Bartlett's Prerequisite Test

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0,873
Bartlett's Test of Sphericity	Approx. Chi-Square	1023,976
	df	28
	Sig.	0,000

Table 10. Communalities Prerequisite Test

	Initial	Extraction
I1	1,000	0,580
I2	1,000	0,621
CI1	1,000	0,651
CI2	1,000	0,725
AE1	1,000	0,578
AE2	1,000	0,548
E1	1,000	0,733
E2	1,000	0,737

The results of the CFA analysis using Lisrel are taken into consideration because the criteria for model fit (goodness of fit) have been met. This can be seen from several aspects, namely; GFI = 0.97 (≥ 0.9) (Jamieson & Grace, 2016); AGFI = 0.93 (≥ 0.90) (Schumacker & Lomax, 2010); RMSEA = 0.044 (less than 0.05) (Conole & Brown, 2018); NFI = 0.99 (≥ 0.9), and CFI = 0.99 (≥ 0.9). Figure 5 is the result of the factor analysis of critical thinking ability. The relationships between variables are all positive. Each question has a loading factor that is high enough to measure the latent factor, so that the questions compiled have been very good at measuring the constructs of each dimension of critical thinking ability. The results of the CFA analysis with Lisrel show that all questions can be used in the limited trial of the use of Project-based learning models and technology integration, because all questions have been constructed by the dimensions of CTS (Ayu et al., 2021). In this study, only 7 questions have been used, namely 1 question of inference, 2 questions of clarification and interpretation, 2 questions of analyzing and evaluating arguments, and 2 questions of explanation. Inference has been considered sufficient to be represented by only 1 question, because the achievement of inference skills from students is quite good and uniform.

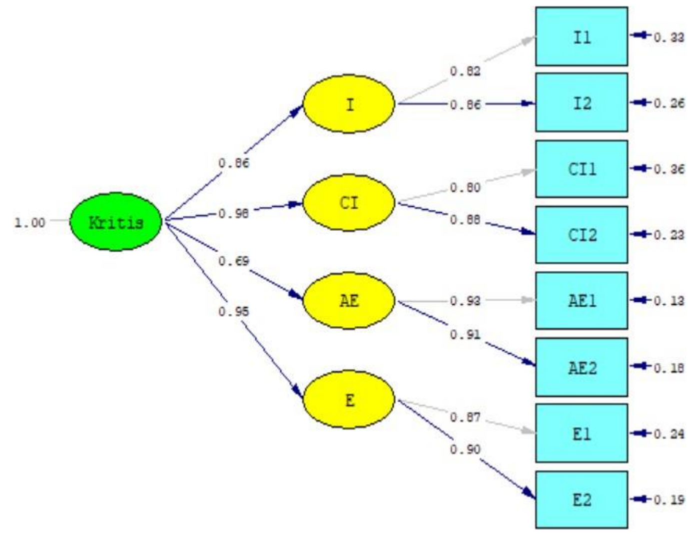

Figure 5. Factor Analysis of Critical Thinking Ability

Measurement Model Analysis

Construct reliability and validity have been shown in Table 11. Construct validity has been shown by the AVE value, where all values are greater than 0.5. Construct validity has also been shown by the factor loading values, as shown in Table 12. All factor loading values have met the criteria of being greater than 0.7, and it has been shown that the relationship between variables is positive. Construct reliability can be seen based on the value of Cronbach's Alpha and Rho_A. It appears that all Cronbach's Alpha and Rho_A values have met the criteria, which are greater than 0.7. All composite reliability values have also met the criteria, which are greater than 0.7 (Boogert et al., 2018). Supported by the P value (0.00) less than 0.05. So overall, based on the aspects of construct reliability and validity, it can be concluded that all questions that are constructed represent and directly affect each aspect of critical thinking ability.

Table 11. Construct Reliability and Validity Analysis Results

Aspects	Cronbach's A	Rho_A	Composite Reliability	AVE	P Value
Inference	1,000	1,000	1,000	1,000	0,000
Clarifying & Interpretation	0,841	1,452	0,913	0,841	0,000
Analyze & Evaluate Arguments	0,871	0,955	0,937	0,882	0,000
Explanation	0,859	0,896	0,933	0,875	0,000

Table 12. Results of Loading Factor Analysis

Aspects	A1	A2	C1	C2	E1	E2	I
Inference							1,000
Clarifying & Interpretation			0,979	0,850			
Analyze & Evaluate Arguments	0,917	0,961					
Explanation					0,919	0,951	

The Role of Digital Technology in Enhancing CTS

The integration of online learning platforms and digital technologies such as AI, GIS, and cloud-based collaboration tools plays a crucial role in developing critical thinking. These technologies enhance students' ability to analyze environmental data, simulate scenarios, and collaborate effectively across distances. AI-powered predictive models and GIS systems enable students to process large datasets, visualize environmental patterns, and explore solutions, fostering higher-order thinking skills. These tools also facilitate real-time collaboration, ensuring that students remain engaged in critical decision-making and problem-solving activities throughout the PjBL process. However, while these technologies provide opportunities for deeper engagement, they also pose challenges. Over-reliance on AI can detract from the critical reflection needed to evaluate information independently, as students may accept AI-generated solutions without questioning their validity. This issue emphasizes the importance of balancing technology use with direct, hands-on learning experiences to maintain robust critical thinking development.

Impact of Hybrid Learning Approach

A hybrid learning approach, combining both online (digital technology) and offline (hands-on project work) activities, is particularly effective in ensuring that students remain engaged in both theoretical and practical aspects of environmental science. The integration of AI for data analysis and GIS for mapping in environmental education enhances the practical experience while also encouraging critical reflection when interpreting results and formulating solutions.

Research by Ayu et al. (2023) supports this hybrid learning model, highlighting that while digital technologies contribute significantly to analytical skills (such as analysis and evaluation), project-based tasks encourage deeper engagement in understanding and clarifying complex environmental issues. The combination of technology and PjBL encourages students to synthesize information from various sources and perspectives, which is vital for effective problem-solving in real-world contexts.

Challenges in Online Learning and Technology Integration

Despite the promising results, the discussion of online learning must focus on specific applications. For instance, in this study, AI tools were not merely mentioned but were applied in the analysis of environmental data, helping students to formulate predictive models. However, further research should explore how different digital tools can be more strategically used to reinforce each critical thinking dimension, particularly in terms of clarifying, interpreting, and evaluating information.

Additionally, the use of cloud-based platforms such as Google Drive, Miro, and Padlet has proven to be effective in facilitating group collaboration, but further integration of these tools into structured learning activities could improve students' ability to engage critically in group discussions and decision-making. Further studies should explore the potential of these platforms to enhance critical thinking by promoting structured debates and reflection on different viewpoints.

Future research should focus on expanding the scope of this study by integrating more diverse student backgrounds and disciplines beyond environmental science. Comparing the proposed model with other existing critical thinking frameworks can offer further insights into the efficacy of hybrid learning and technology integration in fostering critical thinking. Further exploration is also needed to examine the long-term effects of these educational tools on critical thinking development in diverse educational contexts.

Overall, this research has made a significant contribution to the development of technology-based critical thinking indicators and Project-Based Learning. The research methods that have been used are very strong, with comprehensive validation. However, some aspects need to be improved, especially in justifying the selection of critical thinking dimensions, expanding the scope of generalization of results, as well as further discussion regarding practical implementation and comparison with previous models (Ayu et al., 2023). To improve the quality of this research, it is recommended that future studies expand the sample by considering the diversity of students' academic backgrounds, adding the focus of research subjects not only on environment-based courses (science) but also on courses based on social phenomena (Ayu et al., 2023). As well as comparing the model developed with other existing critical thinking models

LIMITATIONS

This study has several limitations that should be acknowledged. The sample size was limited to a specific academic context, which may affect the generalizability of the findings to broader educational settings. Moreover, the study focused solely on environmental education courses, meaning that the applicability of the results to other disciplines remains uncertain. Another limitation lies in the study's time constraints, which prevented an examination of the long-term effects of technology integration on students' critical thinking skills. Additionally, the use of AI and GIS tools requires specific training and technical expertise, which may not be accessible to all institutions, posing challenges for widespread implementation. These factors highlight the need for further research to explore the broader implications and sustainability of the proposed learning model.

CONCLUSION

The results have shown that the critical thinking dimensions that have been developed, namely Inference, Clarifying and Interpretation, Analyze and Evaluate Arguments, and Explanation, have met the criteria of validity and reliability based on Delphi, Rasch, and Confirmatory Factor Analysis (CFA) analyses. The critical thinking dimensions have been developed according to the characteristics of project-based learning with technology integration in learning. This has made it easier for educators to know when to measure each critical thinking dimension in each learning activity. In addition, the pilot test of the instrument on students from various institutions has shown that this instrument is able to measure CTS accurately and consistently, with various characteristics of students and environment-based courses. Thus, this research has successfully developed critical thinking indicators that are relevant to modern learning needs. The findings have contributed to the development of more effective technology-based learning strategies and can be the basis for the development of CTS assessment in various disciplines.

AUTHOR CONTRIBUTIONS

HDA contributed to the conceptualization and methodology of the study, as well as data collection and the writing of the original draft. AJ was responsible for data analysis, visualization, and reviewing and editing the manuscript. HYP provided supervision, validation, and conducted the final review to ensure the accuracy and coherence of the research.

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