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Critical Thinking and Sustainability Awareness for PBL E-Module Development on Siak River Pollution

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ABSTRACT

This study aims to analyze junior high school students' critical thinking skills and sustainability awareness as a basis for developing a Project-Based Learning (PBL) e-module on Siak River pollution. A mixed-methods descriptive design was employed involving 100 eighth-grade students from four schools in the Siak region. Quantitative data were collected using a critical thinking test and a sustainability awareness questionnaire, while qualitative data were obtained through classroom observations and teacher interviews. The results show that students' critical thinking skills are low, with an average score of 40, particularly in evaluating and judging. Similarly, sustainability awareness is also low, with an average score of 39, especially in integrating sustainability values into daily behavior. Qualitative findings indicate that learning is still dominated by textbook-based and teacher-centered approaches, with limited integration of local environmental issues and minimal implementation of PBL. These findings suggest a gap between expected competencies and current practices. Therefore, the development of a PBL-based e-module integrating Siak River pollution is recommended to enhance students' critical thinking and sustainability awareness through contextual and meaningful learning.

Keywords: critical thinking, sustainability awareness, PBL-based e-module

INTRODUCTION

In 21st-century education, students are expected not only to master academic knowledge but also to develop higher-order skills such as critical, creative, collaborative, and communicative thinking (4C) to face increasingly complex global challenges [1], [2] Within science education, critical thinking is parti cularly essential because it supports students in understanding concepts deeply, solving problems, and practicing logical and rational reasoning [3]. Facione defines critical thinking as an intellectual process that involves the analysis, evaluation, and synthesis of information to arrive at logical conclusions, making it a key competence for students in an era of rapid technological development and globalization [4]

Recent empirical studies indicate that the critical thinking ability of junior high school students in Indonesia remains at a low to moderate level. Arini et al report that less than 30% of students reach a high category in critical thinking indicators [5]. Similarly, Hwang et al show that students' critical thinking in science learning is still weak, especially in the aspects of analysis and inference [6]. These findings are consistent with broader literature on higher-order thinking skills, which highlights that low-achieving students often struggle to engage in complex cognitive processes without targeted instructional support. This condition underscores an urgent need for learning models that actively promote critical inquiry and problem solving in authentic contexts.

From an environmental education perspective, schools play a strategic role in building students' awareness and concern for sustainable development. Sustainability awareness encompasses knowledge of environmental, social, and economic issues, along with caring attitudes and responsible actions toward the future of the planet. Through systematic education from an early age, students are expected to become agents of change who contribute to the achievement of the Sustainable Development Goals (SDGs) and Education for Sustainable Development (ESD). However, prior research shows that students' sustainability awareness From an environmental education perspective, schools play a strategic role in fostering students' sustainability awareness, which encompasses knowledge, attitudes, and responsible actions toward sustainable development. However, previous studies indicate that students' sustainability awareness remains at a low to moderate level, particularly in translating knowledge into real-life behavior [7]. This condition becomes more critical when linked to local environmental problems such as river pollution, which directly affects students' daily lives but is not optimally integrated into science learning.

The Siak River pollution represents a real and contextual environmental issue caused by industrial waste and domestic activities, posing serious threats to ecosystems and human health. Despite its relevance, science learning in junior high schools still tends to rely on generic, textbook-based materials that are less connected to local environmental contexts. As a result, students have limited opportunities to develop critical thinking skills and sustainability awareness through authentic problem-solving experiences. This gap indicates that current instructional practices have not yet aligned with the demands of 21st-century education and contextual learning.

In the Indonesian context, the implementation of Kurikulum Merdeka and the Profil Pelajar Pancasila emphasizes the importance of developing critical thinking, character, and sustainability awareness through project-based and contextual learning approaches [8]. Research grounded in Education for Sustainable Development (ESD) also shows that problem-oriented learning models can significantly enhance students' critical thinking skills and sustainability-related attitudes [9], [10]. In addition, digital literacy plays an important role in supporting meaningful learning, as the integration of technology enables students to access, evaluate, and construct knowledge effectively [11], [12], [13]. However, in practice, the integration of local environmental issues into PBL-based digital learning materials remains limited.

To address these challenges, this study proposes the development of a contextual PBL-based e-module that integrates the issue of Siak River pollution into science learning. The novelty of this research lies in combining the analysis of students' critical thinking skills and sustainability awareness as an empirical foundation for designing a locally grounded digital learning resource. Unlike previous studies that tend to examine these variables separately or without contextual integration, this study connects both competencies within a single, contextualized instructional design. Therefore, the purpose of this study is to analyze junior high school students' critical thinking skills and sustainability awareness as a basis for developing a PBL-based e-module on Siak River pollution.

In response to these challenges, the development of PBL-based e-modules emerges as a promising innovation for contextual and student-centered science learning. E-modules can integrate multimedia, simulations, guiding questions, and project scenarios that allow students to investigate local environmental issues such as Siak River pollution anytime and anywhere. Prior studies show that PBL-oriented e-modules not only enhance students' critical thinking and knowledge retention [14], [15], [16], but also strengthen their environmental literacy and engagement because learning is closely related to real-life problems [17], [18], [19], [20]. Therefore, this study aims to analyze junior high school students' critical thinking ability and sustainability awareness as an empirical basis for designing a PBL-based e-module on Siak River pollution. The findings are expected to inform the development of relevant and effective digital learning materials, thereby contributing to the improvement of both science education quality and environmental awareness among Indonesian students.

RESEARCH METHODS

This study employed a descriptive research design with a mixed-methods approach to obtain a comprehensive understanding of students' critical thinking skills and sustainability awareness. The population consisted of all eighth-grade junior high school students in the Siak River area, while the sample involved 100 students from four schools selected through purposive sampling based on their proximity to the river. In addition, science teachers from each school were involved as key informants to provide deeper insights into instructional practices. The data sources in this study included primary data obtained from students through tests and questionnaires, as well as from teachers through interviews and classroom observations, and secondary data in the form of lesson plans, teaching materials, and relevant school documents.

Data were collected using several techniques. A critical thinking test was developed based on indicators proposed by Facione, including analysis, synthesis, problem-solving, drawing conclusions, and evaluation. A sustainability awareness questionnaire was administered to measure students' understanding, attitudes, responsibility, value integration, and motivation toward environmental issues. In addition, classroom observations were conducted to examine learning processes, while semi-structured interviews with science teachers were used to explore challenges in implementing contextual and project-based learning. The use of multiple instruments aimed to ensure data completeness and triangulation.

Quantitative data were analyzed by converting students' scores into percentages using the formula: Score = (obtained score / maximum score) × 100, followed by calculating the mean score using $\bar{X} = \Sigma X / N$. The results were then categorized into five levels, namely very high (81–100), high (61–80), moderate (41–60), low (21–40), and very low (0–20). This procedure was applied to both critical thinking test results and sustainability awareness questionnaire data to determine students' achievement levels across each indicator. The interpretation of these scores was conducted systematically by comparing the obtained mean values with the predetermined criteria to identify the level of students' competencies.

Qualitative data from observations and interviews were analyzed using thematic analysis, which involved data reduction, data display, and conclusion drawing and verification. Relevant data were selected, categorized, and organized into meaningful patterns to identify recurring themes related to learning practices, such as instructional approaches, use of learning materials, and the implementation of Project-

Based Learning (PBL). The integration of quantitative and qualitative data was carried out through a convergent mixed-methods approach, where numerical findings were interpreted alongside qualitative evidence to provide deeper explanations. This triangulation process enhances the validity and reliability of the findings by ensuring that conclusions are supported by multiple sources of data.

RESULT AND DISCUSSION

1. Students' Critical Thinking Ability in Environmental Science Context

The assessment of students' critical thinking ability was conducted using a test instrument specifically developed based on Facione's comprehensive theoretical framework. This instrument encompassed five essential indicators of critical thinking: analyzing information, synthesizing multiple data sources, identifying and solving problems, drawing evidence-based conclusions, and evaluating arguments with independent judgment. The test consisted of five essay-type items, with each item corresponding to one critical thinking indicator and scored using a detailed analytic rubric ranging from 0 to 4 points. The maximum obtainable score for each indicator was 20 points, resulting in a total maximum score of 100 points for the entire critical thinking assessment.

The scoring procedure involved systematic conversion of raw scores to a standardized percentage scale to facilitate interpretation and comparison. The conversion formula applied was: Score = (Obtained Score / Maximum Score) × 100. For instance, a student who obtained 12 points out of 20 on the analyzing indicator would receive a converted score of 60. Subsequently, the mean score for each indicator was calculated using the formula: $\bar{X} = \Sigma X / N$, where ΣX represents the sum of all individual student scores and N equals 100 respondents. The achievement categories were determined based on established educational assessment criteria: Very High (81–100), High (61–80), Moderate (41–60), Low (21–40), and Very Low (0–20).

Table 1. Average Critical Thinking Ability of Junior High School Students in Siak

Critical Thinking Indicator	Average Score (Scale 100)	Achievement Category
Analyzing	45	Low
Synthesizing	38	Low
Identifying and Solving Problems	42	Low
Drawing Conclusions	40	Low
Evaluating and Judging	35	Very Low
Overall Average	**40**	**Low**

The quantitative results presented in Table 1 reveal a concerning pattern of critical thinking deficiency among eighth-grade students in the Siak region. The overall mean score of 40 falls within the "low" category, indicating that students' critical thinking ability is substantially below the competency threshold expected for 21st-century education. More troubling is the uniform distribution of scores across all indicators, with no single indicator achieving even moderate status. The highest-scoring indicator, "Analyzing," recorded only 45 points, while the lowest, "Evaluating and Judging," fell to 35 points in the "very low" category. This 10-point spread suggests that students struggle most with higher-order cognitive processes requiring independent judgment and evidence-based evaluation, while performing only marginally better on basic analytical tasks.

These findings align with previous research documenting widespread critical thinking deficits among Indonesian secondary students. Some previous studies reported that junior high school students achieve high critical thinking levels when assessed using Facione's indicators [21], [22], [23], [24], a pattern confirmed by our data showing aggregate performance in the low category . Similarly, some previous studies demonstrated that students' critical thinking in science learning remains particularly weak in analysis and inference dimensions [6], [25], [26], [27], which corresponds to our findings regarding the analyzing indicator (45) and drawing conclusions indicator (40). The consistency of these results across independent studies suggests systemic educational factors rather than isolated local anomalies.

The qualitative data provide crucial explanatory insights into the mechanisms underlying these quantitative deficits. Classroom observations across all four participating schools consistently documented instructional practices dominated by teacher-centered lectures, textbook reading assignments, and routine exercises focused on information recall. Students were positioned as passive recipients of pre-digested scientific concepts rather than active constructors of knowledge through inquiry and investigation. This pedagogical approach creates a fundamental mismatch with critical thinking development, which requires active engagement with complex, ill-structured problems that demand analysis, synthesis, and evaluation.

Teacher interviews corroborated these observational findings and provided additional contextual depth. One science teacher explicitly stated: "When given the case of the Siak River pollution, many students could list pollutants, but they could not explain the causes and impacts in a systematic manner." This statement reveals that students possess fragmented factual knowledge

without the organizational frameworks necessary for systematic reasoning. Another teacher noted: *"Most students have difficulty interpreting complex information and are not accustomed to processing data logically to formulate independent conclusions."* These professional observations confirm that the low test scores reflect genuine cognitive skill deficits rather than measurement artifacts or temporary performance fluctuations.

The absence of authentic problem contexts emerges as a particularly significant contributing factor. The Siak River pollution, despite its immediate geographical relevance and serious implications for community health and ecosystem sustainability, remains pedagogically inaccessible to students. Observation data revealed that when students encountered this environmental case, they tended to provide descriptive rather than analytical responses, frequently copying information from textbooks or internet sources without connecting it to problem-solving processes. Their responses lacked argumentation structure and evidence-based reasoning, indicating that instruction has not fostered the intellectual dispositions necessary for scientific thinking. This decontextualization creates a double educational disadvantage: students neither master scientific concepts at deep levels nor develop reasoning skills applicable to real-world challenges.

Document analysis of available lesson plans and teaching materials revealed the structural roots of these pedagogical limitations. The reviewed modules followed textbook sequences rigidly, with no incorporation of Project-Based Learning strategies, inquiry-based activities, or local environmental case studies. Without structured opportunities to practice analysis, synthesis, and evaluation in meaningful contexts, students cannot develop these capabilities incidentally. This curriculum-assessment misalignment represents a structural failure in educational implementation rather than individual teacher deficiency, though teachers bear the immediate consequences in classroom practice.

The contrast between our baseline findings and intervention studies is theoretically illuminating. Some previous studies demonstrated that Problem-Based Learning integrated with Education for Sustainable Development contexts significantly improved students' critical thinking skills, with effect sizes indicating substantial practical significance [28], [29], [30]. Similarly, some previous studies reported that Real World Situation PBL enhanced critical thinking across multiple indicators [31], [32], [33]. This apparent contradiction—low scores in our study versus improved outcomes in intervention research—suggests that student performance in critical thinking is determined by instructional methodology rather than fixed ability or demographic factors. The optimistic implication is that appropriate pedagogical innovation can substantially address the documented deficits.

2. Sustainability Awareness and the Knowing-Doing Gap

The assessment of students' sustainability awareness employed a comprehensive questionnaire developed based on UNESCO's framework for Education for Sustainable Development. This instrument measured five interconnected dimensions: cognitive awareness and understanding of environmental issues, affective demonstration of positive attitudes, empathetic responsibility toward environmental problems, behavioral integration of sustainability values into daily life, and motivational readiness to apply learning outcomes in practical action. The questionnaire consisted of 25 items distributed equally across the five dimensions, utilizing a 4-point Likert scale (1 = Strongly Disagree to 4 = Strongly Agree) to capture the full range of student responses. The maximum score for each dimension was 20 points, yielding a total maximum score of 100 points for overall sustainability awareness.

The identical scoring methodology was applied to ensure consistency and comparability with the critical thinking assessment. Raw scores were converted to percentage scale using the formula: Score = (Obtained Score / Maximum Score) × 100. Mean scores were calculated as $\bar{X} = \Sigma X / N$, with N = 100 respondents. The achievement categories followed the same criteria: Very High (81–100), High (61–80), Moderate (41–60), Low (21–40), and Very Low (0–20). This standardized approach enables direct comparison between sustainability awareness and critical thinking competencies, as well as alignment with established educational assessment conventions.

Table 2. Average Results of Sustainability Awareness Questionnaire Analysis

Sustainability Awareness Indicator	Average Score (Scale 100)	Achievement Category
Awareness and Understanding of Environmental Issues	50	Moderate (Nearly Low)
Demonstrating Positive Attitudes	40	Low
Showing Empathy and Responsibility	35	Very Low
Integrating Sustainability Values	30	Very Low
Showing Motivation to Apply Learning Outcomes	38	Low
Overall Average	**39**	**Low**

The quantitative results presented in Table 2 reveal a distinctive and troubling pattern in students' sustainability awareness. The overall mean score of 39 categorizes as "low," indicating inadequate sustainability awareness across the student population. However, more significant than the aggregate score is the substantial disparity between dimensions: the cognitive component (awareness and understanding of environmental issues) achieved moderate status with 50 points, while the behavioral-affective components plummeted to "very low" categories. The most severe deficit appeared in "Integrating Sustainability Values" (30 points), followed closely by "Showing Empathy and Responsibility" (35 points). This 20-point gap between knowledge and practice indicates a severe "knowing-doing gap" that renders environmental education ineffective for sustainable development goals.

These findings align with established research documenting the prevalence of knowing-doing gaps in environmental education. Some previous studies reported similar disparities between environmental knowledge and responsible behavior among secondary school students across multiple national contexts, attributing the phenomenon to educational approaches emphasizing cognitive transmission over experiential engagement [34], [35]. Our data extend this research by precisely quantifying the gap—cognitive awareness at 50 versus behavioral integration at 30—and identifying the specific dimensions most vulnerable to educational failure. The consistency of this pattern across independent studies suggests that the knowing-doing gap represents a systematic feature of conventional environmental education rather than an incidental local variation.

The qualitative evidence provides compelling explanation for the documented quantitative pattern. Teacher interviews consistently revealed that science learning rarely integrates local environmental contexts in ways that foster emotional connection or behavioral relevance. One teacher's statement encapsulates this limitation with particular clarity: "*Students know the Siak River is polluted, but they do not understand how human actions contribute to the problem or what can be done to solve it.*" This observation indicates that environmental topics are taught as abstract scientific content rather than as immediate, actionable community concerns requiring personal response. The geographical proximity of the Siak River paradoxically intensifies the educational failure: students encounter daily evidence of pollution without structured opportunities to understand its causes, consequences, or potential solutions.

Classroom observations corroborated this interpretation through systematic documentation of instructional practices. No evidence of action-oriented learning, environmental project activities, or student-led investigations was observed across any of the twenty classroom sessions. Students were not provided opportunities to apply environmental knowledge in practical contexts, to experience emotional engagement with affected ecosystems and communities, or to develop behavioral habits of sustainability. This absence of experiential learning prevents the formation of the affective connections and self-efficacy beliefs necessary for translating awareness into action. UNESCO's framework for Education for Sustainable Development explicitly emphasizes the integration of cognitive understanding, emotional connection, and behavioral practice; current practices address only the first component, explaining the observed pattern where knowledge exists without corresponding attitudes or intended behaviors.

The material and resource constraints identified through document analysis exacerbate these pedagogical limitations. Teachers reported lacking updated modules, student worksheets, or multimedia resources that connect sustainability concepts with the Siak River context in engaging, interactive formats. The absence of digital learning resources is particularly significant given the characteristics of contemporary students as digital natives who respond more effectively to multimedia-assisted learning than to traditional text-based instruction. Some previous studies demonstrated that digital literacy and contextual learning resources are essential for transforming environmental awareness into sustainable practices, yet such resources are systematically unavailable in the studied schools [36], [37]. This resource gap transforms pedagogical innovation from a professional choice into a structural impossibility.

The comparison with previous intervention research reveals both the severity of current deficits and the potential for substantial improvement. Some previous studies demonstrated that PBL integrated with ESD contexts significantly enhanced sustainability-related attitudes and behaviors, effectively closing the knowing-doing gap through structured experiential engagement [38], [39]. Similarly, Some previous studies reported that Real World Situation PBL improved students' sustainability awareness across all dimensions, including the value integration and behavioral intention components that recorded lowest scores in our study [40], [41]. This contrast between baseline deficiency and intervention success indicates that the knowing-doing gap is addressable through appropriate pedagogical design rather than representing fixed student characteristics.

The theoretical implications of these findings are substantial for environmental education theory and practice. The documented pattern challenges assumptions that environmental knowledge automatically translates into sustainable behavior, supporting instead theoretical models emphasizing the need for integrated cognitive-affective-behavioral educational approaches. The

identification of specific dimensional deficits—particularly the severe weakness in value integration (30) and empathy (35)—provides precise targets for intervention design. The proposed PBL-based e-module must prioritize emotional engagement and behavioral practice components, not merely information delivery, if it is to address the root causes of the knowing-doing gap documented in this analysis.

3. Instructional Practices and Structural Constraints in Science Education

The qualitative investigation of instructional practices employed multiple data collection methods to construct a comprehensive understanding of the educational context. Classroom observations were conducted across twenty sessions in four participating schools, utilizing structured observation protocols to document instructional approaches, student engagement patterns, and learning activity types. Semi-structured interviews with science teachers (n=4) explored professional perspectives on curriculum implementation, resource availability, and pedagogical challenges. Document analysis examined twelve lesson plans and teaching modules to assess alignment with competency-based curriculum mandates. This multi-method approach ensures triangulation and enhances the validity of findings through convergent evidence from independent sources.

The thematic analysis of qualitative data followed systematic procedures: data reduction through coding and categorization, data display through matrices and charts, and conclusion drawing with verification through cross-source comparison. The analysis identified consistent patterns across all data sources regarding instructional approaches, resource constraints, and curriculum implementation gaps. These patterns were organized into meaningful themes representing the structural conditions shaping science education in the Siak region. The integration of qualitative findings with quantitative competency data enables explanation of observed score patterns through identified instructional mechanisms.

Table 3. Summary of Qualitative Findings on Learning Practices

Aspect	Finding	Evidence Source	Frequency/Intensity
Instructional approach	Teacher-centered, lecture-based, textbook-dependent	Classroom observation	20/20 sessions
Student cognitive engagement	Low; descriptive responses dominant	Observation field notes	Consistent across schools
PBL implementation	Absent; no project activities observed	Observation & interviews	All 4 schools
Local environmental integration	Rare; Siak River mentioned only incidentally	Teacher interviews	4/4 teachers
Learning materials	Generic textbooks without local context	Document analysis	12/12 lesson plans
Digital resources	Limited availability	Document analysis & interviews	All schools
Teacher PBL training	Insufficient or absent	Teacher self-report	4/4 teachers
Time for material development	Inadequate	Teacher interviews	4/4 teachers

The qualitative findings presented in Table 3 reveal a systematic misalignment between intended educational outcomes and actual instructional practices. Science learning in the Siak region remains anchored in pre-digital, decontextualized, teacher-centered paradigms despite national curriculum mandates emphasizing contextual, project-based, and digital learning. This misalignment is not random or incidental but structurally produced through interconnected constraints that maintain an equilibrium resistant to innovation. The consistency of patterns across all four schools—despite potential variation in individual teacher characteristics or school resources—suggests systemic factors operating at regional or national levels.

The dominance of teacher-centered instruction emerged as the most pervasive pattern, documented in all twenty observed classroom sessions. Teachers positioned themselves as primary knowledge sources, delivering scientific concepts through lectures and textbook readings while students assumed passive recipient roles. This instructional approach effectively excludes the active cognitive processing necessary for critical thinking development. When students are not required to analyze information, synthesize multiple sources, evaluate evidence, or formulate independent conclusions, they cannot develop these capabilities regardless of innate potential. The pedagogical choice to prioritize content coverage over competency development thus directly produces the low critical thinking scores documented in quantitative assessment.

The absence of Project-Based Learning implementation represents a particularly significant constraint given its established effectiveness for both critical thinking and sustainability awareness. Teachers acknowledged the absence of PBL not as

pedagogical preference but as structural impossibility: they reported insufficient training in PBL design and facilitation, inadequate time for developing contextual learning resources, and lack of appropriate materials and digital infrastructure. One teacher summarized these constraints: *"We know PBL is recommended, but we don't know how to implement it effectively, and we don't have the materials or time to create them."* This statement reveals that curriculum reform mandates (*Kurikulum Merdeka, Profil Pelajar Pancasila*) exist without implementation mechanisms necessary for classroom realization.

The decontextualization of learning materials emerges as a critical factor explaining both critical thinking and sustainability awareness deficits. Available textbooks and modules present scientific concepts in generic, abstract forms without connection to local environmental realities. The Siak River pollution—a phenomenon with immediate relevance to students' daily experience, community health, and regional economic sustainability—appears only as incidental example if mentioned at all. This abstraction prevents students from experiencing science as relevant to their lives and communities, eliminating the motivational and cognitive benefits of meaningful learning. Some previous studies demonstrated that integrating local ecological contexts significantly improves science literacy and environmental responsibility [42], [43]; our findings identify the specific mechanisms—resource gaps, training deficits, material absence—that prevent such integration in practice.

The assessment washback effect reinforces these structural constraints. Teachers face accountability pressures based on high-stakes examinations that emphasize content recall over competency demonstration. When assessment systems reward memorization and punish the time-intensive processes of inquiry-based learning, teachers rationally prioritize examination preparation even when they value critical thinking and sustainability awareness. This creates a self-reinforcing cycle: conventional instruction produces examination success, which validates conventional instruction, which prevents pedagogical innovation. Breaking this cycle requires systemic intervention addressing assessment alignment, resource provision, and professional development simultaneously.

The comparison with successful intervention studies highlights both the severity of current constraints and the potential for transformative change. Some previous studies developed PBL-based e-modules for ecosystem learning that significantly improved student critical thinking through structured inquiry and problem-solving activities [44], [45]. Some previous studies demonstrated that PBL flipbook e-modules empowered critical thinking skills in elementary science education through interactive multimedia engagement [46], [47]. Some previous studies showed that PBL-based e-modules enhanced science literacy among junior high students through authentic problem contexts [45], [48]. These studies share common features—digital delivery, PBL pedagogy, contextual relevance—that directly address the structural constraints identified in our research.

4. Integrated Analysis and Implications for E-Module Development

The synthesis of quantitative and qualitative findings reveals a coherent explanatory narrative connecting instructional conditions with learning outcomes. The convergence of low critical thinking (40), weak sustainability awareness (39), and conventional instructional practices indicates systematic educational failure rather than isolated deficits. This synthesis employs a convergent mixed-methods approach where numerical findings are interpreted alongside qualitative evidence to provide deeper explanatory understanding. The triangulation process enhances validity by ensuring that conclusions are supported by multiple independent data sources, while the integration enables both description of conditions and explanation of causal mechanisms.

The theoretical framework guiding this synthesis posits that critical thinking and sustainability awareness are not independent competencies but synergistically related developmental outcomes. Critical thinking provides the cognitive tools necessary for analyzing environmental problems, evaluating potential solutions, and making evidence-based decisions. Conversely, authentic environmental contexts provide meaningful, consequential scenarios for exercising critical reasoning. This synergistic relationship means that educational interventions can simultaneously address both competencies through integrated instructional design, maximizing efficiency and ecological validity. The documented co-occurrence of deficits in both domains supports this theoretical interpretation, as does the parallel effectiveness of PBL interventions in improving both competencies.

Table 4. Integrated Findings and Intervention Targets

Competency Domain	Current Status	Primary Deficit	Intervention Target
Critical thinking (overall)	Low (40)	Evaluation and judgment (35)	Structured evidence evaluation tasks
Analysis	Low (45)	Systematic reasoning	Scaffolded inquiry activities
Synthesis	Low (38)	Information integration	Multi-source data analysis

Competency Domain	Current Status	Primary Deficit	Intervention Target
Problem-solving	Low (42)	Solution generation	Authentic problem scenarios
Sustainability awareness (overall)	Low (39)	Value integration (30)	Value clarification exercises
Environmental knowledge	Moderate (50)	Application context	Local case study integration
Empathy and responsibility	Very low (35)	Emotional connection	Experiential engagement
Behavioral motivation	Low (38)	Self-efficacy	Action project components

The integrated analysis presented in Table 4 identifies specific intervention targets based on documented competency deficits. The primary targets—evaluation and judgment for critical thinking (35) and value integration for sustainability awareness (30)—represent the most severe weaknesses requiring prioritized attention. The moderate status of environmental knowledge (50) suggests that information transmission is unnecessary; rather, instructional resources should focus on applying existing knowledge in analytical, evaluative, and behavioral contexts. This targeting ensures that limited educational resources are allocated to areas of maximum need and potential impact.

The proposed PBL-based e-module emerges from this analysis as a necessary and evidence-based response to documented conditions. The e-module design must incorporate four essential features derived from research findings: authentic problem contexts using Siak River pollution as the central organizing case, structured inquiry activities scaffolding critical thinking processes from analysis through evaluation, experiential and action-oriented components developing emotional connection and behavioral intention, and digital multimedia delivery engaging contemporary students as digital natives. These features directly address the structural constraints identified—lack of contextual materials, absence of PBL resources, limited digital infrastructure—while leveraging established effectiveness from previous intervention research.

The theoretical contribution of this integrated analysis extends understanding of competency development in science education. By demonstrating that critical thinking and sustainability awareness deficits share common structural causes and can be addressed through integrated intervention, the analysis supports theoretical models emphasizing the interconnectedness of 21st-century competencies. This challenges siloed approaches that address competencies separately through isolated instructional modules. The finding that local environmental contexts can simultaneously serve critical thinking development and sustainability awareness enhancement has significant implications for curriculum design efficiency and ecological validity.

The practical contribution lies in empirical justification for specific e-module design features. Unlike interventions based on general pedagogical principles, the proposed e-module targets precisely documented deficits: the very low evaluation scores (35) require structured evidence evaluation tasks; the very low value integration (30) necessitates value clarification and behavioral commitment components; the moderate knowledge scores (50) indicate that application rather than transmission should dominate information design. This precision increases the probability of intervention effectiveness while optimizing resource utilization.

The policy contribution addresses the implementation gap between Kurikulum Merdeka mandates and classroom realities. Our findings demonstrate that policy pronouncements regarding critical thinking, sustainability awareness, and contextual learning remain unrealized without parallel investment in implementation infrastructure: teacher professional development in PBL facilitation, development of contextual learning materials, provision of digital resources, and alignment of assessment systems with competency goals. The e-module proposal represents one component of necessary implementation infrastructure; broader systemic support remains essential for sustainable educational improvement.

The limitations of this research must be acknowledged to appropriately contextualize implications. The cross-sectional design captures a single moment rather than developmental trajectories, preventing definitive causal claims. Purposive sampling of schools near the Siak River enhances ecological validity but limits generalizability to other Indonesian contexts. Absence of direct student interviews means that learner perspectives are mediated through performance and observation rather than self-report. Most significantly, this study diagnoses conditions and proposes intervention but does not empirically test e-module effectiveness; subsequent implementation research is necessary to validate proposed solutions.

Despite these limitations, the convergent evidence from multiple data sources provides robust foundation for conclusions and recommendations. The consistency of low competency scores across

diverse indicators, the uniformity of instructional practice constraints across multiple schools, and the alignment of findings with established international research collectively support the urgent need for instructional innovation. The proposed PBL-based e-module on Siak River pollution represents a theoretically grounded, empirically supported, and practically feasible response to documented educational challenges, with potential to enhance both science education quality and environmental awareness among Indonesian students.

CONCLUSION

This study analyzed junior high school students' critical thinking skills and sustainability awareness to establish an empirical foundation for developing a PBL-based e-module on Siak River pollution. The findings reveal that both competencies are critically insufficient: critical thinking ability recorded a mean score of 40 with the lowest indicator being evaluating and judging at 35, while sustainability awareness scored 39 with severe deficits in value integration (30) and empathy (35). These quantitative deficiencies are structurally produced by instructional practices dominated by teacher-centered, textbook-dependent approaches that exclude authentic problem contexts and inquiry-based learning, as documented through classroom observations and teacher interviews across four participating schools.

The analysis establishes necessity and direction for instructional innovation. The pronounced knowing-doing gap in sustainability awareness—where moderate environmental knowledge (50) coexists with very low behavioral commitment (30)—indicates that information transmission alone is ineffective. Similarly, the uniform distribution of low scores across all critical thinking indicators suggests that conventional pedagogy systematically prevents higher-order cognitive development. These findings directly inform e-module design: the intervention must prioritize evaluation and judgment tasks for critical thinking, value integration and experiential engagement for sustainability awareness, and authentic Siak River contexts to ensure meaningful learning.

The empirical foundation provided by this study justifies the development of a PBL-based e-module as a strategic response to documented educational gaps. By integrating local environmental issues, structured inquiry, and digital delivery, the proposed intervention addresses the root causes of competency deficits while aligning with Kurikulum Merdeka mandates for contextual, project-based learning. The realization of this e-module promises to transform science education from abstract content transmission into meaningful intellectual engagement, cultivating students who are scientifically literate, environmentally responsible, and capable of critical analysis—essential qualities for sustainable development in the Siak region and beyond.

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